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Designing A Free-Space Optical/Wireless Link

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Abstract

This paper presents the design of a very high-speed data link between two buildings in a University campus that will operate at gigabit rates. The project uses a cutting edge technology of eye-safe laser communication through free space. This is an all-optical design is future-proof in regards to technological advancement in the rate of data transmission and introduction of newer protocols. The two buildings are approximately 500 meters apart. The free-space optical link uses 1550 nm wavelength in normal usage but has a wireless link operating at 2.4 GHz as the back-up. The line of site alignment will be achieved using telescopes initially but will have automatic tracking alignment system. The wireless back-up link is used only in very dense fog conditions. This paper presents the design of only the free-space optical connection, some parts of which are implemented in laboratory setup.

I. Introduction

The technology of establishing a high-speed networking between two buildings or campuses is one of the three: 1) copper wire, 2) wireless and 2) optical fiber technology. The copper technology is low-speed, labor-intensive and requires a regime of permissions. The advantages are high reliability and full availability. The wireless technology uses a few GHz carrier, is medium speed (up to few Gigabits per second), has small link span and requires a regime of licenses. Advantage is the ease of deployment. The disadvantages are low reliability (high bit error rate) and severe fading in rain.

Fiber optic technology poses no foreseeable limit in speed, enables large link span, and has high reliability (very low reliability) and full availability. Laying optical fiber in the ground requires huge expenses and a considerable time and efforts go in obtaining permissions from various agencies[1]. Once laid, the fiber cannot be re-deployed easily. Capital expenditure (CapEx) is tied directly to the off –network customer. If the customer is lost, so is the CapEx. Furthermore, trenching may run into physical obstructions.

The free-space optical (FSO) technology using eye-safe infrared lasers [2]offers fiber-like speed, does not require permissions and can be deployed and reconfigured in a short time. Disadvantages are strict line-of-sight alignment and severe fading in fog and smog conditions.

Fortunately, the wireless technology is not affected in the fog and smog conditions and the FSO technology is not affected in rain[3]. The rain particles are comparable to the wavelength of the wireless frequencies. The fog and smog particles sizes are much smaller than rain drops but are comparable to infra-red wavelengths used in FSO. Therefore, a combination of free-space optical as the main link with a wireless back-up as shown in Fig. 1, is the best candidate technology for fiber-like highly reliable and highly available networking among buildings and campuses. The entire cost of a 0.5-3 mile, 622 Mbs FSO/wireless two-way link is under 200K U.S. Dollars in comparison to million-a-mile laying cost of optical fiber in a downtown environment[8][9][10].

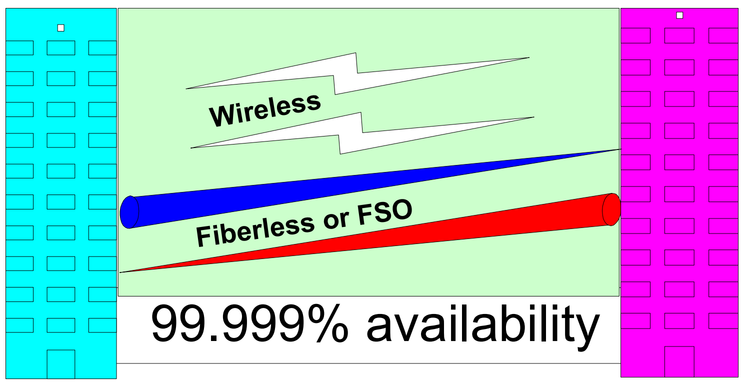


Fig. 1 FSO/Wireless link between two buildings/campuses

II. Project Definition

This paper describes an undergraduate Senior Design project for designing a fiberless link between two buildings approximately 500 meters apart that will enable high-speed networking link at Gigabit rates. The design is limited to only the FSO technology. The feasibility is illustrated in the lab environment due to limited time and resources. The link in normal usage is an optical link at 1310 nm. The line-of-sight alignment is performed using telescopes initially but will have automatic tracking alignment system in full implementation.

Feasibility is illustrated through a fibreless optical link between the two computers as shown in Fig. 2. The data coming out of a computer is a sequence of pulses is in RS-232 compatible. The FSO unit, which consists of a transceiver (transmitter and receiver in a single package) uses LVPECL (Positive Emitter Coupled Logic) signaling. The computer generated data pulses should be converted to LVPECL signal. The illustrated link is a one-way link. It can be made two-way by simply repeating and co-hosting the entire link topology in the reverse direction.

The transmitter in the transceiver unit converts the incoming electrical signal into an optical signal. The optical signal is formed into a very narrow beam by passing through an optical collimator. The beam is transmitted in free space and is collected at the receiver by an optical receptor (for focusing the divergent beam). The received signal is then transformed back to the electrical signal in the photodiode of the receiver circuit of the transceiver unit. The electrical signal is in the LVPECL format and it is converted into the original RS-232 compatible electrical signal format by the converter circuit. For FSO unit to work efficiently there should be a line-of-sight alignment between the optical collimator and the optical receptor.

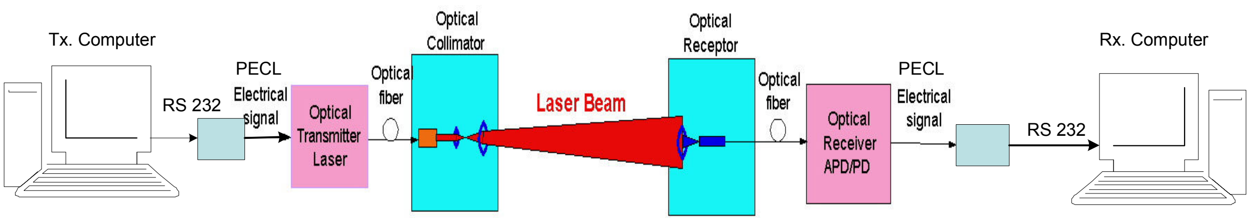


Fig. 2 Fiberless link

III. Enabling Technology

Less than seven percent of all buildings in American cities currently have access to fiber optic network[4]. A main reason for this is the high price of installing new fiber cable in urban areas. To dig and install just one mile of fiber cable costs nearly one million dollars. Even when a customer can afford this price, months may pass before the link is actually installed and is ready for use. For these reasons and others, there is a growing need for an alternate source of high-speed data communication. Optical fiber is replaced by an infrared laser beam in the FSO technology. In urban settings, a FSO link can be established between buildings in few hours time rather than in months. This link can be used permanently or until the fiber cable becomes available. FSO can be used in tandem with existing fiber networks. They can be implemented as backups or as temporary links until fiber becomes available in an area. The FSO technology is data rate agnostic and protocol-transparent and scalable to WDM technology. The FSO technology has Inherent immunity to eavesdrop. The eavesdropper has to come in direct path, therefore, will be completely visible. However, there are a few inherent characteristics of FSO link that must be addressed in any implementation. These include alignment, visibility, beam divergence, beam wandering, scattering, scintillation, solar ambience and last but not the least the interference by the flying birds and objects.

The FSO technology requires maintaining of strict alignment and a physically secure environment to reduce the likelihood of misalignment between the optical collimator and the optical receptor. Some of the reasons of misalignment are a) swaying of upper floors in tall buildings, b) vibrations in the mounting structures, c) variations in the refractive index structure of the atmosphere (beam wandering and scintillation) and d) the objects flying in the line of sight. Active alignment by sensing the received power level and controlling automatically the mechanical alignment is the best guarantee.

Visibility is defined as the distance at which the received light is 2% of the transmitted light power[5]. Following table gives the weather conditions, and visibilities:

Table I

Weather	**Visibility V (meter)**
Dense fog	50
Thick fog	200
Moderate fog	500
Light fog (mist)	1km
Thin fog/Haze	2km
Clear air	>4km

A 1 mrad (0.057°) beam diverges to 1 m (=rdθ) over a 1km distance[6]. The beam divergence losses depend on the ratio of the receptor area to the footprint of the beam as shown in Fig. 3. However, keeping the receptor area smaller or larger than the footprint provides immunity against small structural vibrations and beam wandering. A smaller receptor area involves a loss in the received power.

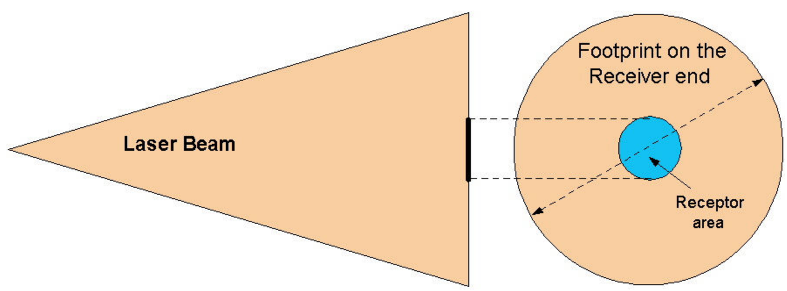


Fig. 3 Beam divergence

The free space between the source and destination can be thought of as a waveguide with random and dynamic alignment of pockets of slightly differing refractive indexes, called the n-pockets. Some n-pockets are large and others are small in size. Light beam passing through large n-pockets undergoes several small but random diversions giving rise to beam wandering[7]. Beam wandering is dependent on the atmospheric turbulence.

Scattering attenuation occurs as the result of interaction of light with aerosol particles[8] in the atmosphere which are comparable to the wavelength of the light used. The scattering of laser beam follows Mie scattering[8] These particles are the most pronounced in inclement weather.

Scintillation refers to the fluctuations in the received light intensity (power) on the receptor area. These fluctuations have time and special randomness and are the result of light passing through small n-pockets. The scintillation is inversely dependent on the temperature and strongly dependent on the atmospheric turbulence and height above the ground[9] or roof surface if used. Following table gives the scintillation losses (Γ(dB)):

Table II

	@200 m	@500 m	@1 km
Strong turbulence:	5 db	12 db	22 db
Typical turbulence : @ 30 ft above ground	1.5 db	3.5 db	7 db
Typical turbulence: @ 300 ft above ground	0.5 db	1.2 db	2 db

The scintillation can be reduced by transmitting more than one laser beams carrying the same data[5]. Four lasers have been found to be sufficient for reducing the Γ(dB) factor considerably. However, no corrective measure is required for shot distances up to 500 meters.

The ambient solar light provides a noise floor at the receiver end. The noise floor can be lowered relatively easily by adding either a hood or a mesh filter over the receptor area[9] [10].

The selection of wavelength of light as the carrier plays a very important role in FSO. The following table lists the comparison of operation at short and long wavelengths[1]:

Table III

	Properties	Short	Long
1	Wavelength	780-900nm	>1300nm
2	Eye-Safe Power	10mW	50-500mW
3	Standard	Class 1	Class 3B
4	Damage to eye in exposure	Permanent	Heat-Sensation
5	Power/Transmit aperture size	X	7X
6	Path attenuation in identical w condition	X+3.5dB/Km	X dB/Km.
7	Solar background radiation interfe	X	X/4
8	Scintillation Variance	X	X/2

In general, many benefits of the long-wavelength transmission would make the clear choice in any commercial or practical applications.

Typical optical losses[3] in the FSO link are

1. Beam forming losses in Transmitter and Receiver (typ. 2-5 dB)

2. Beam divergence losses (typ. 35 dB)
3. Miss-pointing allowance (typ. 10 dB)
4. Atmospheric losses (0.2-300 dB per km)

IV. Design

We opted for long wavelength 1550 nm and class 3A[4] eye-safe power level for our design. The detailed design is presented in the following sections.

4.1 Optical design

FSO link between Library building (SFLC) and the Student Housing in Purdue University Calumet, Hammond.

Distance L: 500 meters
Data rate: Gigabit Ethernet (1.25 Giga bits per second)
Weather conditions for carrier grade reliable operation: Light to Moderate Fog (the visibility V = 0.5 km)

The power loss as a function of the visibility at a distance L km from the transmitter is given by[6]

$$Loss(V) = \frac{A_R}{A_f} e^{-\gamma(v)L}\,\Gamma$$

$$Loss\_dB(V) = 10\log\left(\frac{A_R}{A_f} e^{-\gamma(v)L}\right) + \Gamma(dB)$$

where V: visibility in km

A_R: receptor area $= \pi D_r^2/4$, D_r being the diameter of the receptor

A_F: Footptint at the receiver $= \pi D_F^2/4$, D_F being the diameter of the footprint

Γ: the scintillation constant

$$\gamma(V) = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-\delta(V)}$$

$$\delta(V) = \begin{vmatrix} 1.6 \; if \; V \geq 50 \\ 1.3 \; if \; 6 \leq V < 50 \\ (0.16 \cdot V + 0.34) \; if \; 1 \leq V < 6 \\ (V - 0.5) \; if \; 0.5 \leq V < 1 \\ 0 \; if \; V < 0.5 \end{vmatrix}$$

As per table I data, the scintillation constant Γ for 30-ft mounting and in a typical turbulence is assumed to be 1.2 dB. The transmitter diameter is selected to be a typical value of 5 cm. We have used the receptor diameter of 30 cm. The beam angle θ is selected to be a typical value of 0.3 milliradian. The footprint at the receiver end is calculated as

$$DF = L(km).\theta(mrad) = 15\,cm$$

Since the footprint diameter is less than the receptor diameter, there is no loss due to beam divergence. Furthermore, we have used a link margin of 3 dB to account for link deterioration over time and tolerance variations. Following MATHCAD program calculates and plots the losses for a number of visibility conditions in the range of 200 meters to 2 km.:

V : Visibility, L:distance in km, lambda: wavelength in nm DR: receptor dia
DF: Footprint dia

$\theta := 0.3$ mrad $\quad dT := 0.05$ m $\quad dR := 0.3$ m $\quad \Gamma := 1.2$ dB

$L := 0.5$ km $\quad \lambda := 1550$ nm $\quad V := .2, .3 .. 2 \quad Margin := 3$ dB

$DF := L\cdot\theta + dT \quad DF = 0.2$ meters

$DR := \min(dR, DF)$

$$\delta(V) := \begin{cases} 1.6 \ \text{if} \ V \geq 50 \\ 1.3 \ \text{if} \ 6 \leq V < 50 \\ (.16\cdot V + 0.34) \ \text{if} \ 1 \leq V < 6 \\ (V - 0.5) \ \text{if} \ 0.5 \leq V < 1 \\ 0 \ \text{if} \ V < 0.5 \end{cases}$$

$$\gamma(V) := \frac{3.91}{V}\cdot\left(\frac{\lambda}{550}\right)^{-\delta(V)}$$

$$loss1(V) := \left(\frac{DR}{DF}\right)^{2}\cdot e^{-\gamma(V)\cdot L}$$

$$dbloss(V) := -10\cdot\log(loss1(V)) + \Gamma + Margin$$

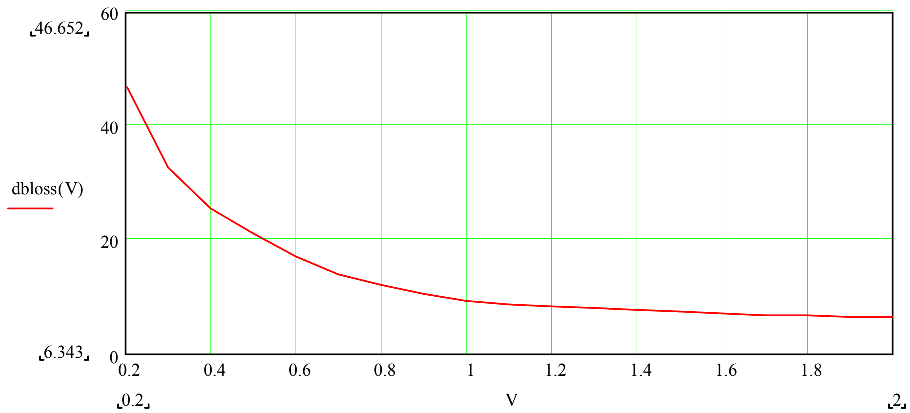


Fig. 4 Loss versus visibility

For a moderate fog condition (visibility V=0.5 km), the link budget is 21.181 dB. We have selected Finisar transceiver FTRJ1519P1XCL [8] with following specifications:

Small form factor (hot pluggable)
Operating wavelength: 1550 nm
Optical power output from transmitter in the range: 0 – 5 dBm
Typical input optical power sensitivity in the receiver: -21 dBm

The optical collimator and the receptor units will be housed in one case on both the transmitter and the receiver buildings. These units are mounted on the side of the wall at approximately 30 feet height above the ground. The optical transceiver and associated electronics are housed inside the building and are connected by a single mode fiber with LC connectors on the transmitter side and with multimode fiber with LC connectors at the receiver side.

In the laboratory illustration design, we have used a 1310 nm transceiver SPLC-20 2x5 Small Form Factor Pluggable Optical Transceiver, mounted on evaluation boards from Stratos-Ligthwave Inc.[11], Chicago. IL. The optical collimator and receptors are identical 5 mm in diameter and procured from San Diego, California.

The collimator is designed to collimate light exiting an optical fiber to a desired beam diameter. The fiber must be fixed precisely in the center of the collimator. The figure 5 below shows the collimator used in the optical assembly.

The project's demonstration prototype incorporated a pair of collimator made by Edmunds Optics. Depending on the positioning of these collimators, they can serve as either a beam collimator or the optical receptor. The collimator accepts LC type fiber cable. This is shown in the pervious figure.

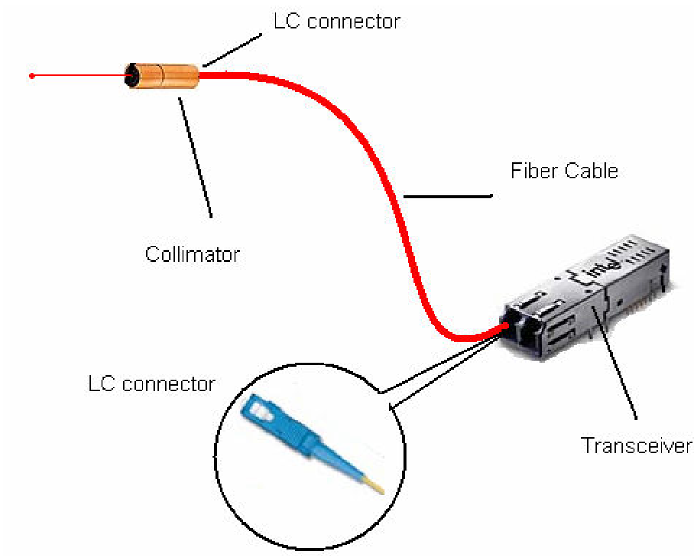


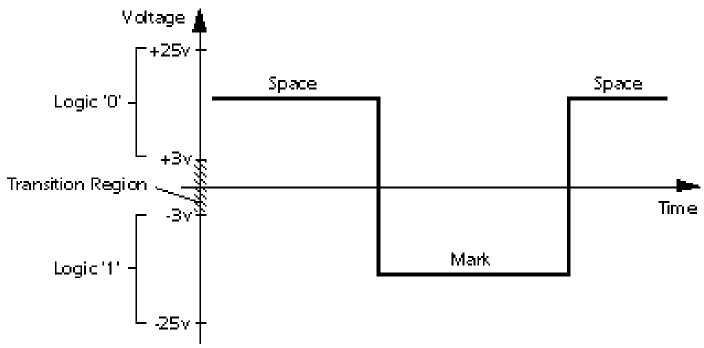
Fig. 5 Fiber Cable connection

The collimator is connected to the transceivers through optical fibers with LC connectors on both sides, as shown in Fig. 5. The transmitter side uses a single mode fiber but the one on the receiver side uses a multimode fiber for the reason of better focusing of the received light from the receptor.

4.2 Electrical Design

The electrical design consists of two 3.3 V, 500 mA power supplies, the circuits for converting single-ended RS-232 signal to differential LVPECL signal and vice versa. The optical transceiver accepts differential LVPECL signals whereas the serial input and output from the computers are in RS-232 format Therefore, circuits are needed to convert between different formats. The power supplies are very well filtered and a careful distribution circuit is used to avoid spurious noise and transient coupling among the transmitter and receiver circuits of the transceiver and ensure signal integrity on the printed circuit boards. In the following sections we give the converter schematics.

The RS-232 standard is renamed as EIA232. The single ended RS-232 signal specifications are given in Fig. 6. However, we have used 12V in place of 25V, which are very commonly used in practice. Single-ended voltage swing in LVPECL is 1.5 to 2.5 V. The circuit diagram for the conversion of the signal from RS-232 to LVPECL is shown in Fig. 7.



	LVPECL
V_{CC}	+3.3 V
V_{EE}	0 V
V_{OH}	+2.5 V
V_{OL}	+1.7 V
V_{BB}	+2.0 V
V_{TT}	+1.3 V
V_{OHPG}	+3.7 V
V_{OLPG}	+2.1 V

Fig. 6 RS-232 and LVPECL signal specifications

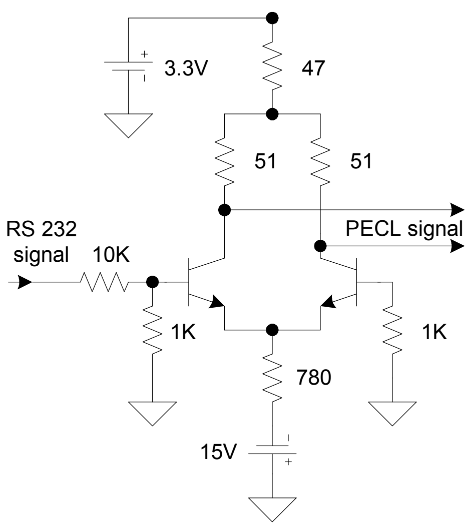


Fig. 7 RS-232 to LVPECL converter

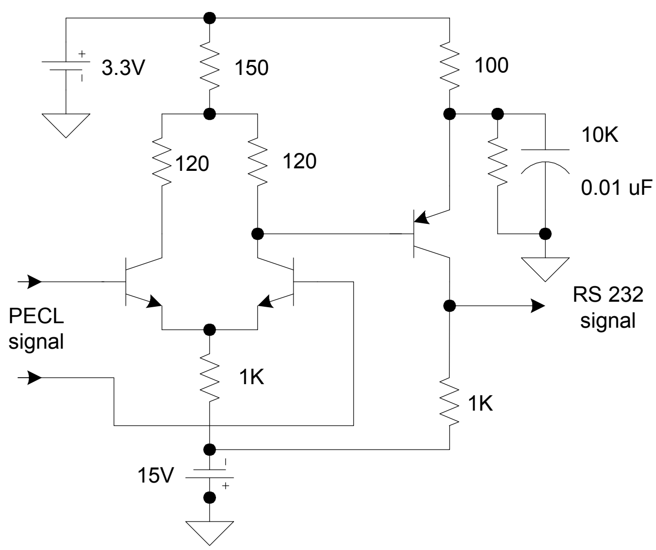


Fig. 8 LVPECL to RS-232 converter

Two software programs, Look RS232 by fCoder Group and Advanced Serial Port Monitor by AGG Software, are used to send the data through the computer's serial ports. Both programs allow the user to select either an input file or a binary string for transmission.

The mechanical assembly of the laboratory model consists of two identical housings, two collimators/ receptors, two adjustable stands and two telescopes. Both, the transmitting and the receiving ends have identical components. The front view of the squared shape metal housing is shown in Fig. 9. The collimators are placed inside the square housing at one of the corners of the housing. The telescope is placed at the other corner. The telescope is used to visually align the collimators on both ends. It is used to visually locate the corresponding collimator.

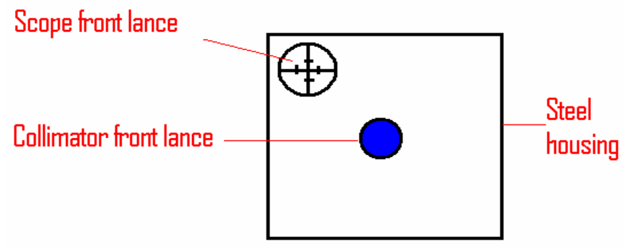


Fig. 9 Housing and the Stand

The hosing part of the mechanical assembly of the laboratory model is made of metal. A camera tripod is used as a stand. With the tripod used as the base, adjustment can be made in any desirable direction. Figure 10 shows the housing mounted on the camera tripod.

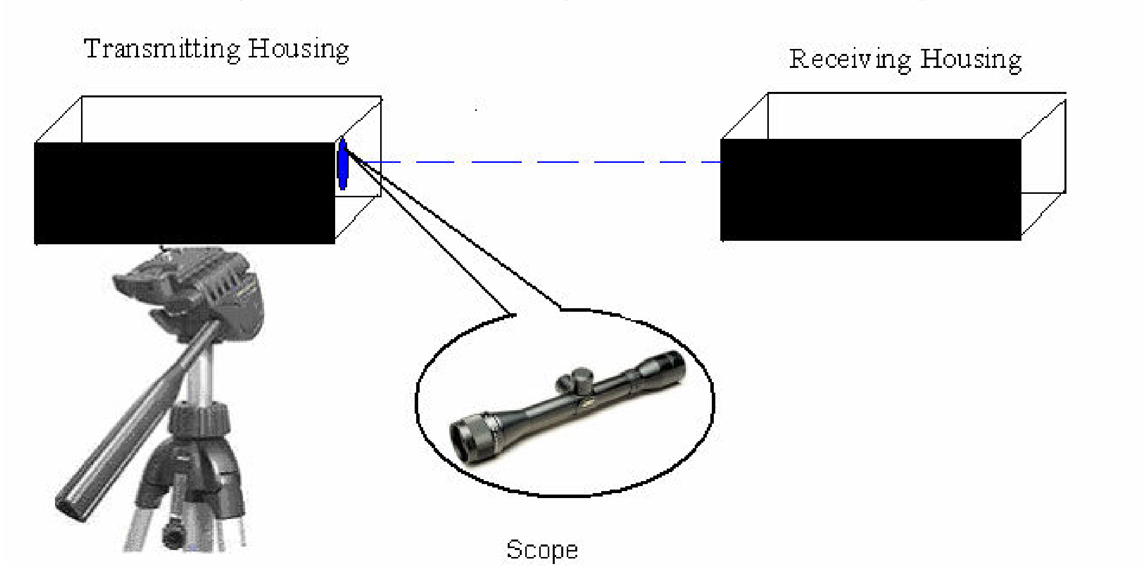


Fig. 10 Telescope location

The telescope is used to visually align the two collimators. It is mounted inside the steel housing, on one of the corner. The scope has a 15mm objective lens. With filed view of 22.5 feet at 100 yards. Figure 10 shows the location of the scope in the mechanical assembly. A cross mark is put on the housing on the receiver side and the telescope on the transmitter side is used for alignment.

V. Applications and Impact of the Project

Our world is fast becoming a small village by adopting faster and faster communication and networking technology. The road to new economy goes through the educational institutions and research laboratories. The way we interact with each other, the way our students are educated today will be very different in the short future than we can imagine now. It is therefore, extremely important that the communities are ready with the communication and networking infrastructure to absorb and adapt the future high-tech life-style. This technology would enable fast dissemination of modern technological advances into the community This is an emerging technology and it will serve as the catalyst for innovation and fast lane transformation to new economy in the neighboring region.

Some of the applications of the FSO/Wireless project are listed as following:

(1) To establish a high-speed networking infrastructure involving higher education centers, schools from K through 12, libraries, other educational and training centers and research centers in a county.
(2) To establish a high-speed networking link among regional medical centers for sharing and interactive exchange of information and resources.
(3) To establish a fast, reconfigurable and redeployable networking link among regional businesses medical centers for sharing and interactive exchange of information and resources.
(4) To establish a fast medium for very high quality video conferencing.

VI. Summary

The project implements a simple and inexpensive high-speed data link between two buildings on the Purdue Calumet campus. The link is designed using free-space optical technology in which, the optical fiber is replaced by a laser beam. All major components necessary to fabricate a Free Space Optical Data Link in the laboratory have been successfully designed. The most important consideration, alignment of FSO transceivers, was achieved through a stable mechanical assembly. The RS-232 signals from the computers are converted to LVPECL signal for interfacing with the transmitter and vice versa on the receiver. The laboratory model was tested first with optical fiber between the transmitter and the receiver. A RS-232 signal was applied as the input to the transmitter. The received signal was a RS-232 copy of the transmitted signal. The fiber was replaced by the collimator and receptor assembly. The signals could be recovered up to distance of 20 feet in the laboratory. A text file from a computer was transmitted and received across the link successfully. This project has given the opportunity to the undergraduate students a first-hand experience in an emerging technology that holds great promise in future. This project also provides experience in troubleshooting of electronic circuits and opportunity to learn about optical components, systems and interfacing them with electronics.

Reference**:** (superscript in body)

[1] "Optical Wireless: The story so far", David J.T. Heatley, David R. Wisely, Ian Neild and Peter Cochrane, IEEE Communications magazine Dec. 1998, pp. 72-82
[2] "Eye safety and Wireless optical Networks (WONs)", Jim Alwan, www.airfiber.com
[3] "Wavelength selection for optical wireless communication systems", David Rockwell and Stephen Mercherle, **www.fsona.com**.
[4] "Hybrid Free Space Optical / Microwave Communication Networks: A Unique Solution For Ultra High-Speed

Local Loop Connectivity", Gerald Clark, Heinz Willebrand, Maha Achour, LightPointe Communications, Inc. San Diego, CA
[5] "Ground-ground Optical Communications Demonstration", A. Biswas, M. Wright, A. Portillo, S. Lee, International Symposium for Deep Space Communications and Navigation, Sept. 21, 1999, Pasadena, California
[6] "Laser beam Propagation in the atmosphere", Hugo Weichel , Tutorialtexts in optical engineering; v.TT3, SPIE Optical Engineering Press, 1990.
[7] "Environmental Performance Test report", Telelase Communications Inc. Walnut Creek, CA
[8] www.airfiber.com
[9] www.fsona.com
[10] www.lightpointe.com
[11] www.stratoslightwave.com

Biography

JAI AGRAWAL is a Professor with joint assignment in Electrical and Computer Engineering Technology and Electrical & Computer Engineering. He received his PH.D. in Electrical Engineering from University of Illinois, Chicago, in 1991, M.S. and B.S. also in Electrical Engineering from I.I.T. Kanpur, India in 1970 and 1968 respectively. Professor Agrawal has worked recently for two years in optical networking industry in the Silicon Valley in California. Professor Agrawal is the Founder Advisor to Agni Networks Inc., San Jose, California. His expertise includes optical networking at Physical and Data link layers, optical and WDM interface, SONET and Gigabit Ethernet and analog electronic systems. He is the author of a Textbook in Power Electronics, published by Prentice-Hall. His professional career is equally divided in academia and industry. He has authored several research papers in IEEE journals and conferences.

OMER FAROOK is a member of the faculty of the Electrical and Computer Engineering Technology Department at Purdue University Calumet. Professor Farook received the Diploma of Licentiate in Mechanical Engineering and BSME in 1970and 1972 respectively. He further received BSEE and MSEE in 1978 and 1983 respectively from Illinois Institute of Technology. Professor Farook's current interests are in the areas of Embedded System Design, Hardware – Software Interfacing, Digital Communication, Networking, C^{++} and Java Languages.

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