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HIGH SPEED TRAIN COMMUNICATIONS SYSTEM USING FREE SPACE OPTICS

R. Paudel, *Student Member, IET,* H. Le-Minh, Z. Ghassemlooy, M. Ijaz and S. Rajbhandari

Optical Communications Research Group, NCRLab, Northumbria University, Newcastle upon Tyne, NE1 8ST, UK
{rupak.paudel, hoa.le-minh, z.ghassemlooy, muhammad.ijaz, sujan.rajbhandari}@northumbria.ac.uk

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Abstract

In this work, we propose a broad-band free space optical (FSO) wireless communications system for high-speed trains. The system consists of optical transceivers positioned outside the train and along the railway track. The train receivers are in the coverage area of base stations positioned along the railway track to ensure continuous link availability. In this paper, we present modelling of two cases for over-ground and underground train systems before embarking to practically implement the system in our research laboratory. Also discussed is the protocol for the data distribution along the track as well as the initial experimental demonstration of the proposed link.

1 Introduction

FSO wireless communication links are a complementary alternative to the well established radio frequency (RF) wireless technology. FSO systems offer a huge unregulated license free spectrum, excellent security, compatibility with the existing optical fibre networks, free from electromagnetic interference and relative safety features [9- 13]. The latter characteristics are widely desirable in many applications (e.g. hospital, hazardous environment, aircraft cabin, etc.) where there is a restriction on the use of RF based systems. However, the eye safety is an issue and permitted transmit power depends on the operating wavelength and the size of the light sources used [6]. At 900 nm wavelength using a laser source the transmitted output power must be limited due to eye safety regulations. Whereas at 1550 nm wavelength the eye retina is less sensitive to the optical power, therefore is relatively safe to operate. FSO systems can vary from the indoor short range (few metres) to the outdoor of a few kilometres link length. The outdoor links with a data rate of over 10 Gb/s over a few kilometres has been reported in [2]. For indoor links data rates as high as of hundreds of Mb/s for wireless home access networks can be achieved with much wider coverage area [5]. The main challenge for wireless optical systems is the very limited mobility compared to the RF cellular wireless systems.

There are a number of other challenges for outdoor optical wireless including line-of-sight requirement, continual transmitter/receiver alignment and signal attenuation due to absorption, scattering and shimmer of the optical signals [1, 10]. Absorption of optical signals is because of the presence of water particles and carbon dioxide within the atmosphere, whereas scattering is due to fog and haze, as well as rain and snow. The nature of scattering depends on the optical wavelength and the size of scattering particles. Dense fog remains the most deleterious weather effect, resulting in over 100 dB/km attenuation coefficient [1, 15]. It consequently limits the achievable link range (distance) to about 500 metres [2].

There is a growing demand for access to a high-speed wireless network by the end users while they are on the move using trains, buses, planes, ships, etc [8]. At present, the train operators offer limited RF based wireless network to the passenger on their intercity high-speed trains, which is slow at the best of time. One alternative solution would be to employ optical wireless systems within the train coaches that is linked to the existing mobile base station (BS) or to the fibre optic backbone network. Both line of sight and non-line of sight (better known as a diffuse system) links could be offered capable of delivering hundreds of Mb/s.

In [3, 7] the potential application of OWC link for passenger trains has been reported, thus demonstrating the practical viability of this new emerging light based technology. In this paper, we outline the ongoing research in this area. We have carried out modelling and numerical analysis for both the over-ground and the underground systems. Discussion on the system protocols and initial practical results are also presented.

The paper is organised as follows. In section 2, the modelling of the system is presented for the two cases: over-ground system and underground system. In section 3, the simulation of the system for both cases is performed in terms of the received optical power. In section 4, the protocols for the appropriate data distribution is discussed. In section 5, initial practical results are discussed and finally section 6 concludes the paper with the possible future work.

2 Proposed System

The proposed train communications system consists of a number of BSs located along the track and transceivers positioned on the roof of the train coaches as shown in Fig. 1. The BSs can be connected to each other and to the backbone network via fibre optic cables. Here the number of train coaches used is six and the train is travelling from left to right with a given speed *v*. The BSs are located in such a way that one BS covers two train coaches and a pair of transceivers is positioned on the roof of each train coach, thus providing continuous full duplex communication link between the train the BSs. In general, the distance of BSs could be different as long as the communications link is continuous.

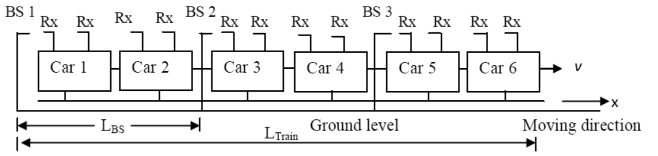

Fig. 1: Proposed train system with OW BSs and transceivers.

2.1 Modelling of the over-ground system

Figure 2 outlines the schematic diagram for the over-ground system with only two train coaches.

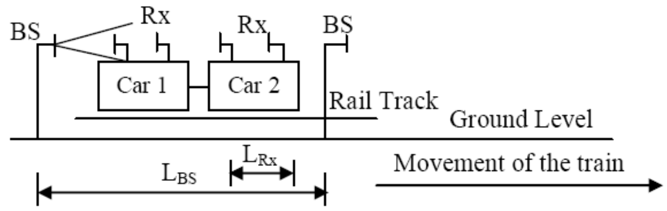

Fig. 2: Proposed system for over-ground train.

As shown in Fig. 2, L_{BS} and L_{Rx} are the separation distance between the two BSs and the two transceivers, installed on the train, respectively. One BS provides the coverage for two train coaches. The transceivers and the BS are at the same height to ensure a line of sight communication link. Note that the height of the BSs and transceiver does not have to be the same provided there is a line of sight link between them.

There are a number of factors that affect the performance of OWC link for both systems. For over-ground links fog, rain as well as sunlight are the major problems. There are also the eye safety issue with regard to flooding the train coaches with optical laser beams via the BSs. Hence the optical BSs must conform to the eye safety regulations if operated at a wavelength below 1550 nm. The detail of eye safe regulation for different wavelengths could be found in [11].

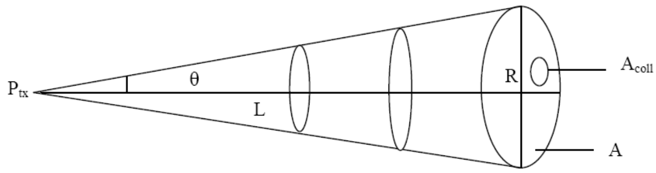

Fig. 3: Variation of received power for over-ground condition

For this case the optical power at various link lengths can be approximated as given in [13] and shown in Fig. 3. P_{tx} is the power transmitted from the BS complying with the eye-safety regulations. The coverage area radius is given by:

$$R = L \tan\theta. \qquad (1)$$

Where θ^o is the transmitter half angle, L is the link range, and $A = \pi R^2$ is the reciver coverage area.

From Fig. 4, it can be inferred that the received optical power at various link lengths is different as the coverage area of the transmitted beam varies with the length.

2.2 Modelling of the underground system

For this case the BSs are located on the ceiling of the tunnel, see Fig. 4. As the train moves, communications is continuously maintained by an array of BSs located along the tunnel linked to each other via optical fibre cables. A number of specific BSs will be switched on as the train moves toward their coverage areas whilst the rest remain switched off. In this scenario, the permitted transmit power could be higher than the over-ground case.

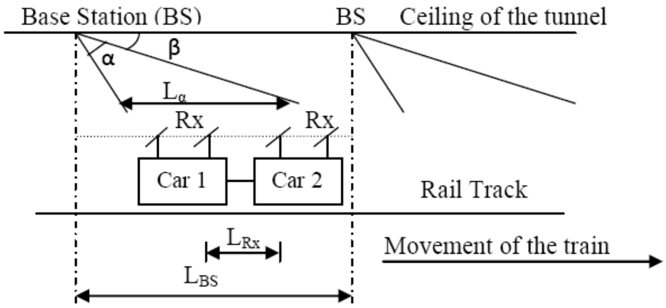

Fig. 4: Proposed underground train system.

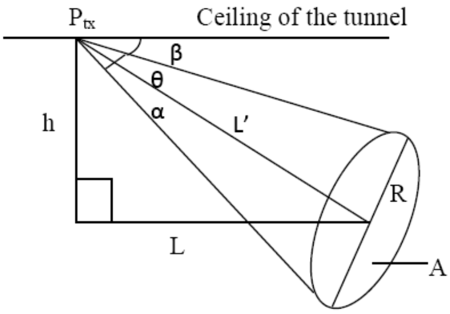

Fig. 5: Evaluation of power for underground condition

Fig. 5 illustrates the transmitted optical beam profile. The coverage area radius is given by:

$$R = L' \tan\theta \qquad (2)$$

Where L' is the axial length of the link, β is the angle at which the transmitter is positioned, h is the height of the tunnel above the top of train coach. If the parameters are optimised such that $\beta + \theta = 45^o$, then we can relate R and L as:

$$R = \sqrt{2}\, L \tan\theta \qquad (3)$$

For both over-ground and underground conditions, an optical concentrator could be used to increase the optical gain and the effective collection area of the receiver. The effective area of the receiver then is given by [4]:

$$A_{in} = \frac{A_{det}\, n^2 \mathrm{Cos}\, \theta a}{\mathrm{Sin}^2 \theta a} \qquad (4)$$

where A_{det} is the detector collection area, θ_a is the field of view (FOV) of the optical concentrator, and n is the refractive index of the concentrator.

The term $\frac{n^2}{\text{Sin}^2\theta\text{a}}$ in (4) is the optical gain of the concentrator for a FOV $\theta_a \leq 90^o$.

3 Numerical Results

The simulation parameters adopted in this work are given in Table 1. In this section, Matlab has been used for the analysis of the system performance for the two different conditions. We have analysed the received power as the train moves along the track. For both systems, the position of the transceivers and the BSs are kept the same. Thus the power received would be in cycle after every 11 m (i.e. the separation distance between transceivers). The first BS would transmit data for two train coaches, which effectively means data transmission for four transceivers using only one BS.

Parameters	**Value**
Receiver Sensitivity	-30 dBm
Transmit power	7 mW (Over-ground case)
Transmit power	10 mW (Underground case)
FOV of transmitter	± 6^o (Over-ground case)
FOV of transmitter	± 15^o (Underground case)
FOV of photodetector	± 60^o
FOV of the concentrator θ_a	9.5^o
Radiant sensing area of the receiver A_{det}	4.84 mm^2
Radius of the concentration lens	15 mm
Refractive Index of the concentrator	1.85

Table 1: Simulation parameters

The plot of received power along the track for the over-ground scenario as the train moves is shown in Fig. 6.

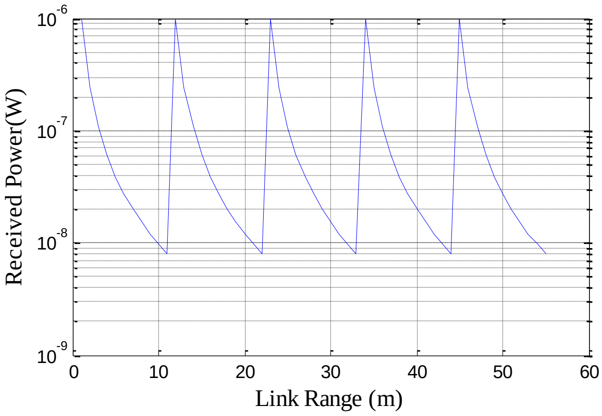

Fig. 6: Plot of the received optical power against the link range for the over-ground system.

In this case, the transmitted optical average power used was 7 mW. The plot also shows that the received power reaches a minimum level of 0.01uW at a distance of 11 m before rising again. In order to improve the power received, the optical concentrator is placed at the front of the photodetector at the receiver, with the results shown in Fig. 7, illustrating a considerable improvement in the received power.

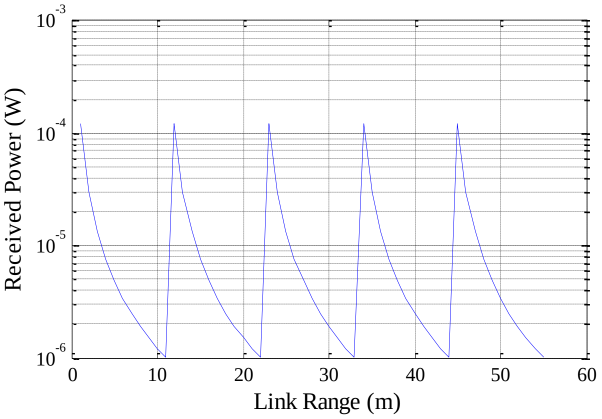

Fig. 7: Plot of the received optical power against the link range for over-ground train using an optical concentrator.

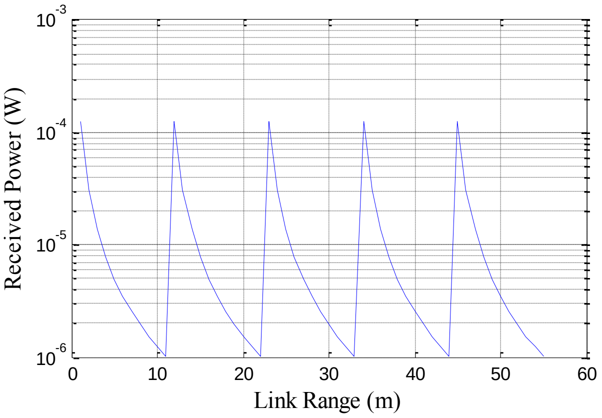

Fig. 8: Plot of the received optical power against the link range for the underground train using an optical concentrator.

For the underground system, the transmitted average power used was 10 mW. The plot of the received power for the underground case was the same as shown in Fig. 6. With inclusion of an optical concentrator, the received power showed an improvement as depicted in Fig. 8, where the power level is well above the sensitivity threshold level of the receiver.

4 System Protocols

Along the rail track, there is no need for all BSs to be turned on all the time. In this paper, we discuss the protocol for the control the data distribution on relevant BSs. Fig. 9 shows the protocol procedure. As the train moves along the track, the BS#2 is switched on and the BS#1 and BS#3 are switched off. The BS doesn't have to be switched on at all times and can be switched on as the train is approaching. The mechanism to switch on and off BSs is based on the signal power level received at each BS. If the train is within BS coverage, the lowest signal received by BS is higher than a pre-defined threshold, therefore BS is switched on. When the train passes the BS, the communications link is ceased resulting signal received at that BS is lower than the threshold and the BS is off.

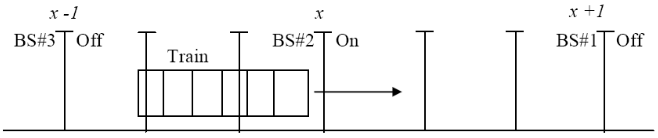

Fig. 9: Protocol procedure for switching ON the proper BS.

We also consider a case of multiple trains being in the same track. A backbone optical fibre cable is used to transmit data to different trains whereas trains could reuse the base stations. Therefore multiple access schemes and protocols are required to efficiently use the hybrid system as well as to prevent data collision. Multiple wavelengths could be also used for different trains as well as add-and-drop multiplexer/demultiplexer could be employed in this scenario, see Fig. 10.

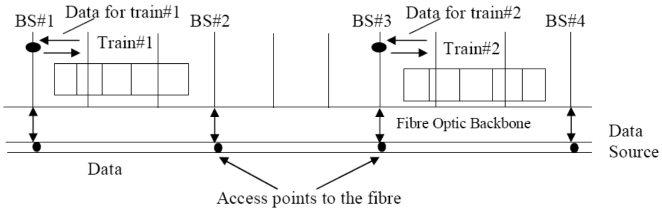

Fig. 10: Protocol procedure when multiple trains share the same track

5 Experimental Setup and Results

As a first step towards the realisation of the proposed system, an FSO link was setup in the laboratory with the block diagram shown in Fig. 11. The laser diode (LD) is driven by a pseudo random bit sequence (PRBS) source at a data rate of 155 Mb/s with non-return to zero (NRZ) on-off keying (OOK) modulation format. The transmitter and the receiver are located at a distance of 1.5 m. The receiver circuit consists of a photodiode (PD) at the front end followed by a transimpedance amplifier (TIA), which is a voltage to current converter, the output of which is connected to the oscilloscope for the display of the received signal.

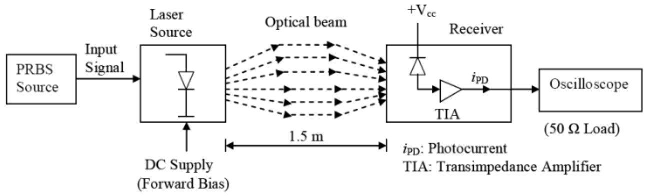

Fig. 11: Experimental link setup.

Parameter		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	750-1100 nm
	Active Area	1 mm^2
	Half Angle (FOV)	$\pm 75^{o}$
	Spectral sensitivity	0.59 A/W
	Rise and fall time of the photocurrent	5 ns
Transimpedance Amplifier (TIA)	Bandwidth	240 MHz
	Rise and Fall Time	1.5 ns
	Supply Voltage	5 V
	Maximum Input Current	10 mA

Table 2: Experimental set-up parameters

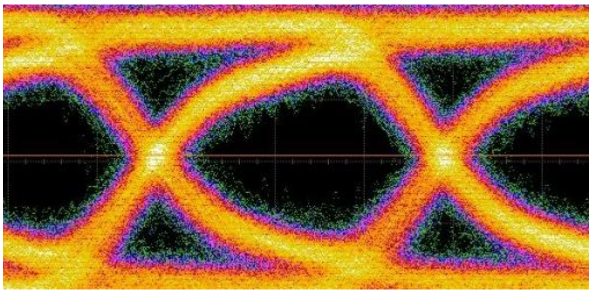

Fig. 12: The eye diagram of the received signal at 155 Mb/s.

The eye diagram for the received signal at a distance of 1.5 m is depicted in Fig. 12. The diagram shows a clear and wide opening of the eye for a data rate of 155 Mb/s, which suggests the possibility of error free transmission. For outdoor environment, there is a requirement for a longer link span which could be achieved using an optical concentrator. Work on increasing the link length and data rate is ongoing.

6 Conclusions and Future Work

In this work, we have proposed a high speed optical wireless ground-to-train communications system for underground and over-ground train systems. Numerical evaluation of the system and system protocols were performed and outlined for the two systems. A preliminary experimental result showed that an error free data transmission at data rate of 155 Mb/s for a link of 1.5 metres.

Acknowledgements

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