Modelling and Analysis of FSO Ground-to-Train Communications for Straight and Curved Tracks

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***Abstract*—In this work, a free space optical (FSO) link for the ground-to-train communications is proposed. Analytical analysis is carried out for the case of the straight as well as curved rail tracks. We show that the transmitter divergence angle, the transmit power and the size of the concentration lens needs to increase for the curved section of the rail track compared to the straight track. We derive the analytical expression (11) for the received power level based on the link geometry for the cases of straight and curved tracks. The received power variation is compared for two cases showing a similar dynamic range. In the worst case scenario when the radius of curvature is 120 m, the transmit power at the optical base station (OBS) needs to increase by over 2 dB when the concentration lens radius is increased by 5 times. Analyses also show that received power increases with the radius of curvature. Finally, results are compared with the existing straight track model.**

Index Terms—free space optical, ground-to-train, base station, link geometry.

I. INTRODUCTION

Free space optical (FSO) communication links are a complementary alternative to the well-established radio frequency (RF) wireless technology. FSO systems offer a huge unregulated license free spectrum and thus high data rates, excellent transmission security, no electromagnetic interference and low error rate transmission[1-3] FSO systems are also desirable in places such as campuses and hospitals where there is restriction for RF wireless links [4]. 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 [5]. For indoor links, data rates up to Gb/s for wireless home access networks can be achieved with much wider coverage area [6]. The main challenge for wireless optical systems is the very limited mobility compared to the RF cellular wireless systems.

There is a growing demand for the access to high speed wireless network by the end users when they are on the move like on trains, buses, ships etc. At present, the limited RF based wireless network is provided by the train operator at a low data rate when the train is on the move. Although RF based communications is a promising technology for fixed wireless local area network (WLAN), its effectiveness is limited when used in trains offering very limited connection capabilities. For a truly office-office network capabilities offered to the commuters within the train, the system can benefit from a combination of FSO and visible light communications that would be linked to the existing mobile base station (BS) or to the optical fibre backbone network.

Ground-to-train FSO communications has been reported previously [7, 8] where FSO link for straight track is demonstrated. Obviously, there would be cases of curved tracks in real scenario, study of FSO link for curved track is essential. This paper reports the numerical evaluation for FSO ground-to-train communications for the case of straight and curved tracks. The paper is organized as follows: the proposed ground-to-train communication links is described in section II. Numerical analysis of the link geometry for a straight and curved track is shown in Section III. Simulation results showing a comparison between the straight and curved track is presented in Section IV. Finally, the concluding remarks comprise the final section.

II. PROPOSED SYSTEM MODEL

The proposed ground-to-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. Here, the communications link for a single coach that provides a continuous communication link between the train and the optical base station (OBS) is shown. The OBSs would be connected to the optical fibre backbone network. As long as the train is within the coverage of an OBS, the communications takes place between the optical receiver on the train and the OBS. When the train passes a specific OBS, communications is provided by other OBS positioned alongside the train track. As shown in Fig. 1, when the train coach passes the BS1 region, the communications is maintained using the BS2. In this way, a continuous communication link between the train coach and the OBS is maintained.

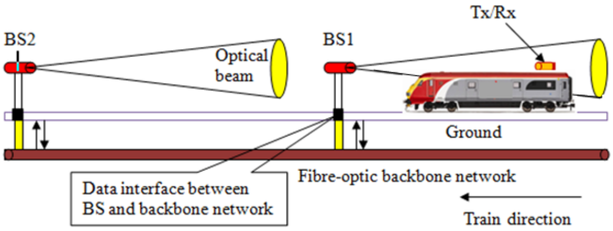

Fig. 1: FSO ground-to-train system

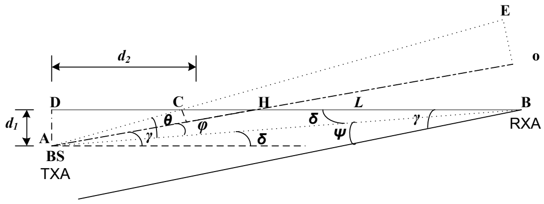

Fig. 2: Proposed link geometry for the train in straight track.

The geometrical model for the ground-to-train FSO link for a straight track is shown in Fig. 2 where the OBS is positioned at a distance d_1 from the track with an offset distance of d_2 from the shortest coverage point. The beam divergence of the transmitter is given by θ. Based on this geometry; the estimation of the transmitter beam divergence is given by [9].

III. NUMERICAL ANALYSIS

In this section, the link geometry for a train in a straight track is studied and angle of irradiance and the incidence angle are estimated based on the geometry. Furthermore, analysis of the situation in the curve will be carried out.

A. Straight track

From Fig. 2, the transmitter irradiance angle φ becomes equal to the receiver incident angle ψ, which can be given as:

$$\phi = \psi = \gamma - \delta = \frac{\theta}{2} \tag{1}$$

As can be shown in [9], the received optical power P_r can be written as:

$$P_r = \frac{A_{\det} P_{tx} (m+1) T_S(\psi) \cos^m(\phi) n^2 \cos(\psi)}{2\pi \sin^2 \psi_c \left[L\cos\gamma + x\cos(\theta_{1/2}) \right]^2}, \tag{2}$$

where A_{det} is the physical area of the detector, P_{tx} is the transmitted power, m is the order of Lambertian emission, T_S is the filter transmission factor, ψ is the incident angle of the receiver, ψ_c is the field of view of the receiver, γ is the tilt angle, L stands for the location of the transmitter along the track, x is the distance from the point A to C (Fig. 2) and θ is the divergence angle. The essential is then the knowledge of the angles ψ and ϕ which were analyzed in [9]. Next subsection derives the angles for case of the curved tracks. Then, we are able to determine optimal geometry for the system to achieve maximal availability.

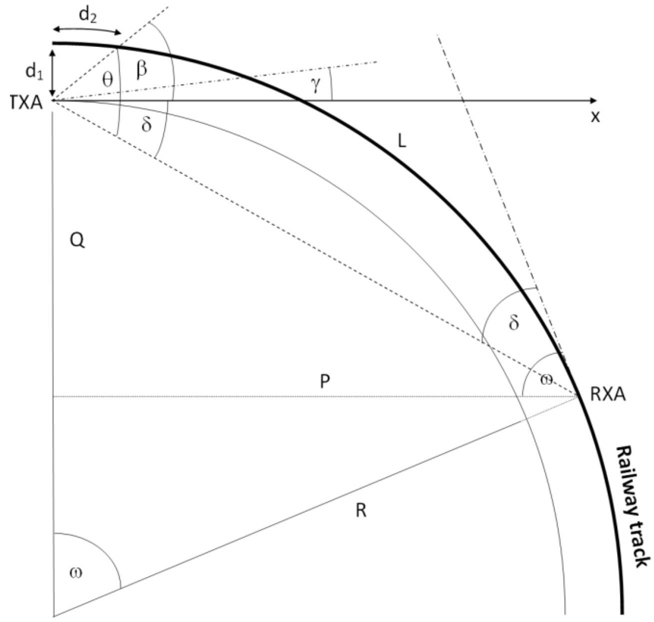

Fig. 3: Proposed link geometry for the train in the curve.

B. Curved track

Since tracks along the path are always somehow curved, the system link budget analysis should consider such situations. According to the analysis of the straight track situation, the worst case occurs when the distance TXA – RXA from the transmitter TXA to the receiver RXA is maximal. With reference to Fig. 3, the angle ω at the intersection of the centre of the curve and points of RXA and TXA respectively is defined as:

$$\omega = \frac{L + d_2}{R}, \tag{3}$$

where R is the curve radius. ω is also the angle between the tangents of the RXA and the TXA. For the link geometry, the transmitter's irradiance angle φ and the angle of incidence at the receiver ψ also need to be calculated. From the equation (1) we can derive the angle γ as:

$$\gamma = \frac{\theta}{2} + \delta, \tag{4}$$

where θ is the beam divergence of the transmitter and δ stands for the angle between the edge of the beam and the x axis. Using trigonometric laws we can obtain for the angle δ:

$$\delta = \tan^{-1}\left(\frac{Q}{P}\right), \tag{5}$$

where Q and P are the respective coordinates of the RXA in y and x axis according to:

$$P = R \cdot \sin(\omega), \tag{6}$$

and from the Pythagorean Theorem we can write:

$$\sqrt{R^2 - P^2} = R - d_1 + Q \Rightarrow Q = \sqrt{R^2 - P^2} - R + d_1. \tag{7}$$

Accordingly, for the transmitter's divergence θ one can write

$$\theta = \beta - \delta = \tan^{-1}\left(\frac{d_1}{d_2}\right) - \tan^{-1}\left(\frac{Q}{P}\right). \tag{8}$$

Variables presented in this subsection so far define the geometry of the link. However, the irradiance angle φ and the angle of incidence with respect to the receiver axis ψ (cf. Fig. 2) change as the train moves along the track. To determine their values we will proceed as follows. The Irradiance angle φ can be defined as:

$$\varphi = \gamma - \delta. \tag{9}$$

Considering that δ and γ are equal for both RXA and TXA, we may assume that $\varphi = \psi$. Finally, for the distance z between RXA and TXA we may write from the Pythagorean Theorem that:

$$z = \sqrt{P^2(L) + Q^2(L)}, \tag{10}$$

where distances P and Q from (6) and (7) change according to L in (3).

Then, the received optical power P_{r} along the track can be expressed as:

$$P_r = P_{tx} \frac{T_S(\psi) A_{\det}(m+1)\cos^m(\phi) n^2 \cos(\psi)}{2\pi \sin^2 \psi_c \sqrt{P^2(L) + Q^2(L)}} \tag{11}$$

In case of the straight track, the LOS propagation is always maintained. However, in the curve section of the track, we must determine the clearance distance S from the track (cf. Fig. 4) in order to ensure a LOS link between TXA and RXA. S can be modelled as the sagitta of the circular arc represented by the rail track. Since we have insufficient known variables to determine the sagitta S then we calculate the smaller sagitta S' in order to determine the clearance S according to:

$$S = S' + d_1 \tag{12}$$

To calculate the sagitta S' we must first know the length C of the corresponding chord of the arc with radius ($R - d_1$) as:

$$C = 2(R - d_1)\sin(\delta). \tag{13}$$

Substituting (13) into the known expression of sagitta of the circular arc with known radius R' yields:

$$S' = R - \sqrt{R^2 - \frac{C^2}{4}} = R - \sqrt{R^2 - (R - d_1)^2 \sin^2(\delta)}. \tag{14}$$

The length of the sagitta S represents the minimal obstacle-free distance from the railway track to ensure a reliable LOS path.

IV. Simulation Results

In order to simulate the optical link performance along the curved track a simulation of the received optical power P_r was carried out for every point along the track length L and the result is shown in Fig. 5. The parameters used for the system simulation are shown in Table I. For a better comparison of the performance for the straight and curved rail tracks, we have adopted the same parameters for the curved track as adopted in [9]. We note that for the curved track with a curvature radius R of 120 m the additional optical transmit power is 10 mW and the concentrator radius R_{coll} is 5 times higher. The received power profile for the straight track is shown in Fig. 5, which is simulated using (2). The received power profiles based on (11) for the curved track for a range of curvature radius is depicted in Fig. 6, showing a lmost a linear relationship. In the worst case scenario we assume R = 120 m. This is represented by the lowest power profile as in Fig. 6.

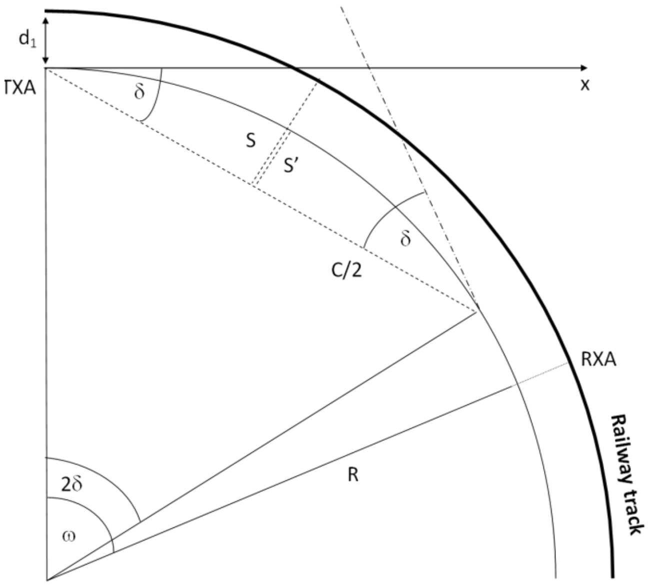

Fig. 4: The geometry of the analysis of LOS operation conditions.

A relatively small FOV of the receiver is caused by a larger radius of the concentrator lens according to the constant radiance theorem [10], which illustrates the relationship between the receiver FOV, the collection area of the lens and the photodetector area. To increase the FOV one may adopt

i) a smaller size concentrator lens, which would impose higher demands on the optical transmit power,
ii) a photodetector with much larger active area but at the cost of reduced bandwidth,
iii) an array of small area photodetectors or
iv) different optical setup to enlarge the FOV [11].

Finally, to verify whether the models developed for both tracks (straight and curved tracks) we plot the received power level against the track length as shown in Fig. 7. There is almost no difference between the two plots, thus proving that the curved track analysis based on (11) can be used generally for the analysis of the ground-to-train FSO communication link.

TABLE I
SIMULATION PARAMETERS

Parameters	Symbol	Value
Optical transmit power	P_{tx}	15mW (st.)/25 mW (curved)
Operating wavelength	λ	850 nm
Transmitter divergence	θ	3.2°(st.)/24.69°(curved)
Active area of the detector	A_{det}	7 mm^2
Responsivity	R_{PD}	0.59 A/W
Receiver sensitivity	S_r	-36 dBm@10 Mbps
Concentrator focal length	f	50 mm
Concentrator radius	R_{coll}	25 mm (st.)/125 mm (curved)
Concentrator semi FOV	Ψ_c	5.15°(st.)/1.02°(curved)
Coverage length	L	75 m
Vertical separation	l_1	1 m
Horizontal separation	l_2	15 m
Refractive index of lens	n	1.5
Tx/Rx tilting angle	γ	2.25°
Filter transmission factor	$T_s(\psi)$	0.8
Curvature radius	R	120/240/500 m

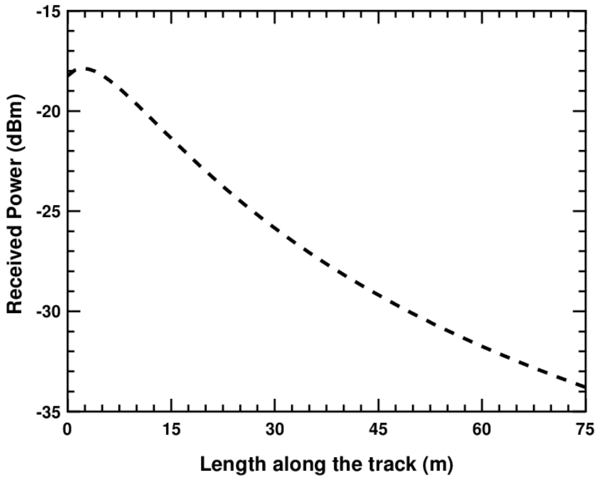

Fig. 5: Received power profile along the track for a straight track.

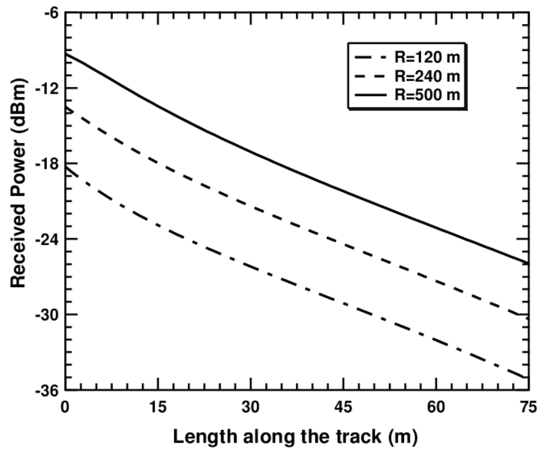

Fig. 6: Received power profile along the track for a curved track with different radius R.

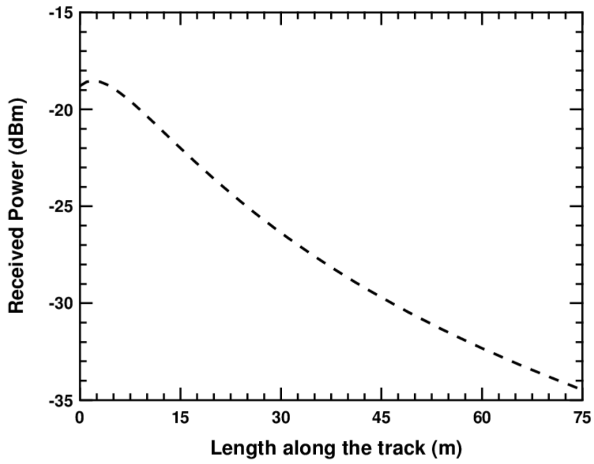

Fig. 7: Received power profile along the track for a curved track with infinite curvature radius R and the same simulation parameters as in Fig. 5.

Taking into account the worst case scenario represented by the lowest power profile in Fig. 6 and the optimal straight track scenario represented by the power profile in Fig. 5, we are able to determine the required dynamics of the receiver as the difference between the maximal P_r of -17.87 dBm in Fig.5 and the lowest P_r of -35.15 dBm in Fig. 6. The minimum required receiver dynamics D = 17.28 dB, which is simply achievable using off-the-shelf components.

V. CONCLUSIONS

This paper has investigated the required beam divergence at the transmitter of and FSO link for straight and curved rail tracks. It was shown that for the curved track, a higher beam divergence angle is required, thus resulting in a higher optical transmit power in order to ensure FSO link availability along the train track compared to the straight track. In the similar manner, a higher receiver FOV would be needed to collect a sufficient amount of optical intensity for the case of curved track. The received power profile for both cases was compared. In order to achieve a minimum power level at the longest point along the track, the required transmit power for the curved track with R of 120 m was over 2 dB higher compared to the straight track in order to ensure the link functionality.

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