Electrical Engineering Department
California Polytechnic State University

Free Space Optical Communication

Senior Project Final Definition Report

December 13th 2019

Anuj Gohil

Advisor: Dr. Xiaomin Jin

Table of Contents *Page*

Abstract	*2*
Introduction and Background	*3*
Product Description	*6*
Product/Technology/Market Research	*7*
Customer Archetype	*8*
Market Description	*10*
Key Partners	*10*
Market Size and Opportunity	*11*
Competing Products	*13*
Business Model Canvas Graphic `	*15*
Marketing Data Sheet	*16*
Marketing/Engineering Requirements and Specifications	*17*
Functional Characterization	*19*
Testing and Verification	*22*
Schedule	*24*
Preliminary Design Analysis	*26*
Analysis of Senior Project	*27*
References	*31*

Abstract

Communication is key to day to day activities for all companies and people. Wireless communication has made us expect more from our tools. Radio Frequency has been the preferred medium for a couple decades, but there is a need for faster secure communication. Free Space Optical Communication is an alternate wireless communication system which uses optics to create a link. It utilizes low-power and converts an analog signal into digital pulses which are transmitted across space to a receiver. Its only caveat is its vulnerability under atmospheric obstacles. The goal of this project is to create a free space optical transmitter and receiver link that can circumvent the attenuation inherent in adverse weather conditions such as fog presence.

The target requirement for the system is to enable multiple wavelength transmission at safe power levels through non-optimal conditions with minimal errors in the link. The receiver reads the signal as a current input which is amplified to establish an optical link. The integration of optical wavelengths will improve the quality of transmission. The system will strive to minimize signal attenuation from atmospheric obstacles such as fog. This solution will offer customers an alternative wireless medium to Radio Frequency in which Free Space Optical Communication offers a higher bandwidth link at faster speeds while consuming less power. It also offers the same high speed bandwidth seen today in fiber optic cables at a fraction of the cost due to the free space element which eliminates physical wires. Intuitive FSO systems that combine these specifications with a potential transmission distance of up to 2 kilometers will prove to be lucratively successful in industry.

The end result will enable more widespread adoption of FSO technology in addition to securing cheap, smaller community footprint data handling for customers of nearly all business structures. Customers will benefit from an ecologically resilient wireless communication option that ensures security and transmission at competitive speeds.

Introduction and Background

Business owners today rely on resiliency and efficiency of their product to generate revenue and remain competitive within their specific market. Efficiency in the data communication field is determined by the time required to communicate information throughout the business network and to the associated business partners and customers. In all business models, time can mean the difference between outcompeting a rival competitor or failing to deliver a service promise. Timing of data transmission can have damaging effects on the sequential flow of tasks within a business's operations should delays occur.

To improve upon the overall time requirement from start to end of a business activity, high frequency optical signal transfer is a promising solution to augmenting the interconnection between communications networks. Fiber optics is an option, however the logistics and costs to install a complex fiber optics network in populated urban environments or widespread less-populated areas is unrealistic. Free Space Optics is a fast-developing technology that can help newly founded companies flourish, and established corporations to stay ahead of the curve.

With creative system architecture FSO offers users the freedom to quickly and cheaply deploy highly efficient communications platforms for day-to-day business operations or for general connectivity in a secure [5]. Designs for this type of system have been researched, developed and tested under requirements that will ensure it stands out in the market. However, there remains a need for further research into the high-speed data transmission (MHz range) and long spatial distance to form a link. At great distances, atmospheric factors come into the equation. The signal attenuation effects from natural phenomena such as fog, rain or snow threatens the vulnerable medium of optical signals to maintain signal integrity during abnormal weather conditions as shown in Figure 1. Locations such as the San Francisco Bay area, densely populated and often under the influence of fog, and the Pacific Northwest, overcast and precipitation dominated, would benefit heavily from a weather prone transmitter to receiver link.

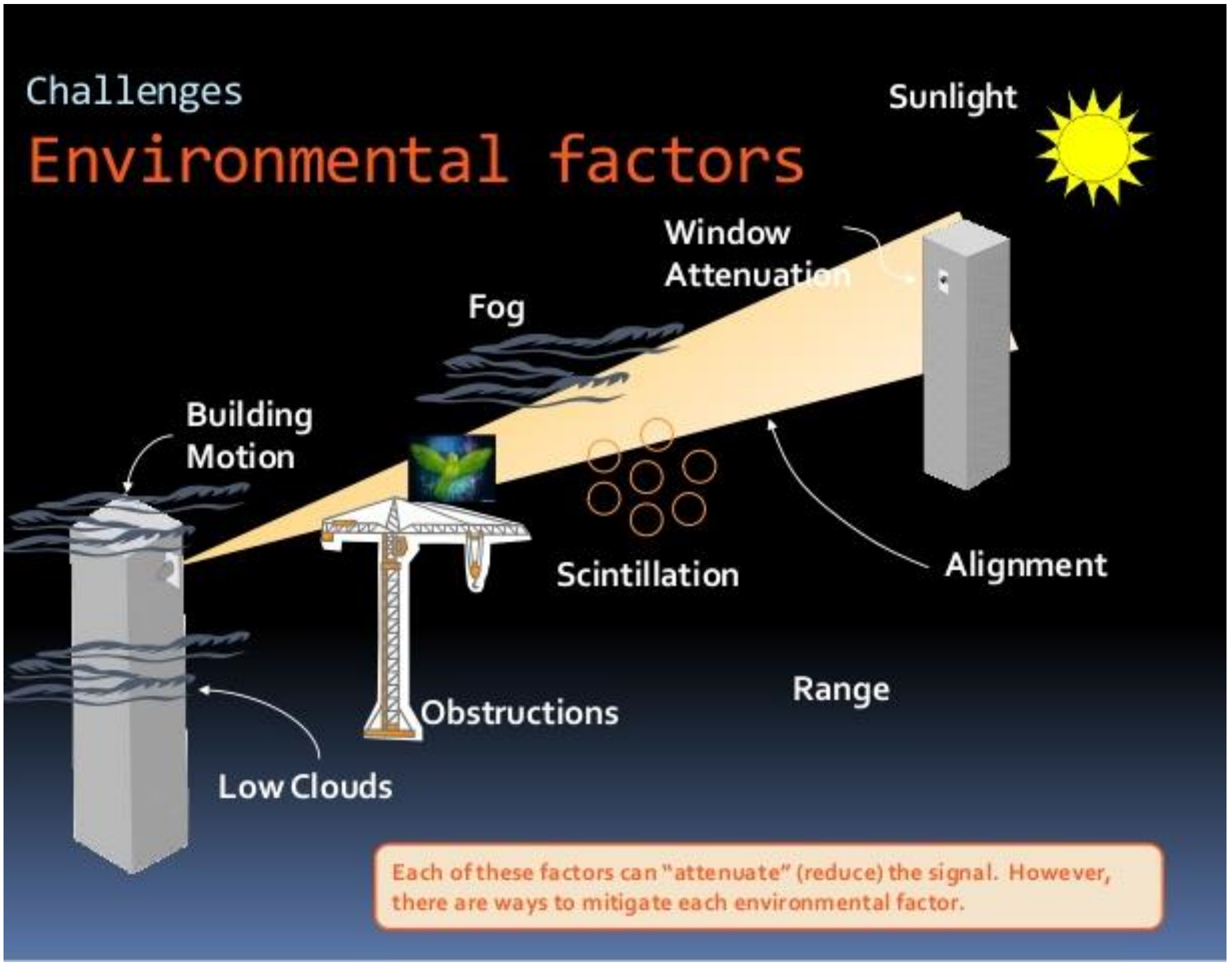


Figure 1: FSO transmission example depicting weather-related challenges [6]

Businesses nowadays are striving to improve their product by finding solutions that can do more with less. Free Space Optical Communication is the clear answer in today's telecommunication infrastructure. The most important aspects to understand are advantages, applications, and current limitations. In contrast to typical data transmission lines, wireless protocols excluded, FSO systems have no dependence on physical hardware connecting the two points. FSO is a unique wireless protocol also because it does not require any licensing, other than safety regulations, to create a long range deployment, unlike radio frequency which requires bandwidth licensing [1]. Add in the high bit and low error rates, and FSO is a powerful tool for networking protocols. This technology utilizes a LED/Laser Diode light source for the Trasmitter and a photodetector for the receiver. These are aligned with each other and a modulated signal is sent over the LED source. It is limited in terrestrial range due to various limiting factors to between 1-2 km currently [2]. In Figure 1 above, there are multiple environmental factors that challenges FSO's success. The most unpredictable limiting factors are related to the weather. Snow is troublesome to correct for with anything but more signal power. Rain is arduous to compensate for due to droplet size. Fog is especially limiting because of its attenuation ability in the range of 10-100 dB/km. Other factors include Atmospheric Absorption, Beam Dispersion, and Scintillation. Background Light can also pose a problem as multiple light sources/reflections will lead to noisy channels.

This system is geared to addressed fog, dispersion and scintillation. Different wavelengths are subject to different effective indexes of refraction as well as different attenuation rates as shown below in Table 1. The goal of this project is to observe the attenuation, and optimize the transmitter/receiver to accommodate the atmospheric obstacles.

Table 1: Attenuations in different weather conditions [4]

Condition	**Attenuation in dB/km**
Heavy Fog	80-200
Light Fog	40-70
Snow	20-30
Rain	4-17
Clear Weather	0.2-3

Free space optics takes existing principles from fiber optics and modifies the medium through which they are transported. This modification has led to a number of notable advantages, including high security due to limited transmission space, little to no electromagnetic interference since there is no over-crowding, optimal functioning across glass for indoor installation, and simple quick deployment. [3]

Product Description

A Free Space Optical Link is a transmitter-receiver pair which uses modulated light to send information between two points. There is no requirement for a physical transmittance medium between the points, just line of sight. This system works well in most conditions, but suffers dramatic performance losses under fog or obstruction.

Figure 2: Real-Life Implementation of Free Space Optics by *LightPointe Communications* [10]

Implementing different light sources with exclusive wavelengths could offer major improvement to mitigate signal attenuation. The transmitted wavelengths will be created using LEDs and/or diode lasers, transmitting at wavelengths which are most immune to attenuation from fog and atmospheric conditions. By varying the wavelength used in the link, the system would be able to circumvent obstacles and prevent interruption significant loss.

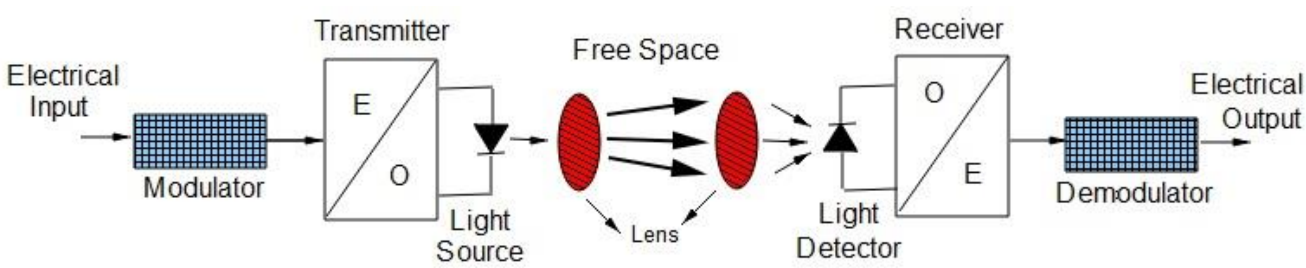


Figure 3: Free Space Optical Link Block Diagram [8]

Product/Technology/Market Research

Existing products in the commercial free space optics market generally integrate alignment capabilities in order to maintain a stable link. Building-to-building links require the transmitter and receiver to be physically aligned in order for information to transmit correctly. Active alignment systems compensate for physical movement between buildings, but attenuation due to environmental conditions, such as fog or rain, presents a separate issue.

This product's design has the capability to be integrated within a wide range of existing network solutions. The transmitter and receiver can be purchased by the customer, who may then install it to their network infrastructure. This system can adapt to the environment by adjusting the optimal operating wavelength and transmitted power. This balance between signal power and wavelength allows the customer to use the product with better efficiency.

From the research at this time of the market, there are some large Free Space Optical companies in operation that already hold many partnerships with companies in the area to provide them with sufficient wireless data transmission. However, none of these companies have a specialized model to handle weather obstacles. The adjustable wavelength function within this product will stand out in the market as an alternate FSO design that can operate 365 days a year whether rain or shine.

Customer Archetype

In marketing an FSO system, the market is large and all successful businesses need data connectivity. Networking companies, and their administrators and network engineers, belonging to any size and type of company would act as the target customer base. These individuals maintain a critical role in ensuring that at any given time, a company can continue to function through interdepartmental communication and connection to the resources necessary for development. Corporate administrators look for several key factors in choosing the technology that supports the foundations of their respective businesses including reliability, security, bandwidth, cost, and quality. These individuals prefer to stay proactive in developing the network architecture, and steer clear of spontaneous systems that bring about disruptions to network service through data flow interruptions, equipment failure, or security breaches. FSO communications majorly support the roles of network administrators in the realms of security, bandwidth, cost, and quality. This product is most evidently an improvement to the reliability condition in contrast to alternative FSO systems. A network engineer studying this FSO system would notice that in the case of fog, a network would not be dropped. This is attractive to the network engineer because she/he would not have to struggle to restore the link, or get anxious about wasting a day of business operations. Network engineers range in profession. In many cases, they are formally employed on behalf of a business. In some cases, these individuals conduct connectivity activity under event and military camp circumstances. Some network engineers perform services such as development of connectivity infrastructure for residential neighborhoods. Casual neighborhood use between friends/family is a possible use of FSO. Those seeking a shift from a major network provider can implement a FSO system throughout a residential area for a bargain compared to major network providers. This option is also desirable for those yearning for private wireless communication. The data is secure between the sources, and the customer can be assured that FSO prevents suspicious multi-billion-dollar companies from the opportunity to gather share one’s data. In any case, the FSO system will remain capable of application across each of these environments and as such may be marketed to network engineers universally.

Companies specializing in networking protocols are our ideal customer. High profile examples include Cisco Systems, Juniper Networks, Aruba Networks, and Arista Networks. Collaborating with these companies will prove to be a mutually beneficial relationship. We would benefit by getting access to a high volume of clients in the networking industry, and also profiting from contracts in the same tier fitting for multi-billion networking companies like those mentioned above.

An FSO system negates the pains of an expensive, insecure cable near street level that requires extra infrastructure and remains liable to interference along its pathway due to inadvertent cable damage. The gains that the FSO system sees favor network administrators and their respective businesses operating in dense urban environments that may or may not endure foggy conditions. These gains include easy access to high speed internet and data communication at inexpensive levels through a number of weather conditions. On top of that, the surrounding community will prosper from the absence of utility poles and underground cable installations.

There are a few companies that create FSO systems for business-to-business applications. The transmitter/receiver link is seen amongst all competitors' systems but they vary in their implementation. In addition, different companies focus on different network demands based on region, industry partnerships, and resources. A list of major companies that would be competing for business with our customer base are listed in Table 2.

Table 2: Notable Competitors in the Field of Free Space Optics

LIGHTPOINTE® WIRELESS FIBER — BACKHAUL RADIOS & LASERS	**LightPointe Communications, Inc.** is a major company based in San Diego, CA specializing in outdoor point-to-point wireless networks. They are the leading manufacturer of point-to-point gigabit ethernet free space optics systems. They have also developed a patented hybrid laser/RF link.
fSONA OPTICAL WIRELESS	**fSONA** is a free space optics company based in Canada. Their SONAbeam systems are designed using 1550 nm wavelength light to create reliable, higher-powered eyesafe systems. In addition, their systems are protocol independent allowing easy integration in any wireless network.
SKYFIBER™	**Skyfiber, Inc.** is an optical wireless broadband (OWB) company based in Texas. Their patent for use of OWB in a mesh network allows them to create effective mesh network for large projects.
FASTLINKS Wireless Network Solutions	**FastLinks LLC** is an optical/RF network design company based in Massachusetts. They focus on design working with clients to implement the best solution specific to their problem.
artoLink®	**Artolink** is a free space optics company based in Russia. They produce different optical link models, the fastest of which is capable of a data-rate of 10 Gbps.

Market Description

Key Partners

In order to enter and thrive in the FSO system market, it is essential that partnerships be developed with other companies. These companies' products would go into the design of the FSO system and help minimize the cost of the overall product. A table of companies that would help us succeed in the market are listed below in Table 3.

Table 3: Key Partners for System Production

THORLABS	Thorlabs is an optical equipment company that manufactures approximately 90% of its products. Their onsite manufacturing enables them to customize products according to customer requests. Under their Strategic Partnership Program, Thorlabs seeks to form partnerships with researchers and organizations.
COHERENT®	Coherent is a company that primarily designs and manufactures laser sources, systems, and instrumentation equipment. They are the world's leading supplier of laser solutions and design lasers for a broad range of applications.
TEXAS INSTRUMENTS	Texas Instruments is one the world's largest semiconductor manufacturer. They are able to supply most components required for the construction of a transmitter and receiver, including op-amps, resistors, and transistors.

Market Size and Opportunity

Compared to most technology-based markets only a relatively small number of companies are involved in the free-space optics market. This product can provide an efficient solution to atmospheric attenuation. Demonstrations and presentations must be held in order to advertise the functionality of this product. Possible venues for demonstration include SPIE Photonics West and The Vision Show.

Attenuation due to weather acts as a primary reason behind the relatively small number of new companies involved in the FSO market. Curing this inhibiting factor on marketability will open up an impressive amount of venues for sales. Figure 3 shows the average days per year that major cities experience fog. Seattle, Atlanta, Raleigh, Houston, each an exemplary dense urban community with a significant culture for business and technology, experience upwards of 160 days of fog a year on average. As the FSO market currently stands, this fog largely inhibits the presence of the technology in Seattle. However, this product's market solution would open up FSO to Seattle, thereby greatly increasing overall market size. This market increase could gain the necessary momentum for numerous weather heavy cities across the U.S. to take up FSO. Our fraction of the FSO market will be the FSO market that has not been explored due to weather inhibitions.

City	Cloud	Fog
Atlanta, Georgia	149	159
Austin, Texas	136	127
Baltimore, Maryland	152	144
Birmingham, Alabama	155	178
Boston, Massachusetts	164	139
Buffalo, New York	208	174
Charlotte, North Carolina	152	168
Chicago, Illinois	176	124
Cincinnati, Ohio	186	166
Cleveland, Ohio	202	157
Columbus, Ohio	190	166
Dallas, Texas	133	91
Denver, Colorado	120	56
Detroit, Michigan	185	156
Hartford, Connecticut	175	162
Houston, Texas	161	194
Indianapolis, Indiana	179	175

City	Cloud	Fog
Jacksonville, Florida	144	198
Kansas City, Missouri	149	123
Las Vegas, Nevada	73	5
Los Angeles, California	103	92
Louisville, Kentucky	171	142
Memphis, Tennessee	151	115
Miami, Florida	115	43
Milwaukee, Wisconsin	175	142
Minneapolis, Minnesota	169	103
Nashville, Tennessee	156	164
New Orleans, Louisiana	146	200
New York, New York	132	131
Oklahoma City, Oklahoma	130	96
Orlando, Florida	130	157
Philadelphia, Pennsylvania	160	164
Phoenix, Arizona	70	7
Pittsburgh, Pennsylvania	203	183

City	Cloud	Fog
Portland, Oregon	222	125
Providence, Rhode Island	164	166
Raleigh, North Carolina	149	198
Richmond, Virginia	160	185
Rochester, New York	200	133
Sacramento, California	100	104
Salt Lake City, Utah	139	46
San Antonio, Texas	141	130
San Diego, California	102	97
San Francisco, California	105	108
Seattle, Washington	226	165
St. Louis, Missouri	164	158
Tampa, Florida	121	133
Virginia Beach, Virginia	153	157
Washington, DC	164	130

Figure 4: Average days per year of fog or cloud cover in major U.S. cities [7]

In a 2018 paper published by *Markets and Markets*, the market for Free Space Optics, $270 Million as of 2018, is expected to grow to $1.45 Billion by 2023. This growth is due to the lack of bandwidth deficiency and free licensing of the FSO system. Visible Light Communication entirely is expected to be a $75 Billion Market by 2023 because of the wide specializations possible for this type of communication, such as countering atmospheric attenuation with this product. This an example of a single innovation bolstering what Light Communication can achieve and how it can garner lucrative profits in the market. [9]

Competing Products

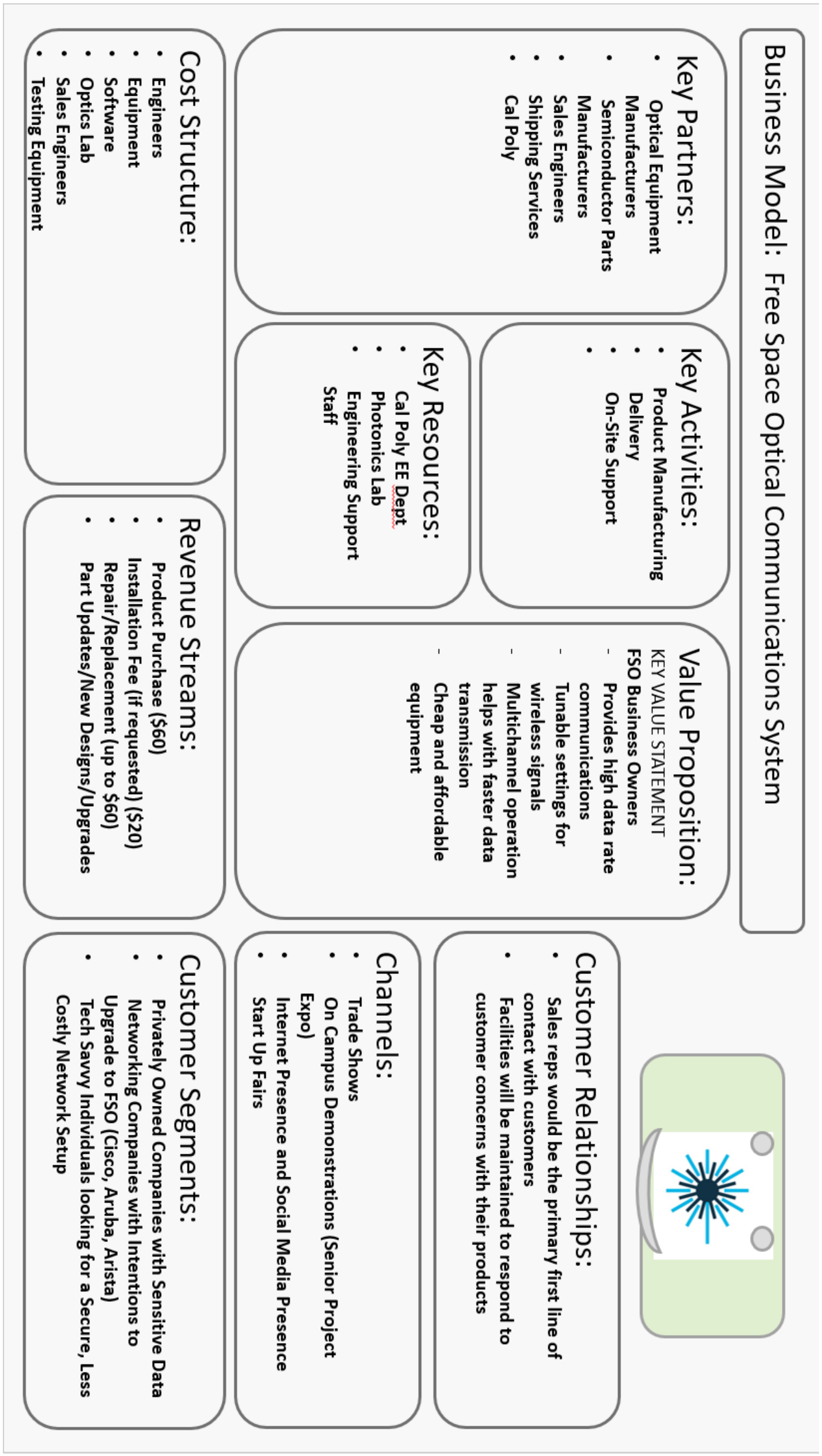
Prior to deploying the product to market, several considerations regarding development and investment must be taken. The implicated costs of design, prototyping, testing, product demonstration and marketing must be assessed. Competing products are an informative reference to establish an estimate for production costs and the timeline necessary to develop. Existing transmitter-receiver products on the market have limited adaptability to environmental conditions. Each of the previously stated competitors provide a unique advantage that still makes it valuable in the eyes of the market. *LightPointe* specializes in point to point gigabit systems, which is useful with its hybrid FSO/RF system. *fSONA* is attractive to the small-time user, such as in households rather than companies. They are protocol independent and allow for easy interaction with any wireless network. *Skyfiber* got into the game early by patenting their broadband mesh design which works for larger corporate sized projects. *FastLinks* acts as a consulting based company in FSO technology, trying to solve case specific problems. *ArtoLink* is an international competitor from Russia, so they hold an advantage by running a secure data transmission platform in a country where there is less of a market for security. Some products from the more powerful competitors have the ability to mechanically align the transmitter and receiver angles and utilize beam divergence in accordance with the fields of vision. Competing products can also increase the output power of the transmitter to compensate for the attenuation due to the atmosphere. Products that advertise a tunable wavelength in addition to these solutions for attenuation are rare. Some current competing FSO systems are described in Table 4 below.

Table 4: Competing Free Space Optics Systems

Product Image	**Product Name**	**Description**
	fSONA SONAbeam 2500Z	The SONAbeam Z series provides an economical solution for short distance links up to 500 meters and deliver up to 2.5 Gbps of full duplex bandwidth. Its 1550 nm wavelength allows it to penetrate harsh atmospheric conditions [11]. Disadvantage: Limited Range

	Skyfiber SkyLINK	The Skyfiber SkyLINK allows for a high capacity broadband link with speeds up to 1.25 Gbps. It is portable allowing for quick installation and redeployment should the needs of the user change [12]. Disadvantage: No fog correction or humidity removal
	LightPointe Aire Xtreme X-FSO	The LightPointe Aire Xtreme Series has speeds of 1.25 Gbps for distances up to 2.8 km at 3dB/km. In addition, the system experiences the lowest latency compared to other systems at 20ns [13]. Disadvantage: Cost
	Artolink M110GE	The M110GE can send data at speeds of 10 Gbps up to 2.5km. It has a RF backup so transmission across the link can continue should the optical portion of the unit fail [14]. Disadvantages: Requires licensing for RF bandwidth

Business Model Canvas Graphic



Marketing Data Sheet

Product/Project Name: Free Space Optical Communication System

Unmet Customer Need: Secure, Fast, Low Cost, Wireless Communication. In recent times, many people have voiced their concerns about how their data is used and at what cost to their privacy.

Unique Value Proposition: The FSO system offers customers the opportunity to have fast wireless communication but completely secure because it employs optical communication rather than radio frequency.

Target Customer: Networking Companies (Cisco, Aruba, Arista) that are looking for innovative wireless networking technology to upgrade their clients. Tech Savvy individuals that are looking for a cheaper alternative to wireless communication that protects the individuals privacy.

Positioning: Personal FSO use is the next revolution after phones and Social Media for communication.

Pricing and Availability:
- $60
- S.P. Expo (product launch event)
- Spring 2020 (launch date)

Product Objectives:
- Gain Customer Base of 1,000
- >4.5/5 Customer and Critical Reviews
- Find High Profile Investors to Scale Up Impact

Customer Benefits:
- Flexible to install system at home anywhere outside
- Effective across distances up to 1.5 km away
- Equipment is lower in price, so less cost to the customer in the case of repairs.

Sustainable Differentiation:
- Far more SECURE Optical design
- Low Power Usage
- Ultra Fast Data Rate = instantaneous communication
- FSO is the new RF

Disruptive Go-to-Market:
- University Campuses (Students live within close distances of each other)
- Holiday Discounts (Free Installation)
- Social Media Campaign
- Publish Advertisements in Scientific Journals
- Reddit Movement (Highlighting Cons to RF)

Marketing/Engineering Requirements and Specifications

To effectively compete in the market, certain customer expectations must be ensured. In addition, to compete with other products in the market this free-space optical communication system must at least meet certain standards. The engineering and marketing requirements that should be satisfied by this product are shown below in Table 5.

Table 5: Specifications for Free Space Optical Communication System

Marketing Requirement No.	Engineering Requirements	Justification
1, 2, 6	Signal detectable at a distance of 1 km for the 625 nm wavelength (most detectable across long distances) used in clear conditions	Comparable transmission characteristics to current FSO technology. This will meet the baseline for a competitive edge.
1, 2, 6	Signal detectable at a distance of 0.5km on a foggy day for a wavelength suitable to fog conditions.	Allows for a wider market in fog-prone cities that have typically resisted FSO technology. This will prove essential to develop in urban environments.
1, 3, 6	Data transmission rate of at least 1 MHz @ 90% bandwidth	Comparable transmission characteristics to current FSO technology. This will meet the baseline for a competitive edge. 90% @ greater than or equal to 1MHz is a must to be a viable alternative to other communication technologies.
4, 5, 6	Dimensions of less than a cubic foot and resilient exterior	Smaller sized devices market more successfully, install easily, and promise a great range of locations for installation. The enclosure should be able to protect the circuitry from the weather in an outdoor environment.

2, 6, 7	Power draw of less than 5 W from mains electricity source	Low power consumption under continuous-use impactsutility bill less. Low power also correlates to a lower ratio of wasted power to transmitted power. Ideally, power draw and transmitted power will present a nearly 1 to 1 match.
2	Eyesafe optical power output as required by ANSI Z136.6 standard	FSO technology incorporates itself into populated outdoor environments where there exists the potential for human interception. Eyesafe standards ensure that the FSO technology does not interfere with the well-being of the community at large.

Functional Characterization

Figure 5 below shows the High-Level Block Diagram of the Free Space Optical Link system.

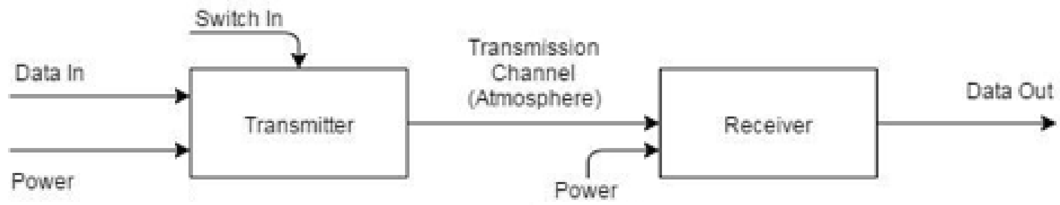


Figure 5: Block Diagram of FSO System

Table 6 provides a description of the inputs and outputs of the Level 0 Block Diagram.

Table 6: High Level Input/Output Functionality

Input/Output	**Name**	**Description**
Input	Data In	The digital data in electrical form that will be transmitted across free space. A *Hewlett-Packard 8116A Function Generator* acts as the data input in the design/testing process.
Input	Power	The transmitter and receiver both receive the same power. This product is advertised as a low-power system, so <12V is the design goal.
Input	Switch In	The switch receives input from the user for operation. If no input is received, the system remains idle, and no power is transmitted. The switch is implemented through a NMOS MOSFET that blocks the current through the circuit without the triggered switch.
Input/Output	Transmission Channel (Atmosphere)	Light will be output from the transmitter block after conversion from electrical to optical signal. The light travels through the channel (atmosphere) where it is received as an input at the receiver block where the signal will be converted to a electrical signal from the optical light.
Output	Data Out	The data at the output from the receiver block. In research/testing purposes, the output is probed through a *Keysight InfiniVision MSO-X 2022A Mixed Signal Oscilloscope*.

The Transmitter subcircuit takes in approximately 12V or less to power the transmitted signal. A current-defining resistor is placed in series to limit the current, and therefore limit the transmitter to low-power. The resistor is then wired to a light emitting device (LED) or laser diode (LD), which will transmit the signal optically to the receiver photodiode. The NMOS MOSFET's Drain is connected to the LED/LD's negative terminal to provide the circuit with a current-sink when turned on. The Gate of the MOSFET takes in the transmit signal and determines the transmitting frequency (ideally above 1MHz). The Source is grounded to complete the current sink of the circuit.

The Receiver subcircuit receives the signal in the form of light from an LED or LD at the photodetector, which converts the optical signal to electrical current. The current is converted to a voltage and inverted through a transimpedance amplifier. A feedback resistor determines the Voltage at the output of this stage and feedback capacitor helps sweep out parasitic noise. The output of the first stage is drawn into a non-inverting voltage amplifier to augment the electrical voltage signal back to the amplitude present in the transmitter subcircuit. Both of the operational-amplifiers implemented are powered by the same 12V or less voltage used in the transmitter to ensure a holistic low-power system design. The output of the second stage voltage amplifier is determined by the feedback and grounded resistor at the inverting input of the op-amp.

Testing and Verification

Table 7 below demonstrates anticipated methods of ensuring that engineering design specifications have been met.

Table 7: FSO Testing Plan

Engineering Requirement / Specification	**Plan of Verification**
Clean Signal Transmission without atmospheric obstruction (Clear)	Implement an isolated chamber with a clear line-of-sight to transmit and receive an electrical signal under clear conditions. Measure and confirm the output signal at the receiver replicates the input signal from the transmitter. Maintain at least 1m between the LED/LD and the Photodiode to observe any noise or signal loss across free space. Use Oscilloscope to measure and record the stable output voltage at receiver when clean signal is received. Use Optical Power Meter to measure and record the stable optical power at the photodiode when clean signal is received.
Environmentally Limited Signal Transmission (Fog)	Cover all openings throughout testing set-up except for one location to release fog into test chamber. Use fog machine to release fog into chamber for 10 seconds, and then close fog machine opening. Observe optical power meter for when it stabilizes at its lowest Watt value, and then open fog machine opening to let fog slowly exit. Measure and record output voltage at receiver until the Oscilloscope clearly displays nearly identical output signal and input signal, and the output voltage has returned to the stable Vout measured in a clear environment. Measure and record optical power at photodiode until the Optical Power Meter displays a measured power equivalent to the optical power at the photodiode in a clear environment.

Data Transmission Rates (Ideal and Non-Ideal Conditions)	In both fog-filled and clear chamber, test the maximum Data Transmission Rate that outputs a clean signal equivalent in form to the input signal. Target greater or equal to 1MHz to ensure system is comparable to the high-speed of FSO systems from competitors.
System Power Draw (High, Typical, and Low)	Install a Optical Power Meter at the photodiode to measure and record the power transmitted across free space. Connect ammeter in series in both transmitter and receiver subcircuits to calculate and sum up total power draw of FSO system. Target a power draw of 5W or less to ensure system is low-power.
Varying Wavelengths through LED/LD (Red, Blue, Green)	Repeat above testing and verification plans with different light sources. Each light source color provides a unique wavelength. The wavelength must be registered in Optical Power Meter. Verify each LED transmits a clean signal without fog, and measure how long until the system returns to optimal Vout and Optical Power when initially in a fog filled chamber. Verify the fastest Data Transmission Rate is above 1MHz, and that the entire system does not draw more than 5W for each light source.

Development and Construction

The first prototype implementing Free Space Optical Communication was built as the final lab for EE443: Fiber Optics Laboratory. The goal of this project was to gain an understanding of how a transmitting end is assembled using laser diodes or LEDs, and how a receiving end is eventually amplified using a photodetector output. The transmitter incorporated a 9V input connected in series to a 50Ω resistor and a laser diode. The NMOS MOSFET used was an IRF540. Figure 5 displays the exact configuration of the transmitter circuit.

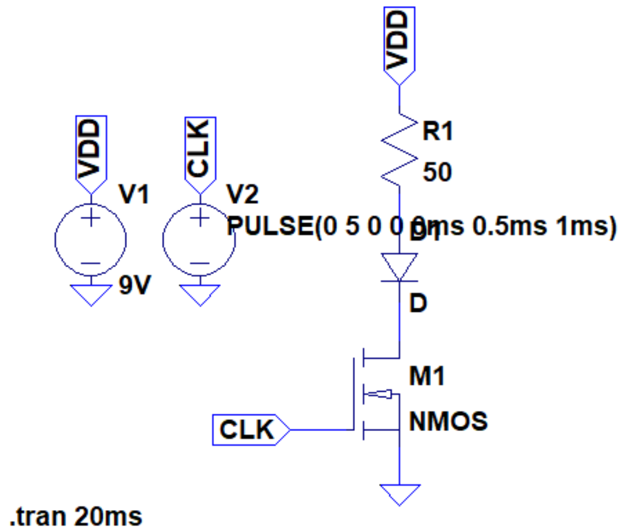


Figure 5: Basic Transmitter Circuit

The receiver circuit operated similar to the functional characterization above, where the first stage was a transimpedance amplifier converting the current received from the photodiode to a voltage, and the second stage was a voltage amplifier. The first stage received a 5V power supply, and the second received a 8V supply. The input current to the first stage increased by a factor of -3300 because of the 3300Ω feedback resistor. The second stage amplified the input voltage by a factor of 79 due to the feedback resistor equaling 7800Ω, and the grounded resistor equaling 1000Ω in a non-inverting amplifier fashion. Figure 6 displays the configuration of the receiver circuit.

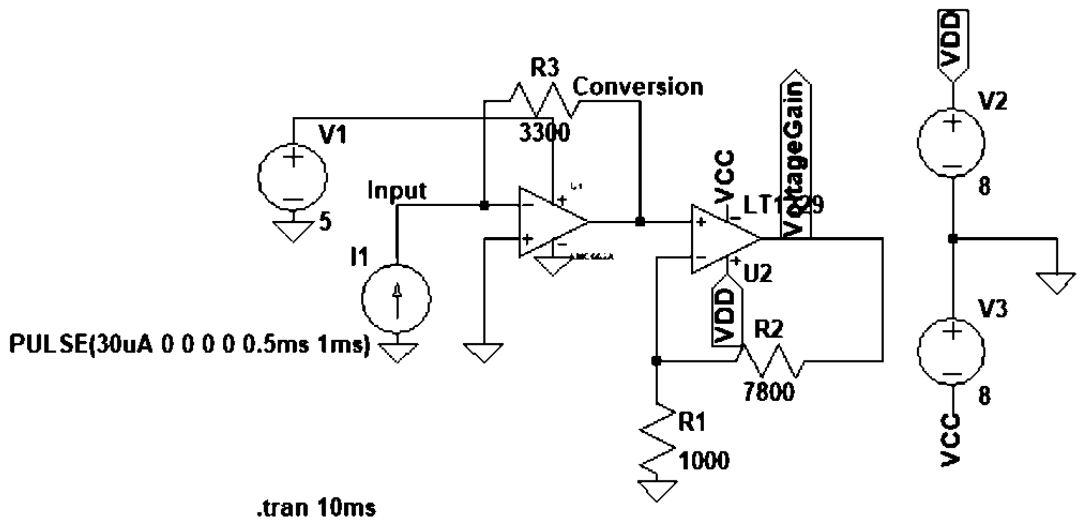


Figure 6: Basic Receiver Circuit

I emphasize that this is a basic implementation of FSO as it had concrete limits that are miles away from characteristics necessary to compete in industry. The transmission frequency was only 1-5kHz. On the other hand, the system was extremely low-power. Figure 7 below depicts the input signal in green, and the received amplified identical output signal in yellow.

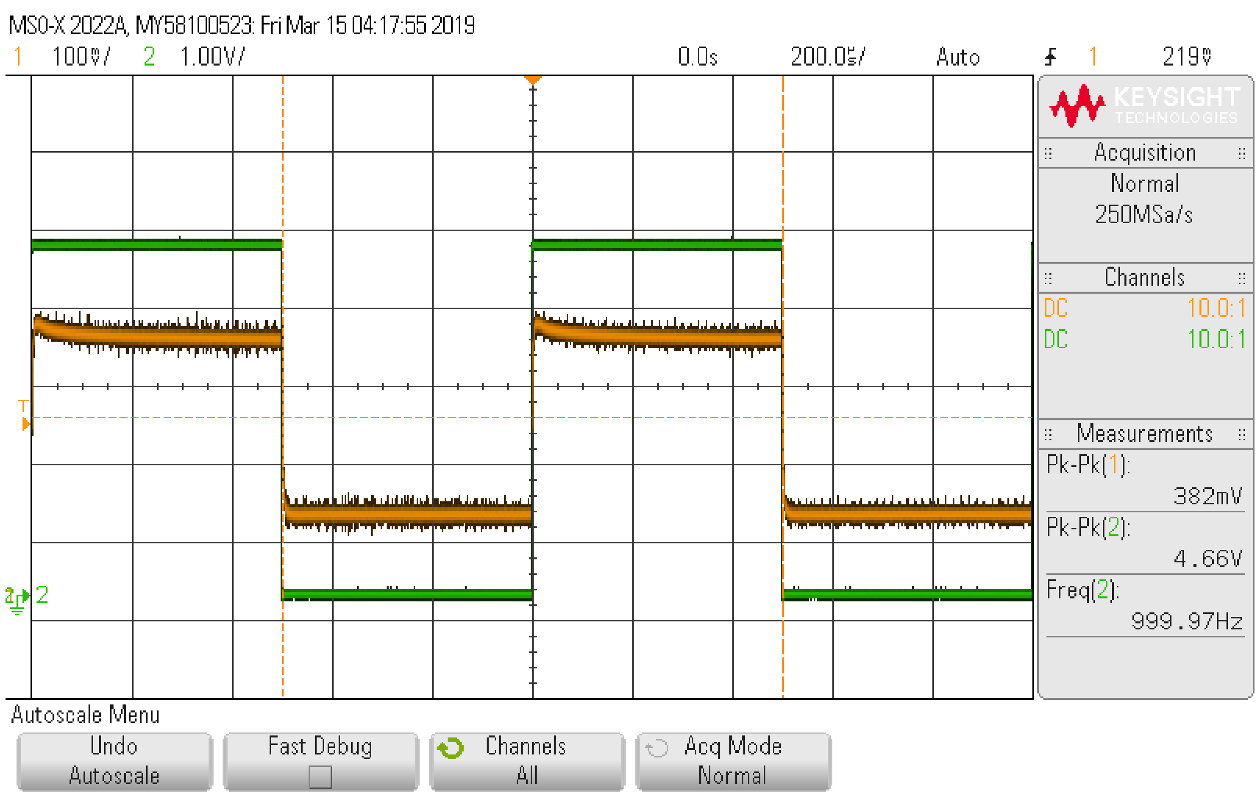


Figure 7: Transmitted Signal (Green) and Received Signal (Yellow)

Following this introduction, I began my research into Free Space Optics and how it is implemented both in businesses and for personal use. Over the course of my research, my advisor exposed me to a FSO company in the Czech Republic, *Reasonable Optical Near Joint Access* (RONJA), which could offer me inspiration on how to design my own high-speed low-power FSO system. RONJA's website has numerous resources on how to build an FSO system, including schematics and part lists for their Transmitter and Receiver designs at a range of operating distances [15].

The next priority was to design a FSO system that could transmit in the MHz range. The transmitting frequency is especially dependent on the light source. LEDs on their own cannot transmit a strong enough signal to be detected across fog and past 1m. Laser Diodes have a stronger concentrated signal where the light does not spread and the phase is aligned, but they are incredibly sensitive to input voltage. It is easy to break an expensive Laser Diode if you are not attentive to its maximum voltage specifications. Unlike LEDs which generate light through spontaneous emission, LDs use stimulated emission, meaning the LD needs to surpass a specific current to begin emitting. LEDs are spontaneously generating; hence their emission can occur at any current. LDs are more powerful than LEDs, but I felt inflexible when using a LD because of its tiny size and limited wavelength. However it did solve the timing issues between the square wave intervals in our system. Figure 8 depicts our same circuit with far cleaner edges due to the intense signaling of the Laser Diode.

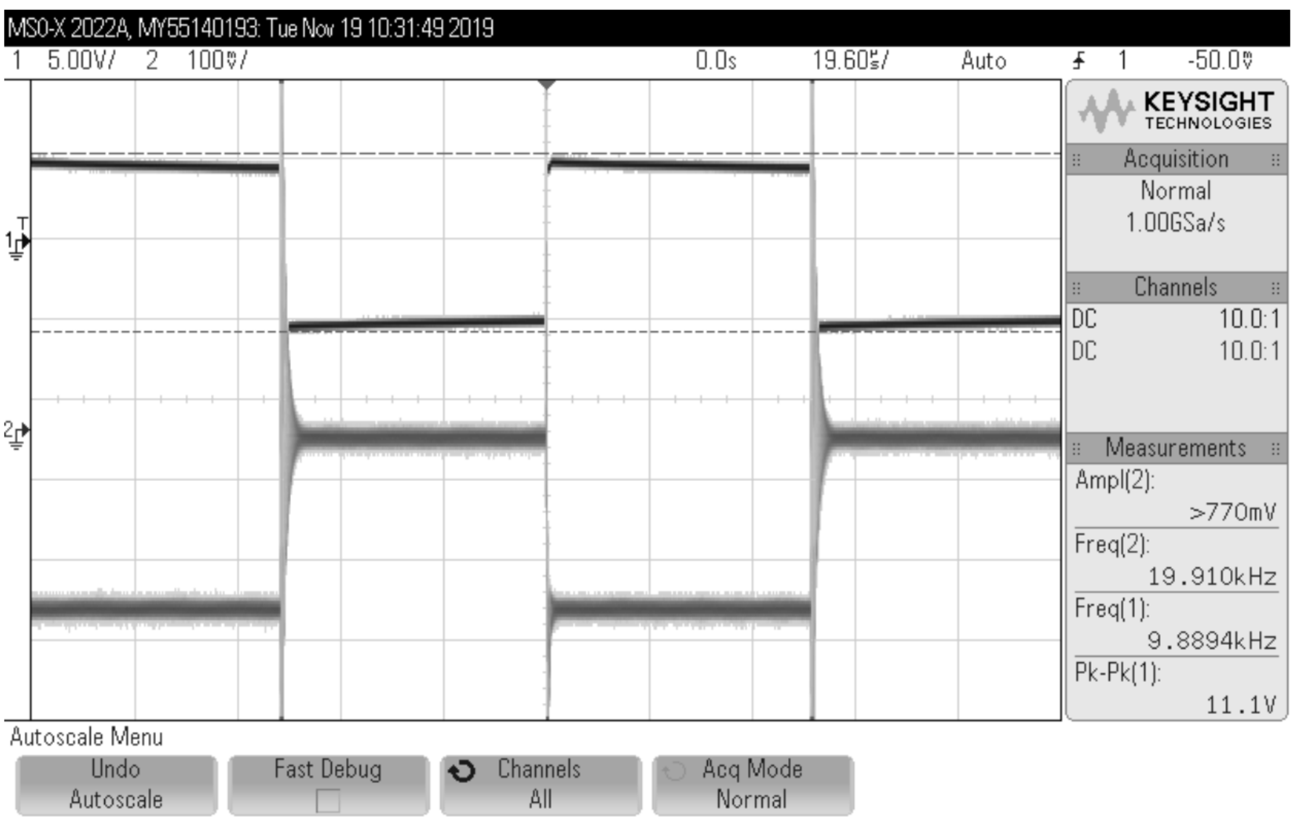


Figure 8: Laser Diode Signal @ 10kHz with no Rise/Fall Time

Lenses are a useful tool to concentrate LEDs scattering beams, and it helps transmit the signal at distances greater than a meter. Adding a Biconvex Lens, specifically the KBX046, enabled my transmitter to transmit a clean signal at the receiver to up to 300kHz. In Figure 9 below, the signal at the output below is being received at 1.22 m. The signal is transmitting 1MHz while maintaining a clean signal. I attribute the noise at the edges to the reflections from many T-Connections and BNC-BNC cables between circuits and measuring tools.

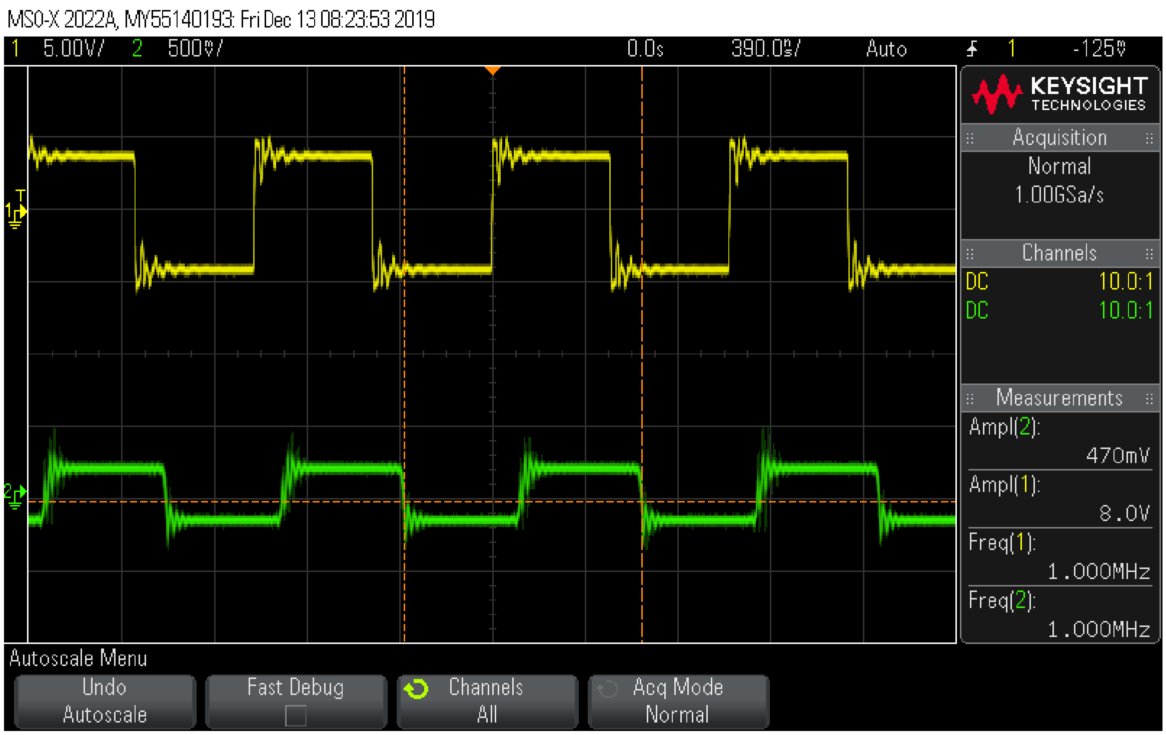


Figure 9: 1MHz across 1.22m through a Biconvex Lens at the Transmitter

Another shift to increase the transmitting frequency and achieve cleaner rise/fall times in our output signal was to upgrade our initial IRLB3813PbF Power MOSFET to the IRF540 NMOS. The IRF540 has 44ns timing characteristics which is an improvement upon the Power MOSFET's 170ns, though this only improves the speed by a 1-3kHz. In figure 8 and 9 below, they can barely be differentiated

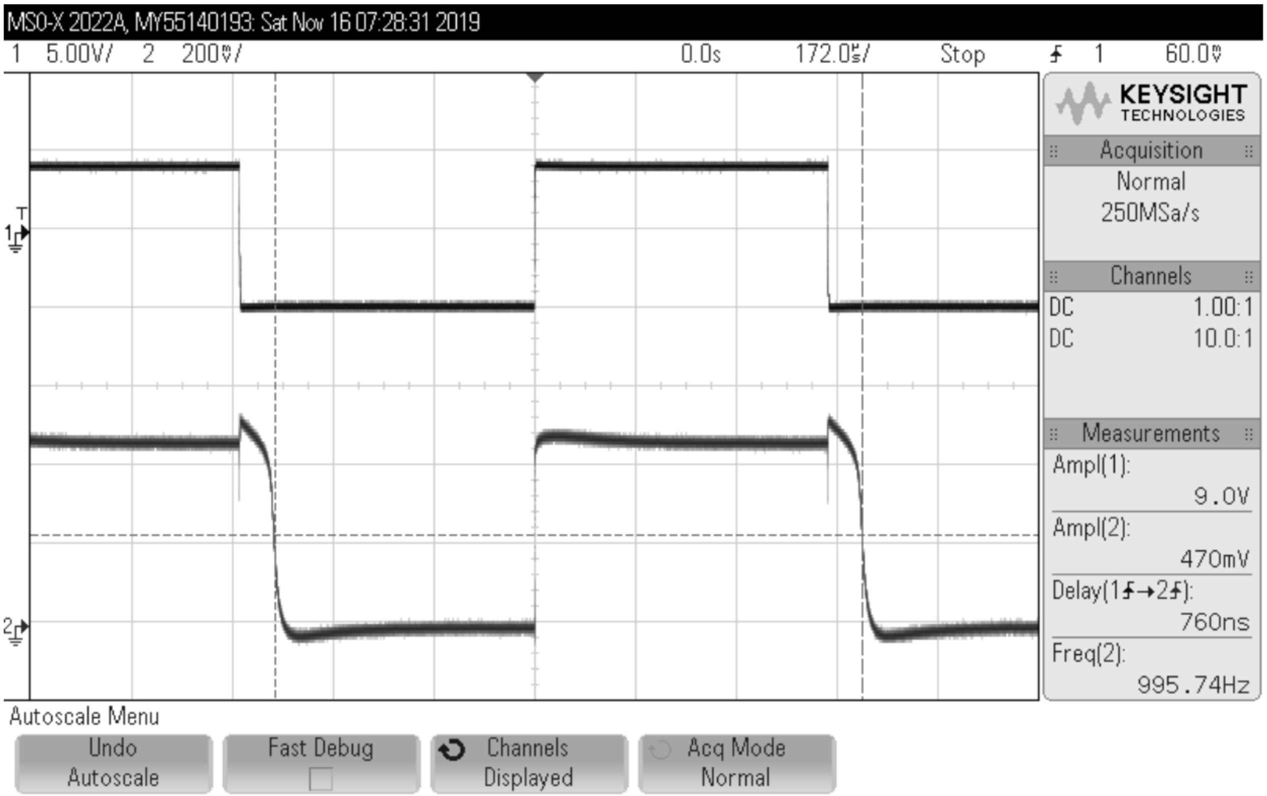


Figure 8: IRLB3813 MOSFET, Fall time = 760 ns, @ 1kHz

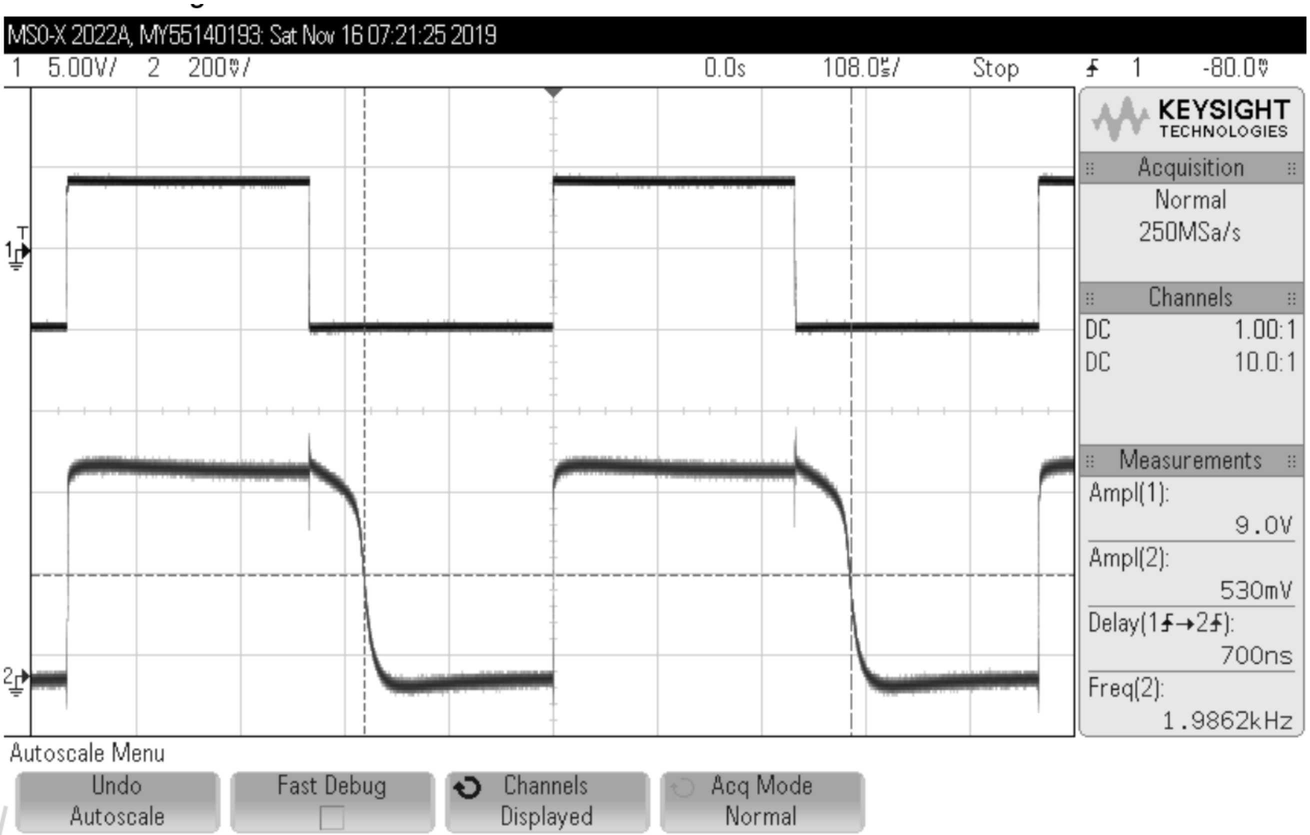


Figure 9: MOSFET IRF540, Fall Time = 700ns, @ 2kHz

On the Receiver side, the maximum speed capable of being received differs based on the Slew Rate and the Frequencies at which the op-amp experiences low distortion. Our initial design utilized the LMC662 CMOS Op-Amp with a 1.1V/µs Slew Rate and a low distortion frequency in the 10kHz range. The LT1229 boasts a 100MHz Bandwidth with a 1000V/µs Slew Rate, which are far more attractive characteristics to increase the bandwidth of our FSO system. The Photodiode used thus far for this system, BPW21R, could also be replaced to improve the transmission quality at high speeds. The BPW21R is not described as a high-speed photo detector in its datasheet, so I propose the BPW43 Silicon Photodiode instead. This photodiode is known for its high-speed capability, and it is tested to run smoothly at 1MHz. In figure 10 below, the lower received signal is transceived through the BPW43 at 1.22 meters. The signal is seen to be sufficiently transmitting at at least 1MHz.

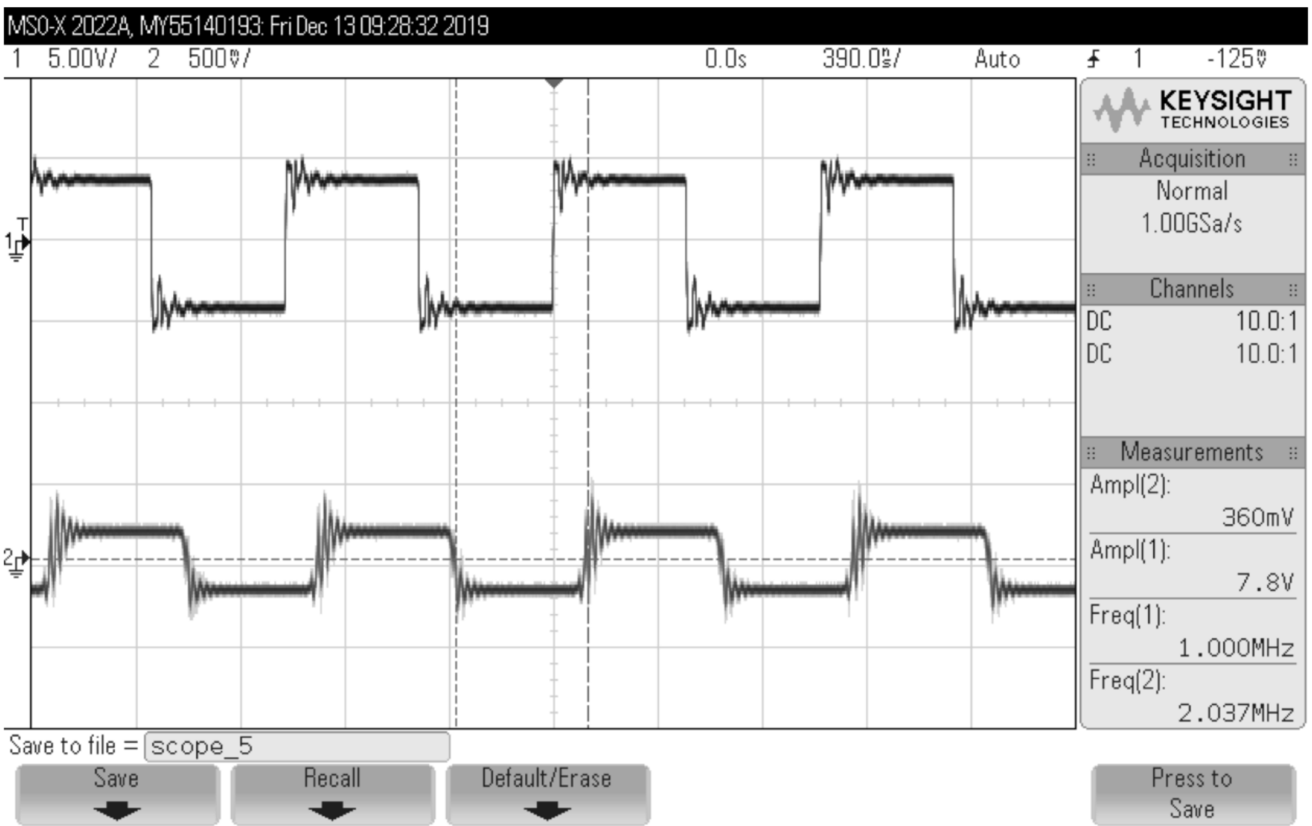


Figure 10: Received signal (below) through BPW43 photodiode @ 1MHz over 1.22 meters

This is also the photodiode used by RONJA in their 10 meter or longer Receiver circuits. With these Op-Amp and photodiode component replacements in our receiver circuit, along with a plano convex lens concentrating the signal into the photodiode, I am confident this FSO system will be able to cleanly transceive low-power signals of speeds up to 5MHz.

Test Results

Using the RONJA 10M Transmitter Receiver Circuits within an isolated 1.22 meter fog chamber, I tested the attenuation behaviors for three different LEDs: Red (615 nm), Green (520 nm), Blue (470 nm). Each RONJA Transmitter and Receiver is powered with 12V, which adheres to our low-power requirement. I used the *Hewlett-Packard 8116A Function Generator* to send a 660mV input signal at 1MHz through the transmitter. The LEDs would output their optical signal through a Biconvex Lens KBX046. The Receiver utilized a BPW43 photodiode, designed for high speeds, and outputs its signal on a *Keysight Mixed Signal Oscilloscope*. The Fog Chamber is 1.22m long coated with an interior water repellant, and a 0.31m diameter to allow enough space to install the Transmitter and Receiver. At the receiver end, I also installed a *Newport Optical Meter Model 1835-C* to measure the optical power at the location of the photodiode.

Figure 11: Test Set Up with Fog Chamber and Fog Machine

To measure I first took baseline measurements for each color LED; so I turned all the power on and enabled the function generator, and recorded the Voltage Amplitude at the drain of the receiver circuit's MOSFET and the Optical Power in Watts at the Receiver, in a clear fog-less closed chamber. These would serve as my baseline values which would help me solve for Attenuation in dB once I collected my fog measurements. Next, I outputted fog from the *American DJ Fogstorm 700* into the opening on the side of the chamber for 10 seconds, and then close the chamber until the power reading from the optical power meter stabilizes at its lowest measurement. Now I begin recording all the measurements for the output Voltage Amplitude and the Optical Power Meter, as soon as I open the side fog chamber to let fog slowly exit. I observe and record the changes in both Voltage and Power until I see the Receiver is slowly receiving a cleaner and cleaner signal at the output from the input. I stop measuring the output voltage once the signal stabilizes and the voltage value is the same to when no fog was in the chamber in the baseline measurements. Though, I continue measuring the optical power meter until its displayed power value is identical to the one I observed in the fog-less baseline measurements.

Next, I convert my Power and Voltage values under fog to dB values. For Power, I used the following equation: $f(P) = 10 \cdot \log\left(\frac{P}{P_0}\right)$ where P is the measured power during the trial at a given time in seconds, and P_0 is the baseline power reading taken in the fog-less trial. For Voltage, I used the following equation: $f(V) = 20 \cdot \log\left(\frac{V}{V_0}\right).$ where V is the measured output voltage during the fog trial at a given time in seconds, and V_0 is the baseline empty chamber value. These equations measure how the attenuation differs as time passes in a fog filled environment. They each calculate how the dB of the chamber differs and affects the signal between transmitter and receiver. It is measured between time and logarithmic power in Figure 12. In this figure, one can determine what LED light or visible wavelength reacts best to atmospheric attenuation affects the power transmitted across the system as time progresses.

Table 8: Red LED Measured and Calculated Values

Fog and without Fog Measurements for Red, Blue, Green						
LED Color	Red LED	Wavelength = 615 nm				
	Without Fog		With Fog			
Time(s)	Baseline Volt	Baseline Pow	Voltage (V)	Power (W)	Voltage dB	Power dB
0	0.36	0.000033	1.51	0.0000003	12.4534889	-20.413927
15			1.47	0.0000006	12.2202967	-17.403627
30			1.45	0.0000013	12.10131	-14.045706
45			1.46	0.0000016	12.1610071	-13.14394
52.5			1.47	0.0000029	12.2202967	-10.561159
60			1.47	0.0000042	12.2202967	-8.9526465
75			1.49	0.0000126	12.3376754	-4.1814339
79			1.49	0.000013	12.3376754	-4.0457059
82.5			1.43	0.0000136	11.9806707	-3.8497503
86.25			1.53	0.0000152	12.5677786	-3.3667035
90			1.55	0.0000162	12.6805839	-3.0899893
105			0.34	0.0000188	-0.4964717	-2.4435609
108.75			0.36	0.0000201	0	-2.1531788
110.5				0.0000214		-1.8810017
112.5				0.0000224		-1.6826592
116.25				0.0000233		-1.5115802
118.5				0.0000243		-1.3290767
120				0.0000259		-1.0521418
150				0.0000276		-0.7760486
180				0.0000305		-0.342141
240				0.0000318		-0.1608682
300				0.0000328		-0.026401
360				0.0000328		-0.026401
420				0.0000331		0.01314054
480						
540						
600						
660						
720						
780						
840						
900						
960						
1020						
	Signal Stable after 98 sec, or 1min 38sec					

The Red LED performed well as the initial sample. After the fog had reached equilibrium in the chamber, the output voltage stabilized at 360 mV, as seen in Table 8 above.

Table 9: Blue LED Measured and Calculated Values

Blue LED	Wavelength = 470 nm				
Without Fog		With Fog			
Baseline Volt	Baseline Pow	Voltage (V)	Power (W)	Voltage dB	Power dB
0.36	0.000078	1.69	0.00000045	13.4316841	-22.388821
		1.63	0.00000175	13.1177021	-16.490566
		1.59	0.00000242	12.9018925	-15.082792
		1.49	0.00000507	12.3376754	-11.870866
		1.57	0.00000857	12.791943	-9.5911378
		1.55	0.00001037	12.6805839	-8.7631585
		1.63	0.00001135	13.1177021	-8.3709874
		1.53	0.00001548	12.5677786	-7.0232365
		1.59	0.00001745	12.9018925	-6.5029917
		1.61	0.00002212	13.0104675	-5.4730948
		1.63	0.0000279	13.1177021	-4.464904
		1.53	0.00003324	12.5677786	-3.7043359
		1.57	0.00003652	12.791943	-3.2956383
		1.53	0.00004374	12.5677786	-2.5121582
		1.59	0.00004805	12.9018925	-2.1040121
		1.67	0.0000528	13.3282794	-1.6946068
		1.59	0.00005702	12.9018925	-1.3606739
		1.61	0.0000624	13.0104675	-0.9691001
		0.36	0.00006761	0	-0.6208367
			0.00007398		-0.2298028
			0.00007582		-0.1231082
			0.00007662		-0.0775246
			0.00007667		-0.0746914
			0.00007712		-0.0492758
			0.00007694		-0.0594242
			0.0000773		-0.0391511
			0.00007707		-0.0520924
			0.00007761		-0.0217692
			0.00007774		-0.0145007
			0.00007739		-0.0340976
			0.00007765		-0.0195314
			0.00007788		-0.0066866
			0.00007792		-0.0044566
			0.00007797		-0.0016707
Signal Stable after 142 sec, or 2min 22sec					

The Blue LED performed differently from the Red LED. The Red LED was rather quick to return to the baseline voltage. Tbough its power measurements took over two times to return to the baseline power. This reflects its inferior characteristics of attenuation with a blue LED compared to Red LED.

Table 10: Green LED Measured and Calculated Values

Green LED	Wavelength = 520 nm				
Without Fog		With Fog			
Baseline Volt	Baseline Pow	Voltage (V)	Power (W)	Voltage dB	Power dB
0.36	0.00002684	1.61	0.0000005	13.0104675	-17.298125
		1.71	0.00000081	13.5338722	-15.202975
		1.53	0.0000012	12.5677786	-13.496013
		1.61	0.00000178	13.0104675	-11.783625
		1.49	0.00000333	12.3376754	-9.0633828
		1.55	0.00000492	12.6805839	-7.3681741
		1.57	0.00000682	12.791943	-5.9499814
		1.55	0.0000091	12.6805839	-4.6974112
		1.57	0.00001232	12.791943	-3.381718
		1.53	0.00001538	12.5677786	-2.4182618
		1.63	0.00001804	13.1177021	-1.7254598
		1.57	0.00002018	12.791943	-1.2386135
		1.65	0.00002119	13.2236289	-1.0265155
		1.53	0.00002161	12.5677786	-0.9412774
		1.63	0.00002371	13.1177021	-0.5385096
		1.55	0.00002409	12.6805839	-0.4694571
		1.63	0.00002425	13.1177021	-0.4407077
		1.61	0.00002464	13.0104675	-0.3714181
		0.36	0.00002522	0	-0.2703743
			0.0000254		-0.2394879
			0.00002603		-0.1330834
			0.00002568		-0.1918749
			0.00002553		-0.217317
			0.00002541		-0.2377785
			0.00002584		-0.1649
			0.00002549		-0.2241268
			0.00002576		-0.1783665
			0.00002598		-0.1414336
			0.0000262		-0.1048122
Signal Stable after 141 sec, or 2min 21sec					

The Green LED also took over twice as long as the Red LED. Granted, the green LED is weaker in terms of intensity compared to the Red or Blue LED which contributes to its lengthy transmission signal. However, the Attenuation trend is noticeably similar between the LEDs. Though I suspect the voltage measurement in the oscilloscope is affected by the reflection coefficients from the 3 or 4 T-connectors and BNC connectors between wires. Judging from the Kaleidograph graph of LED Power vs Time in Figure 12 it is clear that the Red LED reacts most effectively under fog circumstances. In figure 12, one can notice that the Red LED reaches 0 dB within 98 seconds, which is almost 50 seconds sooner than the Green or Blue LED. It is not surprising because the power measurements from the voltage output reverts to the clean signal. In contrast the Blue and Green LEDs required over 2 min and 22 seconds to achieve a clear signal following the filled fog chamber. Figure 12 depicts the LED characteristics through the fog chamber through the kaleidograph application.

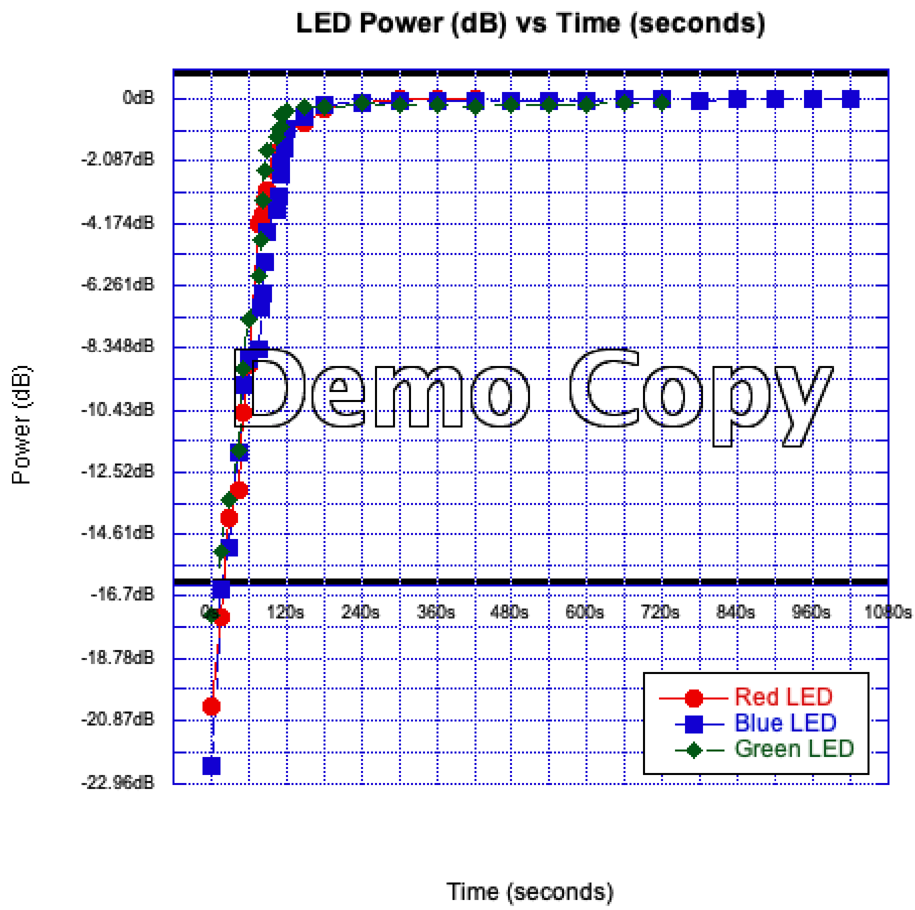


Figure 12: LED Power vs Time (seconds)

Figure 13 depicts the relation between the LED decibel in terms of voltage and power.

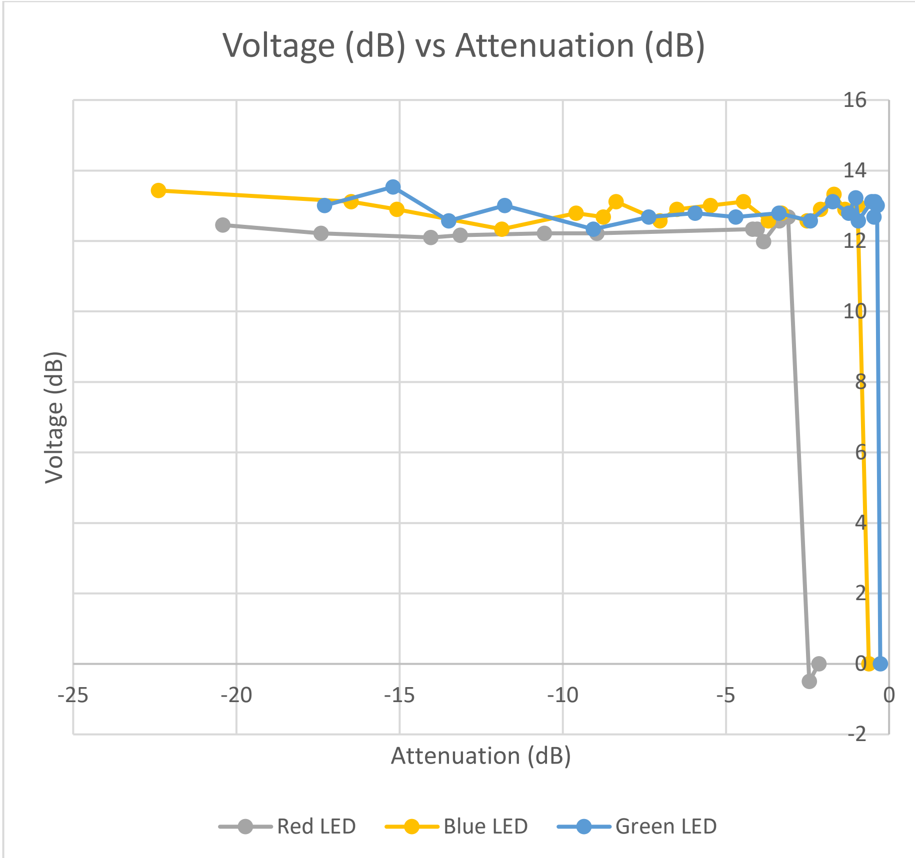


Figure 13: Voltage (dB) vs Attenuation (dB)

The Red LED reflects the soonest return to 0 decibel under fog conditions.

Preliminary Design Analysis

After some research, Twibright Labs' *Reasonable Optical Near Joint Access (RONJA)* free-space optical point-to-point system would be best suited for our design. RONJA's design is open-source and gives us a starting point for our system design. The transmitter and receiver schematics are shown in Appendix G [15].

To minimize the attenuation of the data signal across the atmosphere, our design will vary the optical wavelength best suited for condition at the time of transmission. Two possible design approaches to accomplish this would be to either use two optical sources with different output wavelength and switch between them according to the weather condition or to use a tunable wavelength source.

Another approach would be to use a humidity sensor to trigger a flag to switch between the sources if the humidity is higher than a certain percentage. This would work in most applications but would lose the responsivity to various size fog which the multiple source model had in the first place, this is especially relevant if considering using a tuneable source as fog particle size is a strong factor in the attenuation seen by various wavelengths. Transmitting the flag could be accomplished either by transmitting the result across the optical link with the data or to use a rad io frequency (RF) transmitter and receiver transmit the flag and have that control the switch between the output wavelengths.

One last possibility would be to use the data protocol to assist by having a retransmit counter, this would be roughly analogous to a bit error and could trigger the source variance.

Analysis of Senior Project

Project Title: Free Space Optical Communication

Student: Anuj Gohil

Advisor: Professor Xiaomin Jin

Functional Requirements

I. The Free Space Optical system comprises of a compact, directed optics system that allows for networked communication between establishments in clear conditions and fog conditions at 1MHz over at least 1 meter.
II. The system has adjustable LEDs each with unique wavelengths to assist in circumventing atmospheric attenuation.
III. In operation, the system will not draw more than 5 W, ensuring it is a low-power system.
IV. The two individual sub circuits take up less than a cubic foot each, and have a resilient exterior to be flexible on location installation.

Primary Constraints

Limited prior experience with free-space optical systems poses a challenge to the final implementation of this product. My collective knowledge of electronic circuit design and analysis allows the primary focus to be on the optical and data transmission aspects. A significant challenge during the testing and verification process will be environmental conditions. That is, verification of maximum range of the system and its performance under certain environments will be subject to current weather conditions. In theory, artificial conditions may be created or simulated with known specifications of the completely constructed system.

Economic

The entirety of the product supply chain will have economic impacts, including natural resource processing, resource/component shipping, component manufacturing, product assembly, user guide creation, and customer delivery. In theory, the product will be provided free of cost to potential customers for beta testing and advertisement. If marketing is successful for this product, then customers will pay for the transmitter/receiver system and will be offered a warranty for technical support.

The customer can benefit financially by purchasing this inexpensive free-space optical system rather than modifying existing infrastructure for new data connections. Building-to-building links allow businesses to establish a secure stable data connection at an affordable price and minimal setup labor. An estimated cost of the components to build the system are shown in Table 9 below.

Table 9: Estimated Cost of Components

Component	**Cost**
Light Sources (Lumileds LXZ1-PD01)	$4.00
Photodiode (BPW43 or SFH203)	$0.30
Actives (transistors, diodes, inverters, regulators)	$5.00
Passives (resistors, capacitors, inductors)	$10.00
Microcontroller	$10.00
Enclosures (adhesives, sheet metal, screws)	$10.00
Printed Circuit Board	$5.00
Total	**$44.30**

The cost estimation of the project can be determined from the parts cost and the labor cost. Assuming each team member works 5 hours a week on the system design and testing for 20 weeks of Winter and Spring Quarters, the total man-hours spent on this project would be (1 members x 5 hours/week x 20 weeks) = 100 man-hours. The lowest labor cost ($Cost_l$) at a pay-rate of \$20/hour would be a total labor cost of \$2,000. The highest labor cost ($Cost_h$) at a pay-rate of \$30/hour would be a total labor cost of \$12,000. The most-likely cost ($Cost_m$) at a pay-rate of \$25/hour would be a total labor cost of \$10,000. Using Ford and Coulston's Cost Estimation Equation, the estimated labor cost is shown below [14].

$$Cost = (Cost_l + 4Cost_m + Cost_h)/6 = (\$2{,}000 + 4(\$10{,}000) + \$12{,}000)/6 = (\$54{,}000)/6 = \$9{,}000$$

If Manufactured on a Commercial Basis

Many potential competitors do not publicly list prices for their product models; rather, they will provide price quotes upon request. As such, it is difficult to estimate a purchase price for this product. The estimated manufacturing cost for this product will be $50 each with only components taken into consideration. A significant portion of the product cost will be due to the labor-intensive soldering of components and construction of the enclosures.

As an estimation, the user will require less than 2 hours of labor for initial setup and troubleshooting of both the transmitter and receiver. After the initial setup, the only costs incurred will be power consumption. An estimated <$0.05/hr will be the electricity cost for this system to be operated.

Environmental

This product has few direct environmental impacts aside from electrical power consumption. The light source wavelengths used in the product are not harmful to humans or animals unless the light is focused on an eye for extended period of time. The product will indirectly consume resources such as metals, water, gas and electricity when manufacturing and delivery is considered.

The main environmental benefit of this product is the prevention of wire installation between buildings. Existing fiber optic infrastructure will not need to be disturbed by construction workers in order for this system to operate, removing the requirement for extensive trenching between city buildings and helping to mitigate the effect of “dead fiber” so common in metropolitan areas.

Manufacturability

The prototype for this product will be constructed from discrete components soldered onto a printed circuit board. The enclosure for both the transmitter and receiver will be assembled from pre-made templates with slight modifications. The primary issue with the manufacturing of this product is the sheer amount of physical components and soldering required for the completed system. In the future, components may be discontinued or made obsolete by new technology. For such a case, equivalent components will be selected to replace these components while maintaining the functionality of the complete system, this would have an added benefit of likely reducing the cost of manufacture further. This product benefits greatly from existing manufacturing infrastructure, requiring minimal assembly after PCB boards are screened and soldered.

Sustainability

The system will be powered by 120V AC wall outlet through an AC-to-DC converter. As such, the user will be able to connect a single cable for power, and battery life will not be a concern. The physical packaging and internal components of both the transmitter and receiver will be resistant to temperature changes and humidity. With a satisfactory seal on the packaging, internal components will have a longer lifespan, so users can be confident in the product’s reliability.

Maintenance of the system is the foremost concern when integrating a LED or laser diode. Ideally, the light sources will be easily accessible for replacement, since constant current and heat will naturally degrade their lifespans. The lenses may occasionally need to be cleaned in order to maintain signal strength. The lower power requirements in this product will also help to lengthen lifespan, keeping eye safe conditions will prevent excess power consumption. In addition, the switching mechanism between the two light sources should be electrically controlled by a microcontroller in order to avoid physically moving parts. The goal of this product is to encourage a single setup for the system with minimal human interaction thereafter.

Ethical

The circuitry used within the product is a modification of a free, open-source project known as RONJA by Twibright Labs. The specific model being modified is the Ronja 10M Metropolis. The final designs will also be published under the same open-source licence for others to expand upon. The function of each circuit component has been identified and is modified in order to meet this product’s engineering specifications with regards to current, voltage, and power consumption.

This product is intended to establish a reliable data link over through free space. Data within an optical communication system is extremely difficult to intercept without affecting the signal itself, and without prior knowledge of the equipment used to transmit and receive the data. This enables secure and private transmission, as source spreading would be both detrimental to the attenuation rates as well as to the customer. The lack of data processing place no more ethical constraints upon the design than an ethernet cable would as there will be no possibility of customer data loss due to the transmitting media, in this case, the FSO link.

Health and Safety

The primary safety concern for free space optical systems is eye safety. Prolonged exposure to high-powered LEDs and lasers will cause damage to one’s eyes. This system is designed to comply with the ANSI Z136.2 and ANSI Z136.6 eye safety standard. This standard contains many provisions for keeping free space optical links power output in reasonable ranges which cannot damage human eyes. In practical usage, the transmitter and receiver will be placed in locations with little to no human traffic, such as multi-story buildings. When the system is positioned in such locations, the potential for any safety hazards is even further mitigated.

Social and Political

Suppliers of this product’s circuit components will benefit from the sales of each part. The projected market size of free-space optical systems will allow this product and potential key partners to profit. Regarding component manufacturers, the country of origin may adversely affect U.S. economy if a large portion of components are manufactured overseas. With regards to customers, trial runs of this product can be offered to interested businesses and feedback can be collected for future improvements.

Potential competitors may react to the release of this product by decreasing prices of their own products. In such a scenario, price cuts by competitors can be accomplished in numerous ways which will result in a chain reaction.

Development

In the development of this product, several modifications will be made to existing transmitter/receiver circuits. Extensive circuit analysis is required in order to maintain the integrity of the original circuit while also meeting product specifications with regards to electrical and optical power. To test bit error rate and signal-noise-ratio, additional equipment such as an optical spectrum analyzer must be utilized for measurements. Such equipment is already available for use in Cal Poly laboratories. In addition, microcontroller code will be implemented for light source switching.

References

[1] 4gon.co.uk, 'Introduction to Free Space Optics (FSO) Wireless Networking Technology - 4Gon', 2015. [Online]. Available: http://www.4gon.co.uk/solutions/introduction_to_free_space_optics.php. [Accessed: 26- Oct- 2019].

A brief introduction of free space optics from 4GON Solutions, a wireless technology company based in the UK. They discuss the advantages, performance and security of FSOs. In addition, they talk about the technical issues faced by FSOs including attenuation due to fog and humidity.

[2] E. Ciaramella, Y. Arimoto, G. Contestabile, M. Presi, A. D'Errico, V. Guarino and M. Matsumoto, '1.28 terabit/s (32x40 Gbit/s) wdm transmission system for free space optical communications', IEEE J. Select. Areas Commun., vol. 27, no. 9, pp. 1639-1645, 2009.

An IEEE journal article on a wavelength division multiplexing FSO system. It discusses the benefits and drawbacks of using FSO, In addition, it presents a FSO system that improves the capacity and reliability of FSO systems in a terrestrial link.

[3] H. Henniger and O. Wilfert, 'An Introduction to Free-space Optical Communications', Radio Engineering, vol. 19, no. 2, pp. 205-207, 2015.

A radio engineering journal article on FSO systems. The article discusses modulation schemes as well as atmospheric influences on the performance of FSO systems. In addition, the article shows which wavelengths are suited for free space transmission and which are attenuated too heavily to be used.

[4] P. Singal, S. Rai, R. Punia and D. Kashyap, 'Comparison of Different Transmitters Using 1550nm and 10000nm in FSO Communication Systems', International Journal of Computer Science and Information Technology, vol. 7, no. 3, pp. 107-113, 2015.

A journal article from the International Journal of Computer Science and Information Technology that discusses different FSO links. They discuss the effects of weather on the performance of a FSO system. In addition, they discuss the differences in wavelengths in FSOs as well as the sources that produce the wavelength to optimize the performance in foggy conditions.

[5] H. Refai, 'Comparative study of the performance of analog fiber optic links versus free-space optical links', Optical Engineering, vol. 45, no. 2, p. 025003, 2006. 37

An optical engineering journal article on the performance of fiber optic links vs. FSO links. The article discusses the advantage of fiber optics in long range transmission. The performance of both types of link are comparable in short ranges but FSO links are the inexpensive solution for the "last mile" of transmission.

[6] C. Kaur, 'Free Space Optics Communication', Slideshare.com, 2014. [Online]. Available: slideshare.net/Rajanmishra1994/free-space-optics-communication-37202244 [Accessed: 25- Oct- 2019].

Gives multiple graphics and diagrams of FSO links. These slides are useful in understanding the history, architecture and challenges of FSO links.

[7] Currentresults.com. 'Annual Days of Cloud and Fog at US Cities - Current Results', 2015. [Online]. Available: http://www.currentresults.com/Weather/US/cloud-fog-city-annual.php. [Accessed: 26- Oct- 2019].

Gives the average days per year of fog in major US cities. This information is critical in determining which cities have been prevented from the full use of FSO link. It improves our market analysis by seeing which cities would most benefit from our attenuation mitigating FSO.

[8] Alkholidi, 'Free Space Optical Communication – Theory and Practices', Intechopen.com, 2014. [Online]. Available: https://www.intechopen.com/books/contemporary-issues-in-wireless-communications/free-space-optical-communications-theory-and-practices. [Accessed: 1- Dec- 2019].

Provides more insight into the practical uses of Free Space Optical Communication. It also provides many relevant graphics on the nature of FSO and helps describe my product's technical functioning.

[9] Markets and Markets, 'Free Space Optics and Visible Light Communication Market by Component, Transmission Type, Application, and Geography,' Marketresearch.com, 2018. [Online]. Available: https://www.marketresearch.com/MarketsandMarkets-v3719/Free-Space-Optics-FSO-Visible-11904984/. [Accessed: 4- Dec- 2019].

This source gives updated details about the current state of the Free Space Optics Market and what it will be expected to grow to by 2023. The arguments it provides aid my argument in how my product will be successful in the market.

[10] E. Thomas, 'Maximum Progress of Free Space Optics FSO Communication Market,' Marketexpert24.com, 2019. [Online]. Available: https://www.marketexpert24.com/2019/09/09/maximum-progress-of-free-space-optics-fso-communication-market-with-an-eye-catching-cagr-during-forecast-2019-2025-marked-by-lightpointe-laser-light-communications-plaintree-systems-wireless-excell/. [Accessed: 4- Dec- 2019].

This source provided insight into how our competitors products are being using in the real world. It helps us understand the current market for FSO technology and how we can improve on what our competitors offer.

[11] Fsona.com, 'fSONA: Products', 2015. [Online]. Available: http://www.fsona.com/product.php?sec=2500z. [Accessed: 25- Oct- 2015].

One of the competitor's product descriptions and specifications giving us possible target values to achieve for our FSO link.

[12] S. LaSalle, 'SKYFIBER SkyLINK 1.25 GHz', Skyfiber.com, 2015. [Online]. Available: http://www.skyfiber.com/windows/marketingscreens/skylink/skylink.php. [Accessed: 25- Oct- 2015].

Information on a competitor's FSO link giving us its capability and possible target values to achieve in our FSO link.

[13] Nebula.wsimg.com, 2015. [Online]. Available: http://nebula.wsimg.com/793e82b2beac48cb90c347bd86776d12?AccessKeyId=C1431E109BF92B03DF85&disposition=0&alloworigin=1. [Accessed: 15- Oct- 2015].

Specifications on a competitor’s FSO link giving us information on its capability and possible target values to achieve in our FSO link.

[14] Artolink.com, 'FSO (Free Space Optics) Artolink equipment for high speed wireless optical communications', 2015. [Online]. Available: http://artolink.com/page/products/free_space_optics_Artolink_10Gbps/. [Accessed: 25- Oct- 2015].

A competitor’s FSO link description and specifications. Although the speeds are not realistic in our application, they show the capability of FSO links and how varied the market is within enterprise networks.

[15] RONJA, 'All Schematics', 2015. [Online]. Available: http://ronja.twibright.com/schematics/. [Accessed: 21- Nov- 2015].

Twibright Labs’ open-source optical point-to-point system schematics. Includes both the transmitter and receiver schematics mentioned in the paper as well as other open-source hardware schematics for other designs.