

# High Speed Short Range Optical Wireless Ground-to-Train Communications

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**Abstract**— There is a huge demand for seamless high-speed communications in fast moving trains. People want broadband services while on board as in their home or in the workplace. This demand drives the motivation for a high speed dedicated optical wireless link. Here we propose a free space optical ground-to-train communications system which consists of optical transceivers placed on the train and along the railway track. A mathematical model for three different scenarios when the train is moving has been developed. The optical link analysis, results as well as a simple proof of concept are also presented.

**Index Terms**—wireless communications, optical wireless communications, ground-to-train communications.

## I. INTRODUCTION

FREE-SPACE optical (FSO) communication is a cost effective and license free data access technique that is gaining huge popularity over the last few years [1]. FSO systems offer wider modulation bandwidth that can achieve very high data rates (in excess of Gb/s) and immunity to electromagnetic interference compared to the radio frequency (RF) counterparts [1-3]. The main drawback of FSO is the limitation of permitted transmit power due to the eye safety regulations, ambient light interference from both artificial and natural light sources and limited mobility [4].

Application of FSO communications can vary from short range (within few meters) in indoor environment to a longer length (in excess of 500 m) at outdoor. Outdoor links up to a range of a few kilometres have been reported where the data transmission rate could reach up to several Gbit/s [5]. Whereas the emerging short range and indoor optical wireless communications (OWC) could provide hundreds of Mbit/s over several meters for home wireless network access [6]. In both types of applications transmitter and receiver are almost stationary, or have a low degree of mobility.

Applications of FSO communications on mobile terminals are interesting but very challenging due to the nature of narrow field-of-view (FOV) of the system, which is also bounded by the limited transmit power. Traffic light and car-to-car communications are under development and testing [7] whereas high-mobility ground-to-train FSO communications is emerging as an interesting but very challenging topic. Different studies [8-10] have shown that there is a demand for the use of high bandwidth applications in a moving train which in turn, requires high speed data connection. At present,

passengers on a moving train demand data connection services with the same quality as in home or at their workplace environment. According to [11], most of the business travelers work on trains and would use wireless broadband services if it was available. Therefore there is a requirement of high speed data transmission between train and base stations (BS) to ensure seamless data services for all the passengers. Various works [12]-[16] have been done in order to provide seamless wireless internet connections in a fast moving train. Although RF based communication is a promising technology for fixed wireless local area network (WLAN), its effectiveness is limited when the nodes are moving at very high speeds which motivates the interest in using FSO as a possible means of communication for high speed trains.

FSO technology can be used for high speed communications due to the unlimited bandwidth available at optical wavelengths. Also, the optical transmitters such as lasers and LEDs can support high data rate [17]. Some work [18, 19] regarding ground-to-train communications using FSO has illustrated a huge potential as of yet unexplored.

OWCs may be either infrared (IR) communications or visible light communications (VLC). Most of the optical wireless systems are designed to operate in the near-IR wavelength of around 850 nm. This is mainly due to the safety issues and the availability of low cost optical components [3].

The use of white LED in VLC systems is further supported by [20] where an experimental demonstration using 16 LEDs in the transmitter acquires a bandwidth of 25 MHz and data rate of 40 Mb/s along with the illumination in the room for lighting purpose. Data rates as high as 100 Mb/s can be achieved with low bit error rate (BER) using on-off-keying (OOK) non-return-to-zero (NRZ) modulation [21]. Siemens [22] has reported 200 Mb/s VLC and in some scenarios, the data rate could reach 500 Mb/s. However, LEDs have low modulation bandwidth limiting the transmission speed whilst in motion. Hence, IR communications using laser diodes (LD) can be used for high speed applications in fast moving trains. However, the transmitted power is restricted due to the safety regulations [3].

In this paper, the mathematical modeling of a single link FSO communications for the train system, optical link budget calculations and initial practical results are presented. The paper is organised as follows. Section II explains the different scenarios of ground-to-train communication system, section III presents the link budget calculations for the link, section IV

presents the simulation results, section V presents the experimental link set up and finally section VI concludes the paper.

## II. GROUND-TO-TRAIN COMMUNICATION SYSTEM

The proposed ground-to-train communication system consists of a number of BSs, and transceivers on the train cars. The number of transceivers in a single car is assumed to be two (see Fig.1). When the train is stationary, the nearest BS communicates with the receiver on the roof of the train. The BSs are placed along the rail-track in the ground at different positions. The movement of the train in this case is from left to the right.

Let the number of cars of train =  $C$ .

Number of transceivers on the train =  $N$ .

The maximum allowable link length =  $L_{comm}$ .

Maximum Separation between the two base stations =  $L_{BS}$

Length of the train =  $L_{train}$ .

The train is moving in the x-direction along the track with a speed of  $v$  m/s. The separation between the two transceivers  $\Delta d$  in a car is given by:

$$\Delta d = \frac{L_{train}}{N}. \quad (1)$$

There are certain criteria for continuous communication between the train cars and the BSs. The number of transceivers for three different scenarios is explained below.

### A. Single transmitter and single receiver (SISO – single input single output)

The simplest form of communication is SISO in which only one transmitter and a receiver would be communicating at any instant of time. The BSs are positioned at certain distances in the ground along the rail-track which consists of a pair of transceivers. The transceiver on the BS would communicate with the nearest transceiver in the train car. Different conditions for this communication are explained further.

The criterion for continuous communication is as follows:

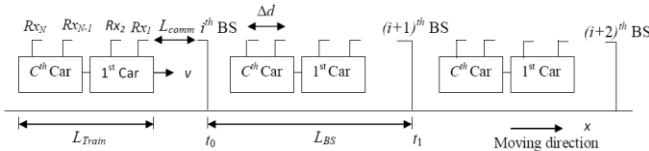


Fig. 1: Train moving along the track at different instants

- At  $i^{\text{th}}$  BS at instant  $t_0$ , the first receiver is positioned at  $x = L_{comm}$ .
- At  $(i+1)^{\text{th}}$  BS at time instant  $t_1$ , the last ( $N^{\text{th}}$ ) receiver is positioned at  $x = L_{train}$  where

$$t_1 = \frac{(L_{comm} + L_{train})}{v}. \quad (2)$$

- At  $(i+2)^{\text{th}}$  BS at instant  $t_2$ ,  $x = 2L_{train}$  where

$$t_2 = \frac{(L_{comm} + 2L_{train})}{v}. \quad (3)$$

Similarly, at  $(i+n)^{\text{th}}$  BS at instant  $t_n$ ,  $x$  is given as

$$x = nL_{train}, \quad (4)$$

where,

$$t_n = \frac{(L_{comm} + nL_{train})}{v}. \quad (5)$$

In order to ensure seamless communications between the BSs and the train, the criterion for the BS is given by:

$$L_{BS-SISO} \leq L_{comm} + L_{train}, \quad (6)$$

where  $L_{BS-SISO}$  is the separation between the consecutive BSs in SISO configuration.

From (6), the maximum possible separation between the two BSs can be given as

$$L_{BS-SISO} = L_{comm} + L_{train}. \quad (7)$$

The criterion for number of receivers on the train is as follows:

The communication link  $L_{comm}$ , and the separation between two consecutive transceivers in a train can be related as

$$L_{comm} \geq \Delta d. \quad (8)$$

Combining (1) and (8) yields,

$$N_{SISO} \geq \frac{L_{train}}{L_{comm}}. \quad (9)$$

Thus (9) gives the required number of receivers for the SISO configuration.

### B. Single transmitter and multiple receivers (SIMO – single input multiple output)

In this case, one BS transmits the signal to multiple receivers in the train. The diversity in this case is employed at the receiver which implies that there would be multiple outputs from a single transmitter at the BS. The criterion for communication and for the BS would be the same for this scenario as well but the number of receiver would be given by:

$$N_{SIMO} > N_{SISO}. \quad (10)$$

Among the multiple receivers, the power level comparison between the received signals can be performed and different combination rules like maximum ratio combining (MRC), equal gain combining (EGC), and selection combining (SC) can be used for optimum performance.

### C. Multiple transmitters and multiple receivers (MIMO – multiple input multiple output)

MIMO can be used in the system for bidirectional parallel data transmission in order to improve the link capacity. The main challenge with the high-mobility MIMO system is updating of the channel matrix. The transmission rate achieved in this case could be in the range of Gbits/sec [23]. For the MIMO configuration, there would be many BSs and they would communicate with multiple receivers on the train. The criteria for the BS can be approximated as

$$L_{BS-MIMO} = \frac{L_{BS-SISO}}{M}, \quad (11)$$

where,  $M$  is the number of parallel links,  $L_{BS-MIMO}$  is the separation between consecutive BSs in MIMO case.

Since SISO and MIMO are out of the scope of this paper, the link budget for the SISO configuration is analysed in the following section.

### III. LINK BUDGET CALCULATIONS

The link budget calculations and the coverage area for the SISO configuration can be estimated as given by [24], which can be used to estimate the required transmitted power for various link lengths.

$P_{Tx}$  is the optical transmitted power emitted from the transmitter that is located at various BSs which incidents on the photodetector (PD) having collection area  $A_{det}$  positioned on the roof of the train cars (see Fig. 2). Considering a transmitter half angle of  $\theta$ , the beam radius  $R$  and coverage area  $A$  at a distance  $L$  from the transmitter is given by;

$$R = L \tan(\theta). \quad (12)$$

$$A = \pi R^2. \quad (13)$$

To increase the collection area at the receiver, an optical telescope (lens) can be incorporated at the receiver (see Fig. 3). Hence the collection area of the receiver  $A_{coll}$  is given by

$$A_{coll} = \pi(R_{coll})^2. \quad (14)$$

where  $R_{coll}$  is the radius of the concentration lens, which is used to achieve the optical gain.

The use of an optical concentration lens can significantly improve the optical gain and reduce the transmit power but at the cost of a narrower FOV as given by the constant radiance theorem [24]:

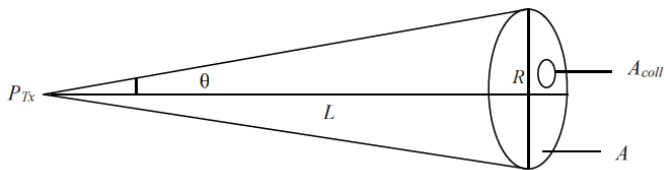


Fig. 2: Transmitted beam from the transmitter to the receiver

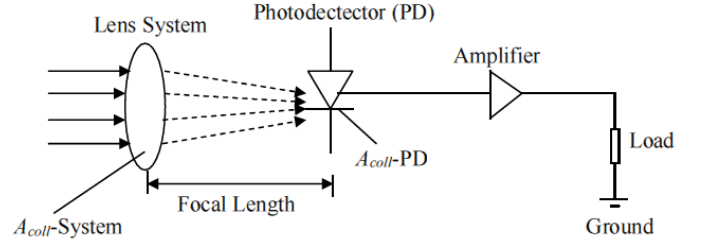


Fig. 3: Use of an optical concentration lens system.

$$A_{coll} \sin\left(\frac{FOV}{2}\right) \leq A_{det}. \quad (15)$$

For a truly diffuse system, the power received by the detector is set by the detector area. The resulting FOVs of the receiver obtained using (15) are given in Table 1 which shows that the FOV is reduced as the diameter of the lens is increased. Hence there is a trade-off between the optical gain and the FOV.

### IV. NUMERICAL RESULTS

To evaluate the appropriate transmit power required for the communication link, Matlab simulations have been performed with the system parameters given in Table I. The optical transmit power versus the link length is shown in Fig. 4 which clearly demonstrates that as the link length increase, the required optical transmitted power increases.

TABLE I  
SIMULATION PARAMETERS

Parameters	Value				
Receiver Sensitivity	-30 dBm				
FOV of transmitter	$\pm 6^\circ$				
FOV of photodetector	$\pm 60^\circ$				
Radiant sensing area of the receiver $A_{det}$	4.84 mm <sup>2</sup>				
Diameter of the concentration lens (mm)	10	15	20	25	30
FOV of the receiver (calculated using (15))(degree)	28.7	19.1	14.3	11.4	9.5

In this analysis, a number of commercially available concentration lens with different sizes are investigated. For a fixed link length, the required transmit power reduces significantly with increasing lens radius. As the lens radius increase, the optical gain per increment in radius decreases. For example, at a link length of 10 m, there is a reduction of  $\sim 14$  dBm of transmitted power when  $R_{coll}$  is increased from 5 mm to 7.5 mm, however there is only  $\sim 3$  dBm reduction in the transmitted optical power when  $R_{coll}$  is increased from 12.5 mm to 15 mm. Hence, optimisation between the link length, size of optical concentrator and the transmitted power is obligatory for a safe and reliable transmission of data for various lengths along the rail-track.

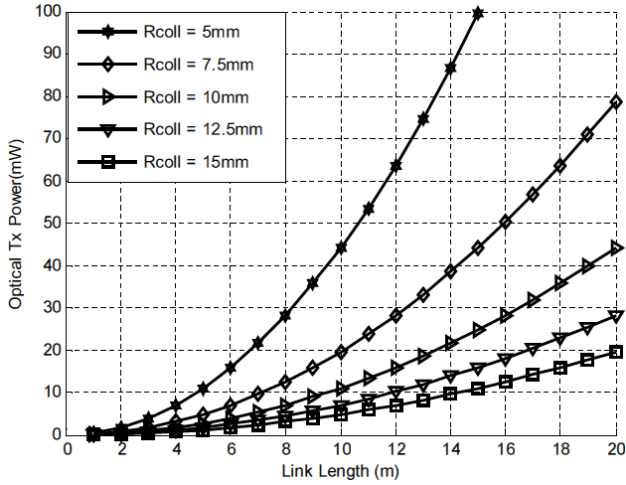


Fig. 4: Plot of required optical transmit power versus the link length for a range of the concentration lens radius.

## V. EXPERIMENT SETUP AND RESULTS

An experimental FSO link was set-up in the laboratory as a first step towards the implementation of the system. Fig. 5 shows the block diagram of the link setup. The laser is driven by a pseudo-random bit sequence (PRBS) source at 20 Mbit/s with OOK-NRZ modulation. The receiver front-end consists of a PD (SFH 225 FA) followed by transimpedance amplifier (TIA) IC (AD8015). The output of TIA is connected to oscilloscope for visual display of received signal.

TABLE II

EXPERIMENT SET UP PARAMETERS OF LD, PD AND TIA.

Parameters		Value
Laser Diode (LD)	Peak Wavelength	830 nm
	Maximum optical power	10 mW
	Class	IIIB
	Beam size at aperture	5 mm by 2 mm
PIN Photodiode (PD)	Wavelength of maximum sensitivity	900 nm
	Spectral range of sensitivity	740-1120 nm
	Active Area	4.84 mm <sup>2</sup>
	Half Angle (FOV)	±60°
	Responsivity	0.63 A/W
Transimpedance Amplifier (TIA)	Rise and fall time of the photocurrent	20 ns
	Bandwidth (3 dB)	240 MHz
	Rise and Fall Time	1.5 ns
	Supply Voltage	5 V
	Optical Sensitivity	-36 dBm
	Output Impedance	50 Ω
	Maximum Input Current	10 mA

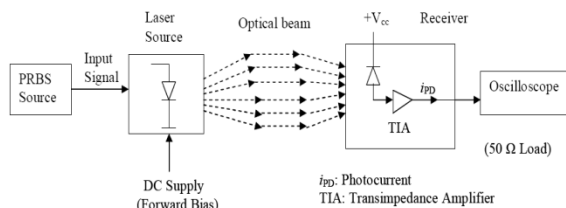


Fig. 5: Experimental link setup.

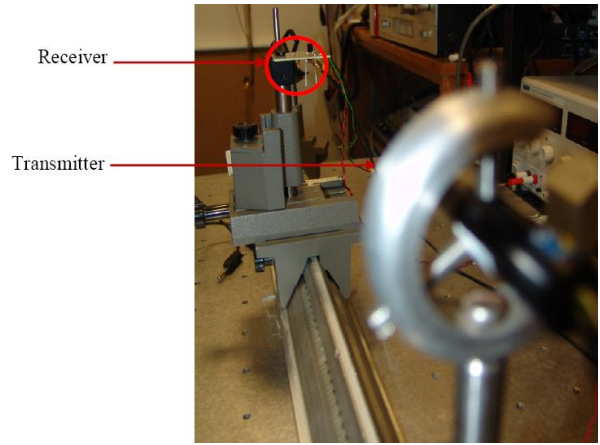


Fig. 6: Photograph of the optical wireless link.

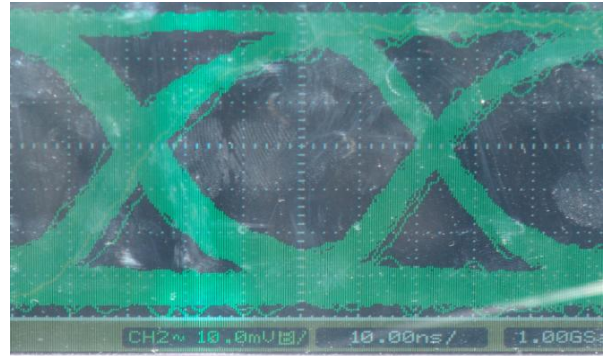


Fig. 7: The eye-diagram of the received signal.

The picture of the optical link setup is shown in Fig. 6 with the transmitter and receiver as shown.

The eye diagram for the optical link at a link length of 30 cm is shown in Fig. 7. The clear and wide opening of eye width for a data rate of 20 Mbit/s shows the possibility of error-free transmission of data. The link could perform at higher data rates as the bandwidth of transmitter and receiver are well above 20 MHz. In this experiment we limit the data rate at 20 Mbit/s due to the availability of high-speed data source. A longer link could be achieved by using concentration lens at the receiver. The full duplex communication link demonstration of such a system at higher data rates is in the development stage and results will be disseminated in future publications.

## VI. CONCLUSION

In this paper, we have proposed a ground-to-train communications based on the optical wireless scheme. Mathematical modelling and link budget calculation was presented for different communications models and a set of operation criterion were also determined. The results obtained have suggested that several meters long link could be implemented within the allowed eye-safe margin if the receiver collection area is sufficiently large using an optical system. A practical demonstration of the link has been presented for a SISO system. Though the link operates over a

relatively short range, the concept developed is applicable to systems with longer ranges, which is currently under study.

## VII. ACKNOWLEDGEMENT

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