On-Board and Train-to-Wayside Free Space Optical Link: Design and Characterization

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Abstract. Nowadays, online connectivity has become an important factor in the current competition between different means of transportation. Being one of the most comfortable and satisfactory means of transportation, a train acts as a mobile office for a wide range of customers. This demands for a high speed connection in order to provide personalized digital services. A reliable and highly secure link is needed for real time information required for signaling, control, safety and security. In this paper a free space optical (FSO) communication link is designed, implemented, and tested at different data rates reaching 5 Mb/s. A small scaled link between train waysides and carriages is implemented in order to set the geometrical boundaries for a practical scaled up link. A 1 m train track is built in laboratory to set the track length and angle of transceiver boundaries for continuous transmission. The received signal voltage is measured and bit error rate (BER) is calculated along the track. The experimental results are compared to the ray trace model simulation results. The experiment is conducted with different field of view (FOV) light emitting diodes (LEDs) in order to check their impact on short and long distance links. Obtained results showed full train track coverage of 90 cm is achieved using the 13̊-LED, where the 3̊-LED was limited to 85 cm. A modification to the geometrical dimensions is suggested in order to suit the real train track. According to the designed circuits, a bandwidth can reach up to 337 Mb/s. At a speed of 500 kb/s, 9 m of coverage and nearly 38 m are obtained for the 13̊-LED and the 3̊-LED, respectively. On the other hand, at the maximum bit rate of 337 Mb/s, the coverage is reduced to 1 m and 5 m for the 13̊ and the 3̊-LEDs, respectively.

Keywords: Free space optics (FSO), Infrared (IR) Transceiver, Light emitting diode (LED), Railway Communication.

1. Introduction

Railway statistics have recently shown high share in total inland passenger transportation. According to Eurostat; the statistical office of the European Union, 381 billion passenger-kilometres were travelled over the national railway networks of the 28 European members (EU-28) in 2014. This indicates a 7.6% of total passenger transportation compared to 6.7% in 2003. Railway turnover of EUR 78.354 billion was reported in 2011 for EU-28, showing a real high market value industry [1-2].

In view of the vital role of railway transportation today, smart transportation plays another important role. This concept has been an emerging trend and proposed solutions for many challenges including but not limited to security, safety, smooth traffic flow, emergency calls and business transactions especially over long trips. For these reasons, the requirement for high data rates over trains has been essential in order to cover the needs of the hundreds of passengers onboard. The high speed mobility of such transportation puts some limitations on radio solutions. Problems like Doppler delay and angular spread cause intersymbol interference. Thus, current communication systems cannot meet the customers’ satisfactory bit rate which according to studies, will be in order of Giga bits per second [3]. Evolution of 3G technologies to 4G has increased the throughput to 100 Mb/s; however, in high mobility environment the required quality of service will not be maintained. Nowadays, GSM for Rail (GSM-R)
with a maximum data rate of 200 kb/s is used for train control. A downlink of 3 Mb/s and uplink of 2 Mb/s were reported for fast moving trains in Taiwan [4]. Besides channel limitations, broadband wireless communication systems used with fast trains needs a different structure from the existing conventional cellular network; otherwise direct communication with base stations will dramatically affect the signal quality [5]. Furthermore, satellite mobile communications, though provide very high data rates, are not suitable for underground trains.

On the other hand, the emerging of free space optical (FSO) communication offered real solutions for many of the previous limitations with very high data rates and robustness to electromagnetic interference and multipath fading. More privileges regarding license-free spectrum, high security and current optical fibre based infrastructure compatibility make FSO a strong competitor to broadband technologies. Consequently, FSO in train communications has become a hot research topic despite introducing new challenges regarding eye safety, atmospheric conditions and mobility effect on receiver field of view [6].

Ground-to-train employing FSO has been under investigation by different research groups within the past few years. Researchers from Keio University and Railway Technical Research Institute in Japan have implemented a practical field experiment on a moving train, using visible laser diode (LD), in order to study the viability of typical train coach length (25 m) coverage by an FSO link. They were able to achieve a seamless link with BER of 10^{-6}. Another field experiment, using a fast moving car with the transceivers placed along the train track, proved the possibility of one way tracking using an optical link over 1350 m and two way tracking over 150 m straight train tracks. The study later has moved to the handover level to achieve 566 Mb/s with less than 5% packet loss and continuous tracking for a 270 km/hr moving train [7-10].

In another research conducted by R. Paudel et al., mathematical and simulation models have been provided for over-ground and underground systems using FSO links [11]. Simulations have showed the possibility of getting 75 m coverage at 10 Mb/s with BER of 10^{-6}, using models for Lambertian and Gaussian sources and expanding the scope of study to straight and curved tracks. Laboratory experimental studies over a part of a small scale train track have resulted in an acceptable BER of 10^{-13} over 1 m [12-14].

In this paper, an experimental approach is investigated in order to set the boundaries of the FSO transmission system. A preliminary experiment is conducted in the laboratory to investigate the distance and FOV limitations of the transceiver and verified by simulation results. A small scale train experiment is implemented; based on the boundary dimensions from the preliminary experiment, in order to observe the received power along the train track. The obtained results are verified by a ray trace model, which is used to present the suggested extended railway communication architecture. The designed system is studied at the maximum data rates and the maximum coverage by the ray trace model simulation. The presented approach provides insight on the system design subject to extensive experimental measurements to estimate the system coverage. In other words, the effort here is to focus on advancing a commercially applicable system with a motivation to minimise the prescribed resources such as the transmitters and receivers on top of the train coaches or along the railway track. Besides, the experimental inspection comprises the ultimate accessible data rate in the laboratory. Nevertheless, simulation is employed to assess the compatibility of the schemed specifications with a large scale system. Correspondingly, despite the fact that this research topic has been investigated before, the considered study offers a different perspective.

This paper firstly introduces the transmission system and the train model in the following section, followed by the preliminary laboratory experiment and the obtained results in Sec. 3. The experimental setup and results are presented in Sec. 4. In Sec. 5, the extended system is presented and the results are discussed. Finally, Sec. 6 concludes the paper findings.
2. Proposed system

2.1. Experimental model

In this section, the proposed communication system is discussed. A block diagram for the implemented FSO link is presented in Fig. 1. The main blocks of the system are the data source, the transmitter, the channel, the receiver and the data processing stage. The implemented transmitter and receiver circuits are designed to handle data rates up to several Mb/s. However, the input data generated using the pseudorandom source (Lab-Volt 9421-00) with a length of \(2^{10}-1\) is limited to 5 Mb/s. The pseudorandom source is preferred in order to generate a general form of data which can be later replaced by different message types. The input bits modulate an infrared (IR) LED (SFH 4350 and SFH 4550) with a wavelength of 850 nm using a non-return-to-zero (NRZ) on-off-keying (OOK) modulation scheme. At this wavelength inexpensive high-performance transmitter and detector components are available in addition to reduced atmospheric absorption (i.e. attenuation < 0.2 dB/km). A LED driver circuit controls the on-off biasing current that feeds a 50 mW-LED. Incident light is focused by a 5.5 cm lens on the surface of an infrared filtered PIN photodiode. A PIN photodiode is a feasible choice when compared to different light detectors due to the reasonable speed, high sensitivity and low cost. Light pulses are then converted into nA-current values which are amplified into detectable voltage using a transimpedance amplifier (TIA) utilizing the ultra low noise operational amplifier (opamp) AD8099. The digital storage oscilloscope (DSO) Gw Instek GDS-1102-U is used to monitor and save the received signal frames. A picture for the basic back to back system can be seen in Fig. 2. The designs of the transmitter and the receiver circuits are presented as a preliminary stage of this research in [15].

Figure 1. FSO communication link.

Figure 2. Back to back FSO link.
This implemented FSO link is applied between the source placed on a fixed base station (BS) at point B and the detector located on top of the train carriage moving from point A to point C as presented in the train track model in Fig. 3 (a). The geometrical representation for the proposed model is illustrated in Fig. 3 (b) to explain the experimental approaches for finding the maximum transmission coverage. The transceivers tilt angle $\theta$ plays a vital role in changing the maximum coverage length which represents the maximum distance allowed between detectors on top of the train.

The optical signals are intensity modulated (IM) in every color. Working on an actual LED traffic light, the half-power semi angle, $\phi_{\text{HP}}$, of LED takes the value of $15^\circ$. The position of a vehicle is identified by the distance in the lane direction, $x$, and the distance in the width direction, $y$ as shown in figure 3. A vehicle is on the first lane, where there is an LED traffic light in position $y = 0$ m. Supposing that the width of a lane is 3.5 m and the width of a vehicle is 1.8 m, $H_l = 5.3$ m represents the height of traffic light, $H_r = 1$ m represents the height of the receiver itself from the road, and $z$ is the height difference between $H_l$ and $H_r$, as used in [3]. According to the law of cosines [16]

\begin{align}
L^2 &= (D_{\text{max}})^2 + (D_{\text{min}})^2 - 2(D_{\text{max}})(D_{\text{min}})\cos \alpha \\
\theta &= \cos^{-1} \left( \frac{L^2 + (D_{\text{max}})^2 - (D_{\text{min}})^2}{2 L D_{\text{max}}} \right) \\
V &= D_{\text{max}} \tan \theta
\end{align}

where $L$ is the displacement vector between points C and A on the track, $D_{\text{max}}$ is the maximum achievable distance maintaining line of sight (LOS) between the source at point B and the detector at point A (i.e., angle of incidence is $0^\circ$) and $D_{\text{min}}$ is the minimum distance between B and C. Moreover, $\alpha$ is the maximum angle of incidence on the receiver at point C, $\theta$ is the transceiver tilt angle from the horizontal track and $V$ is the vertical distance between B and the horizontal track at point D.

2.2. Numerical analysis

In this section a non-directed LOS ray tracing technique is used to calculate the channel impulse response, which is suitable for an environment without reflectors. This mathematical model is based on the equations presented in [17]. The emitter is modelled as a point Lambertian source. This leads to simulating the received power and comparing it with the required optical sensitivity to achieve a reliable BER. The received power can be given by:
where $P_R$ the received power, $d$ is the distance between the transmitter and the receiver, $R_E(\varphi, n)$ is the emitter generalized Lambertian radiation pattern and $A_{\text{eff}}(\varphi)$ is the effective receiver signal collection area. The radiation pattern can be defined as:

$$R_E(\varphi, n) = \frac{n + 1}{2\pi} P_E \cos \varphi$$

(5)

where $\varphi$ is the angle of radiation, $n$ is the number of radiation lobe that specifies the emitter directionality and $P_E$ is the transmitter radiated power. The receiver effective area can be modelled as:

$$A_{\text{eff}}(\varphi) = A_r \cos \varphi \text{rect} \left( \frac{\varphi}{FOV} \right)$$

(6)

where $A_r$ is the detector physical area and $FOV$ is the receiver field of view. In order to evaluate the system performance, the receiver sensitivity is calculated at a reasonable BER. This parameter defines the minimum received voltage at the required BER. In this section the BER is set to be $10^{-9}$. The minimum received power $P_{\text{min}}$ is calculated using [18] as follows:

$$P_{\text{min}} = \left( \frac{\sigma_1 + \sigma_0}{2} \right) \left( \frac{Q}{R} \right)$$

(7)

where $\sigma_1$ and $\sigma_0$ represent the standard deviation values for one “1” and zero “0” received voltage levels, $R$ is the photodetector responsivity and $Q$ is the normalized distance between the signal threshold and the distribution mean known as Q-factor and defined as follows:

$$Q = \frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}$$

(8)

where $\mu_1$ and $\mu_0$ represent the mean values for one “1” and zero “0” levels. The model takes into consideration the effect of shot noise, dark current noise and thermal noise as analyzed in [15]. Background noise is neglected as the experiment is conducted in a dark laboratory. Transimpedance amplifier equivalent input current noise analysis is investigated as discussed in [19]. BER can be set to the desired value by setting a decision threshold to the Q-factor, and thus the minimum received optical power. The relation between BER and Q-factor is shown in Eq. (9).

$$\text{BER} = \frac{1}{2} \text{erfc} \left( \frac{Q}{\sqrt{2}} \right) \approx \frac{\exp(-Q^2)}{Q \sqrt{2\pi}}$$

(9)

where, erfc(.) is the well known complementary error function in statistics [18]. The approximate BER form can be used accurately with minimized error with $Q > 3$, which exceeds the desired value ($Q = 6$).

3. Preliminary experiment

3.1. Laboratory setup

In order to evaluate the performance of the FSO link between ground and train, some measurements are significant to set the boundaries for such application. In this experiment, the eye diagram is used to identify the maximum distances and coverage angles allowed. This is done using two perpendicular tracks that are responsible for varying the angle of incidence and the distance between the transmitter and the receiver. The received voltage is measured using the DSO, i.e. oscilloscope, and the samples are recorded. Further, the samples are filtered using a 4th order butterworth low pass filter using computer software in order to remove the unwanted noise. The BER is calculated for the eye patterns after the low pass filter, where a threshold of $10^{-9}$ is set. This threshold is the most common BER for communication applications. In addition, most fiber optic links that are designed for telecommunication applications have a maximum BER standard of $10^{-9}$. 
Measurements are taken at 5 cm steps between the transmitter and the receiver planes along a track of 100 cm length, which is chosen as a practical distance in a lab environment. For each step, different angles are considered each 1°. Due to the minor angle step size, the system is designed to translate the angle steps into horizontal distance variations on the horizontal track using Eq. (3) as shown in Fig. 4(a). Measurements are taken till the obtained eye diagram reflects a Q-factor not less than 6, which is the calculated threshold for the maximum standard acceptable BER for telecommunications applications according to Eq.(9). The aim of this experiment is to find the suggested values for $D_{max}$, $\alpha$ and $D_{min}$ which are previously described in Fig. (3). The experiment is executed according to the laboratory setup shown in Figs. 4(a) and 4(b), at three different data rates: 500 kb/s, 1 Mb/s and 5 Mb/s, using two LEDs that have the same power but differ in their FOV. The suggested value for $D_{max}$ which represents the vertical track length, is 100 cm while $D_{min}$ is set to 10 cm at $\alpha$ equals 0° and 17°, respectively. The experimental specifications are summarized in Table I.

**TABLE I** EXPERIMENTAL SPECIFICATIONS

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| **Transmitter (LED):**           |                        |
| FOV                              | $\pm 3 / \pm 13$       |
| Maximum Power                    | 50 mW                  |
| Peak Wavelength                  | 850 nm                 |
| Modulation                       |OOK NRZ                 |
| Data Rate                        | 5 Mb/s                 |
| **PIN Photodiode:**              |                        |
| Spectral Range of Sensitivity    | 750-1100 nm            |
| Peak Wavelength                  | 900 nm                 |
| Spectral Sensitivity             | 0.59 A/W               |
| Active Area                      | 1 mm$^2$               |
| FOV                              | $\pm 75$               |
| Dark Current                     | 1 nA                   |
| **Lenses:**                      |                        |
| Converging Lens Diameter         | 5.5 cm                 |
| Converging Lens Focal Length     | 14.8 cm                |
| In Contact Lens Diameter         | 2 cm                   |
| Lenses Overall Gain (Measured)   | 28                     |
| **Transimpedance Amplifier:**    |                        |
| Gain Bandwidth Product           | 3.8 GHz                |
| Feedback Resistance              | 410 $\Omega$          |
| Rise - Fall Time                 | 30 - 50 ns             |
| Non-inverting Spontaneous Voltage noise | 0.95 nV/\sqrt{Hz} |
| Inverting spontaneous current noise | 2.6 pA/\sqrt{Hz} |
3.2. Preliminary results

3.2.1. Experimental results

In order to evaluate the performance of the executed experiment, it was helpful to illustrate the relation between the received voltage and the channel length. The obtained experimental measurements are plotted in Figs. 5(a) and 5(b) for the 3° and 13°-LEDs, respectively. Both figures illustrate the obtained results after curve fitting using Eq. (5). For the same angle of incidence; as the distance increases, the received voltage decays. At any specific distance, the received signal voltage decays as the angle of incidence increases. From these figures, it is noticed that $\alpha$ equals 10° and 17° for the 3° and 13°-LEDs, respectively. Although both LEDs emit the same power, a less FOV means more confined power within it. These curves are directly related to the following curves in Figs. 6 (a-d) which show the eye diagrams at the boundaries of each experiment.

**Figure 5.** Measured received voltage vs distance using (a) 3° LED (b) 13° LED
Figure 6. Eye diagrams for the received signal along the train track at 5Mb/s for 3°-LED at 10 cm (top left), 100 cm (top right), 13°-LED at 10 cm (bottom left), and 100 cm (bottom right).

The eye diagrams in Figs. 6(a) and 6(b) indicate the quality of the received signal at both ends of the track using the 3°-LED. From a further analysis for the eye diagram parameters, the BER is calculated to ensure its value is below the maximum threshold of 10^-9. The same analysis is performed for the 13°-LED in Figs 6(c) and 6(d). As the detector is nearer to the source, the eye diagram has better characteristics; as shown in Figs. 6(a) and 6(c), than the other end as illustrated in Figs 6(b) and 6(d).

3.2.2. Numerical results
To validate the obtained experimental results, a simulation for the demonstrated theoretical model in Sec. (2.2) is performed in this section. The relation between the received optical power and the distance between both transceivers is shown for both LEDs in Figs. 7(a) and 7(b). In this model, the data rate has no impact on the received power. However, it has a clear impact on the Q-factor which can be taken as a measure to signal-to-noise ratio (SNR), and consequently the BER. The decision threshold point is set at the receiver sensitivity level at which BER= 10^-9 after taking into consideration the different noise effects that the system is subjected to. The receiver sensitivity power level shown in Figs. 7(a) and 7(b) is for the maximum experimentally tested data rate of 5 Mb/s with a value of -37.83 dBm. From Fig. 7(a), it is noticed that the maximum view angle at 10 cm is 10° at a sensitivity of -32.71 dBm, while the 0° received power level (i.e. -12.22 dBm) at 100 cm is above the threshold level.

The receiver sensitivity values for 1Mb/s and 500 kb/s are -41.23 dBm and -42.83 dBm, respectively. In Fig. 7(b), it is clear that the 17 power level at 10 cm and the 0° power level at 100 cm are above the receiver sensitivity threshold indicating an acceptable BER. Moreover, it is noticed that the view angle theoretically can exceed 17° which is not the experimental case as shown in the preliminary experimental results section, and thus the simulation results are not congested by more view angles. The emphasis in this simulation is on validating the experimental boundary distance and view angle limits within BER of 10^-9.

4. Small scaled train experiment

4.1. Experimental setup
The results obtained from the preliminary experiment are the basis of the small scale train model described in this section. For the 3°-LED experiment, the small scale train model is built based on the results of the previously described model in Figs. 5(a) and 7(a) as shown in the previous section, where
D_{max} = 100 \text{ cm} \text{ and } D_{min} = 10 \text{ cm} \text{ at 0° and 10° incidence angles, respectively}. \text{ The obtained geometrical dimensions for the proposed model using Eqs. (1-3) are } L = 90.1 \text{ cm}, \theta = 1.1^\circ \text{ and } V = 1.9 \text{ cm}. \text{ Using the 13'-LED changes the specifications to } L = 90.48 \text{ cm}, \theta = 1.84^\circ \text{ and } V = 3.2 \text{ cm}. \text{ The importance of the previous parameters is to show the maximum coverage length which is an indication for the maximum distance between the transmitters along the train track. This has a direct impact on the number of transceivers to be placed on top of the train, which is an important parameter in the cost estimation of the proposed system. Figure 8 shows the laboratory small scaled train experimental setup. This experiment helps in the system redesign to extend the coverage to a real track system as shown in Sec. 5.}

![Figure 7. Simulated received optical power vs distance for different angles at 5 Mb/s for (a) 3˚ LED and (a) 13˚ LED](image)

![Figure 8. Train track experimental setup](image)

### 4.2. Train track experiment results

The results in this section can be explained in the scope of the preliminary results and simulation constraints. The experiment conducted where the signal voltage is based on measuring the received signal voltages along the train track. The boundary dimensions are used to setup the track as discussed in Sec. (4.1). The results demonstrated in Figs. 9 (a) and 9(b) show the relation between the received voltage and the distance along the train track for the 3˚ and 13˚-LEDs, respectively. The aim of this experiment is to measure the actual received signal and validate the design boundaries obtained from the preliminary experiment in Figs. 5(a) and 5(b).
In Fig. 5(a), the measured data starts at a value near the 10° voltage level in the preliminary experiment. The voltage continues to be bounderized by the maximum and the minimum voltage values measured at each distance. From one end of the track till the other end, the measured voltage varies between the maximum view angle voltage at 10 cm and the minimum 0° voltage at 100 cm as predicted. This provides a non-violating response to the previously discussed preliminary experimental and simulation results. In Fig. 5(b), the voltage along the track starts at a value near the 17° preliminary voltage level. The voltage increases as the distance increases till reaches the 2° voltage level at 25 cm. The view angle in this region decreases reaching 6° then 4°. At 30 cm the voltage reaches the 0° voltage level. From this point, the view angle is constant and the distance only increases. Consequently, the voltage continues to fade as the distance increases moving by this boundary limit. Unlike the 3°-LED, the voltage exceeds the maximum boundary with a minor deviation of 1 mV. In the 3°-LED experiment, the voltage variation between two points is a few mVs, while in this experiment the voltage deviation between steps is much smaller. In the preliminary experiment, the angles are translated into horizontal distances as discussed in Sec. (2.1). This approximation introduces the voltage deviation from the train track where the transmitter is tilted at the required angle directly. Also, the train track experimental measurements are plotted on a curve fit for the preliminary experimental results which introduces a small deviation from the actual measurements.

Although the 3°-LED experimental results indicate full track coverage, the suggested vertical distance $V$ is non-practical. This is because the 3°-LED needs to be placed on the train path where $V < 2.25$ cm (i.e. the lens radius). In order to modify the dimensions for $V$ to be more than 2.25 cm the same as in the 13°-LED experiment, the boundary specifications have to be changed according to Eqs. (1-3) as follows: $D_{\text{min}} = 15$ cm while according to Fig. 6, the maximum view angle measured $\alpha$ remains to be 10°. The new setup results in $\theta = 1.75°$ and $L = 85.2$ cm. This provides an acceptable vertical distance $V = 3$ cm. As a result, more privilege is given to the 13°-LED as it provides full track coverage. On the other hand, in order to maintain practically accepted results with the 3°-LED, partial track coverage is achieved.

### 5. System extension

As mentioned before, the receiver circuit is designed to handle a higher bit rate than the tested 5 Mb/s. In order to calculate the maximum bit rate; which is equal to the maximum bandwidth ($B_{\text{wmax}}$), the following relation which is obtained from the transimpedance amplifier circuit analysis in [20] is used.

$$B_{\text{wmax}} = \sqrt{\frac{2\pi GBW}{RF CD}}$$

The equation parameters are stated in Table I and this theoretically indicates a maximum bandwidth $B_{\text{wmax}} = 336.85$ Mb/s. Consequently, the receiver sensitivity is recalculated using Eq. (7). In the geometrical setup of the small scale train track experiment $D_{\text{max}}$ is limited to the length of the preliminary experiment track of 1 m. In order to extend the system, $D_{\text{max}}$ is calculated after considering the noise performance at different bit rates based on the received signal power that exceeds the receiver sensitivity. $D_{\text{min}}$ is chosen to match the small scale experiment, but $V$ is calculated to check the viability of the system. If $V$ is less than 2.25 cm, $D_{\text{min}}$ is chosen of a larger value, then $\alpha$ at this distance is obtained from the preliminary experiment results. Finally, $L$ is calculated to know the maximum coverage distance. Finally, the maximum distance between two transmitters alongside the train track for each data rate is known.

### 5.1. Extended system results

In this section, the numerical analysis is used to redesign the geometrical setup of the train track based on more practical dimensions. The results for the three experimentally tested bit rates are presented beside the results for the maximum bit rate that the designed circuits can handle (i.e. 336.85 Mb/s). The system extension is explained for both the 3° and 13°-LEDs.
In Fig. 10, the received power at 0˚ and 10˚ is plotted Vs distance in meters which results in the boundary limit for $D_{\text{max}}$ and $D_{\text{min}}$ respectively. The receiver sensitivity at 336.85 Mb/s is added to the values plotted in the same figure with an approximate value of -25 dBm. Referring the receiver optical sensitivity starting with the maximum and ending at the minimum bit rates, $D_{\text{max}}$ values are 5.027 m, 21.88 m, 32.73 m and 38.93 m in order. Regarding the maximum $D_{\text{min}}$ values, they are the intersection points between the 10˚ received power curve and the receiver sensitivity threshold limits. According to the geometrical setup, $D_{\text{min}}$ is chosen to be 10 cm. This figure illustrates that this value is within the acceptable range at the 3 experimentally tested data rates.

![Figure 9. Experimental train received signal using (a) 3-LED and (b) 13-LED](image)

![Figure 10. 3-LED simulated received power for the extended system](image)

The results are expected due to the fact that increasing the data rate affects the performance, and thus the maximum coverage distance. As for the 336.85 Mb/s data rate, the 10˚ curve does not intersect its
receiver sensitivity before 10 cm. This indicates that $D_{min}$ of 10 cm at the view angle 10° is not a valid dimension for the 336.85 Mb/s. The received power is simulated at a view angle that is less than 10°. The new view angle is obtained from the preliminary experimental results. A view angle of 9° does not give the required results as its received power does not also intersect with the receiver sensitivity at 336.85 Mb/s before 10 cm. The acceptable results are obtained from the view angle 8° as shown in the modified model proposed in Fig. 11. The 8° curve intersects with -25.05 dBm at 42 cm which is higher than the required $D_{min}$.

![Figure 11. 3°-LED simulated received power for the modified extended system](image)

![Figure 12. 3°-LED simulated received power along the train track at 336.85 Mb/s](image)

In Fig. 12, a simulation for the received power along the suggested train track indicates coverage of 4.899 m at 336.85 Mb/s, which is noticed to be bounderized as expected between the power levels at $D_{max}$ and $D_{min}$. Similarly, the coverage distances obtained for 5 Mb/s, 1 Mb/s and 500 kb/s in order are: 21.68 m, 32.53 m and 38.73 m.
Applying the system modifications to the 13˚-LED system, it is noticed from Fig.13 that $D_{\text{min}}$ at 10 cm falls within the acceptable range. $D_{\text{max}}$ values range from 1.176 m to 9.104 m from the maximum till the minimum bit rate. This gives coverage distances of 1.08 m, 5.02 m, 7.56 m and 9 m, in order, at 336.85 Mb/s, 5 Mb/s, 1 Mb/s and 500 kb/s.

![Figure 13. 13˚-LED simulated received power at the boundary angles](image)

From the previous results, it is noticed that the 3˚-LED has a better performance in the extended system than the 13˚-LED performance. This can be expected as for the long distances, the light beam power is more concentrated the narrow beam of the 3˚-LED. In large data rates, the coverage distance is nearly 5 times better than that of the 13˚-LED. In small data rates the coverage distance is nearly 4 times better. The data rate has a noticeable effect on the performance. This is the reason for reducing the coverage distance to keep the same BER threshold in all the tested data rates.

However, when testing the vertical distance $V$ for the 13˚-LED system with the suggested dimensions, its values are found to be between 2.9 cm and 3.2 cm. In a real track system this is not the real distance between the track and the base stations alongside the track. However, this passes through the check of $V \geq 2.25$ cm, in order to make sure that the transmitter is not on the train path. Further investigation and recalculation for the coverage distance might be needed for real systems where $V$ is based on already placed lampposts or electricity towers alongside the train, which is out of the scope of the current work as the aim is to get the maximum boundaries for the coverage distance.

In case of the 3˚-LED, the tilting angle of the receiver on top of the train will be undefined with the suggested dimensions. Therefore, $D_{\text{min}}$ has to be increased till reaching 20 cm instead of 10 cm, which is, as shown in Fig. 15, beyond the limit (42.25 cm). In this case $V$ has an acceptable value of 3.5 cm in all data rates, except for the 500 kb/s where $V = 15.5$ cm. This modification has nearly no noticeable effect on the values of $L$.

6. Conclusion
In this paper, a preliminary experiment is implemented to study the performance of an FSO ground-to-train link. After setting the boundary limits of this experiment, a geometrical model for an FSO railtrack is suggested. A 90 cm track length experiment is conducted using two 50 mW-LEDs with different FOV constrained by simulation boundary results based on the theoretical model. The 13˚-LED gives
more FOV, and thus full train track coverage in the suggested small scale model. Although the experimental results of the 3°-LED indicate full train track coverage, the results cannot be practically applied. Therefore a modification to the conditions of the experiment is forced to achieve partial track coverage of 85 cm. Error-free transmission with Q-factor > 6 (i.e. BER < 10^-9) is achieved along the train track at 5 Mb/s for both the 3° and 13°-LEDs.

The system is extended to fit real railway systems. The maximum tested bit rate is 5 Mb/s; however, the circuit is designed to handle a bit rate reaching 336.85 Mb/s. The system is modified with new geometrical dimensions and tested by simulation for the maximum coverage. At 500 kb/s, the 13°-LED provides 9 m coverage. On the other hand, the 3°-LED provides 38.7 m at the same bit rate and BER. At the maximum bit rate, the 13°-LED provides 1 m track coverage while the 3°-LED exhibits nearly 5 times better coverage.

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