# Experimental Demonstration of Vehicle to Road Side Infrastructure Visible Light Communications

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***Abstract*— The increasing use of light emitting diodes in traffic lights offer excellent opportunities for implementation of visible light communications (VLC) based wireless technology as part of intelligent transport systems in smart environments. In this paper, we experimentally demonstrate vehicle to infrastructure (V2I) communications based on the VLC technology using a real traffic light and a camera over a link span of up to 80 m. We show a reduction in the modulation depth of the signal from 100% to 50% in order to track the light source when sending '0' symbols. Also presented is the effect of operating the camera in the focused and defocused modes. The results show transmission success rates of 100% and 90% over link spans of 70 m and 80 m, respectively under specific test conditions.**

***Keywords*— *Intelligent transport systems, modulation depth, traffic light, VLC technology, V2I***

## I. Introduction

The ability of vehicles to wirelessly exchange information with the neighbouring vehicles and road side infrastructure, known as Intelligent Transport Systems and Services (ITS), can greatly improve road safety and transportation. With the increasing number of vehicles yearly, the need for improved road infrastructures and enhanced transportation management systems is also on the increase in order to reduce road accidents, improve traffic flow and the quality of life [1-3]. The Global status report on road safety 2018 issued by the World Health Organisation states that 'deaths from road traffic crashes have increased to 1.35 million a year. That is nearly 3700 people dying on the world's roads every day' [4]. Consequently, providing safe traffic information and warnings to drivers will provide additional capabilities for enhancing traffics on the roads and improving safety through real time data exchange between vehicles and traffic infrastructure.

Currently, for ITS, the established wireless technology for vehicular communications is based on the dedicated short-range communications (DSRC), which is a 5.9 GHz radio frequency (RF) technology [5-7] for vehicular environments, which allows communications between vehicles within the vicinity and road side infrastructures. The DSRC technology supports several applications in vehicular environments such as intersection collision warning and emergency braking warning [7]. However, communications in vehicular environments using the RF technology often experience low packet reception rate on dense roads where the number of vehicles are high [5-8]. Furthermore, using the RF technology, which is usually omnidirectional, for vehicular communications include the difficulty in visually recognizing the position of the transmitters (Txs) [5].

Interestingly, researchers have been investigating an alternative or complementary technology to the RF-based DSRC technology, known as the VLC technology for application in vehicular environments [9-12]. Light emitting diodes (LEDs) can be switched on and off at very high speeds, thus allowing them to be used for illumination as well as data communications and indoor localization [11]. Such features have generated immense interest within the telecommunications and lighting industries, whereby the optical wireless communications technology can now be implemented using LED lights and an optical receiver (Rx) (i.e., photodiodes or image sensors (ISs)) in both indoor and outdoor environments [2]. Moreover, the increased use of LEDs in traffic light and car head and tail lights makes the use of VLC one possible and interesting option in ITS, thus releasing the pressure on the spectral usage of RF-based wireless technologies.

The research works in the area of VLC for ITS applications have being reported in the literature. In [12], a V2I VLC link for moving vehicles on the highway was investigated. A blue LED, which was used to avoid interference from other light sources, was adopted as Txs from the road side infrastructure (i.e., street lamps). Moreover, zone detection (ZD) and adaptive decision threshold (ADT) methods were proposed to counter the adverse effects of sunlight and cloud, which offered improved signal to noise ratio (SNR) of 16-26 dB as against a SNR of 0.15-1.45 dB without using ZD and ADT. A V2I link between the traffic light and the vehicle was proposed and investigated in [13] whereby an infrared emitter was used in a traffic light for transmitting colour codes depending on the colour of the traffic light being on as part of the automatic braking system when the traffic light is red. In [14], a handover procedure for a moving vehicle communicating with streetlights in a V2I VLC system was reported. The results showed that, for a missing handover rate of up to 10% the algorithm achieved an average bit error rate (BER) of $10^{-3}$, which is just below the forward error correction BER limit of $3.8 \times 10^{-3}$.

Most works reported in the literature on VLC-based V2V and V2I systems have been based on either simulations or experiments using off the shelf LEDs as the traffic lights. However, in this work, the proposed VLC based V2I link uses the actual traffic light as the Tx and a camera as the Rx in an outdoor environment. Importantly, in VLC based V2V and V2I systems, the Rx position constantly changes with respect to the Tx due vehicles moving around. However, it is necessary to be able to track the light source during communications in order to avoid disruption. This is important especially when sending a ‘0’ symbol, whereby the LED is off if a modulation depth (MD) of 100% is used and therefore it will be difficult to track the light source. Consequently, we investigate a reduction in MD of the signal from 100% to 50% in order to track the light source when sending ‘0’ symbols. Furthermore, we present measurements for both focused and defocused camera modes up to a transmission link span of 80 m.

The rest of the paper is organised as follows: Section II describes the system while results and discussion are presented in Section III. Conclusions and future work are given in Section IV.

## II. SYSTEM

Fig. 1 shows the schematic block diagram of the proposed VLC system. It is composed of a real LED-based traffic light (i.e., SIEMENS ELV traffic light) as the VLC Tx and a camera (Canon Rebel SL1 EOS 100D) as the Rx. Note, other cameras including those currently available in new cars can also be used as an optical Rx. In this paper, we use the green light of the traffic light as the Tx for demonstration purpose since it is on most of the time.

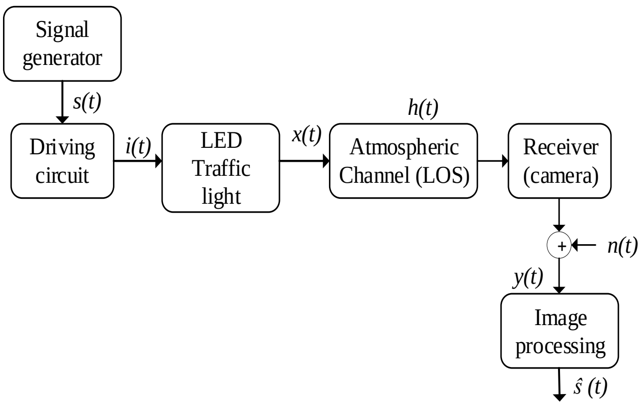


Fig. 1. The schematic block diagram of a VLC-based V2I system.

At the Tx an OOK data stream $s(t)$ is used for intensity modulation of the traffic light (i.e., green LEDs). The data stream is a packet with a header and payload of 21 and 175bits, respectively. The intensity modulated light $x(t)$ is transmitted through the outdoor channel and captured on the Rx side using a camera. For the line of sight (LOS) link, the received signal is given by [15]:

$$y(t) = \eta x(t) \otimes h(t) + n(t), \quad (1)$$

where $\eta$ is the quantum efficiency of the IS of the camera, $h(t)$ represents the combined impulse response of the channel and camera while $n(t)$ denotes the additive white Gaussian noise including the ambient light induced shot noise, which is the dominant noise source in this case, the signal and dark current related shot noise sources and the thermal noise.

The channel DC gain for the LOS link can be expressed as [15]:

$$H(0)_{LOS} = \begin{cases} \frac{A_{IMAGE}(m+1)}{2\pi D^2_{T-CAM}} cos^m(\phi) g(\varphi) T_S(\varphi) \cos\varphi, & 0 \le \varphi \le \Psi_{CAM} \\ 0, & \varphi > \Psi_{CAM} \end{cases} \quad (2)$$

where $A_{IMAGE}$ is the surface of the image of the traffic light on the IS of the camera and it depends on the distance of the camera from the object, $D_{T-CAM}$ is the distance between the Tx and the camera, $g(\varphi)$ and $T_S(\varphi)$ are the gains of the optical concentrator and the optical filter, respectively. $\phi$ denotes the irradiance angle, $\varphi$ is the incidence angle, $\Psi_{CAM}$ is the field of view (FOV) semi-angle of the camera and $m$ represents Lambertian order of emission of the Tx, which is given by [15]:

$$m = -\ln 2 / \ln\,(cos\theta_{1/2}) \quad (3)$$

where $\theta_{1/2}$ is the half power angle. Lambertian radiant intensity is expressed as [15]:

$$R(\phi) = \frac{(m+1)}{2\pi} cos^m(\phi) \quad (4)$$

The detailed model of the proposed link is shown in Fig. 2. The angle of incidence is given by:

$$\varphi = tan^{-1}\,(H_{G-F}/D_H), \quad 0 < \varphi \le \Psi_{CAM} \quad (5)$$

$$H_{G-F} = H_G - H_F \quad (6)$$

The LOS transmission distance between the traffic light and a vehicle is given by:

$$D_{T-CAM} = \sqrt{H^2_{G-F} + D^2_H} \quad (7)$$

where $D_H$ is the horizontal distance between the traffic light and the dashboard (DB) mounted camera on the vehicle, $H_G$ is the height of the green traffic light from the ground and $H_F$ represents the height of the DB camera from ground. Note that, the minimum distance of $D_H$ (i.e. $D_{H-MIN}$) for which communications can be established is dependent on two parameters of (*i*) the height difference between the DB mounted camera and the traffic light denoted as $H_{G-F}$; and

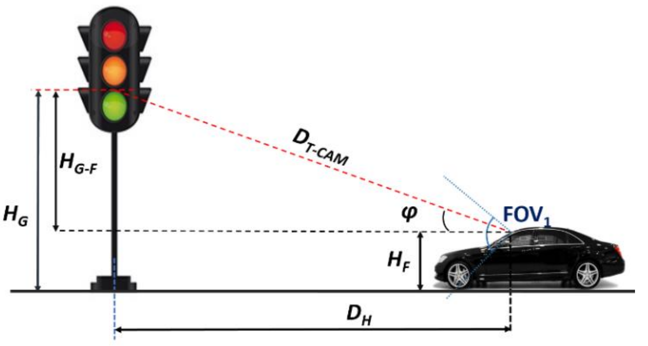


Fig. 2. Configuration of the V2I VLC system

(*ii*) the FOV of the camera, whereby the maximum incident angle $\varphi_{MAX}$ equals $\Psi_{CAM}$ and is given by:

$$D_{H-MIN} = H_{G-F}/\tan(\varphi_{MAX}), \qquad \varphi_{MAX} = \Psi_{CAM} \tag{8}$$

Here, we have assumed that the DB camera is directly facing the traffic light with no tilting angle. The average received optical power for the LOS link at the car is given by [15]:

$$P_{R\_LOS} = H(0)_{LOS} P_T + n(t) \tag{9}$$

where $P_T$ is the transmit power.

## III. Results and Discussions

Fig. 3 shows the measured beam profile of the green traffic light, which is close to Lambertian as in (4). By fitting a Lambertian curve to the beam profile we obtained Lambertian order *m* of 14. The measured spectral wavelength of the green traffic light is depicted in Fig. 4 with a peak wavelength $\lambda_{peak}$ of 504.7 nm.

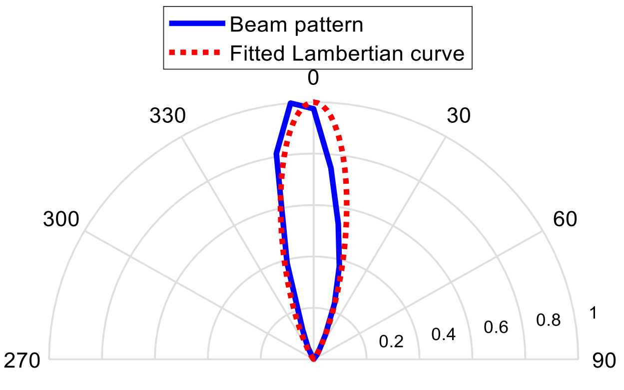


Fig. 3. The normalized beam profile of green traffic light

The experimental setup of the V2I VLC system is shown in Fig. 5. The minimum height calculated from the top of the green traffic light to ground is 2.38 m as in [16-17] for road junctions and places where the headroom or the width of the road is permanently restricted. Also, the average heights of cars are 1.116 – 2.035 m [18], and we have used an average car height of 1.610 m in order to determine $H_F$ and assumed the DB camera to be at this same height. Note, $H_{G-F}$ and $H_G$ are 0.77 m and 2.38 m, respectively.

A short traffic message of '---HIGHSTREET ROAD IS CLOSED' was transmitted over the link. At the Rx, the captured videos stream using the camera with a resolution and a frame rate of 1280×720 and 60 fps, respectively is processed offline in MATLAB. All the system key experimental parameters are listed in Table 1.

We captured a video stream for transmission spans of 5 m, 10 m – 80 m in steps of 10 m, and for MDs of 50% and 100%. In addition, we carried out measurements for the above links for focused and defocused camera modes. Note that, as was observed, the longer the link span, the smaller would be the size of the captured image of the traffic light for the focused camera mode. Consequently, the size of the light source beyond the transmission range of 40 m did not appear to be changing for the defocused camera mode, with only light intensities being lower.

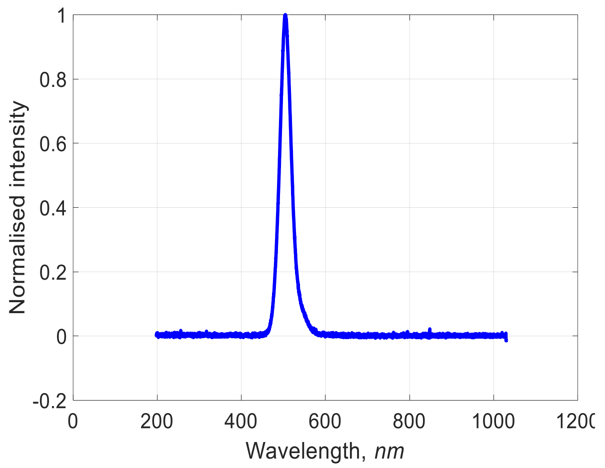


Fig. 4. The measured spectral wavelength for green traffic light (a peak wavelength of 504.7 nm).

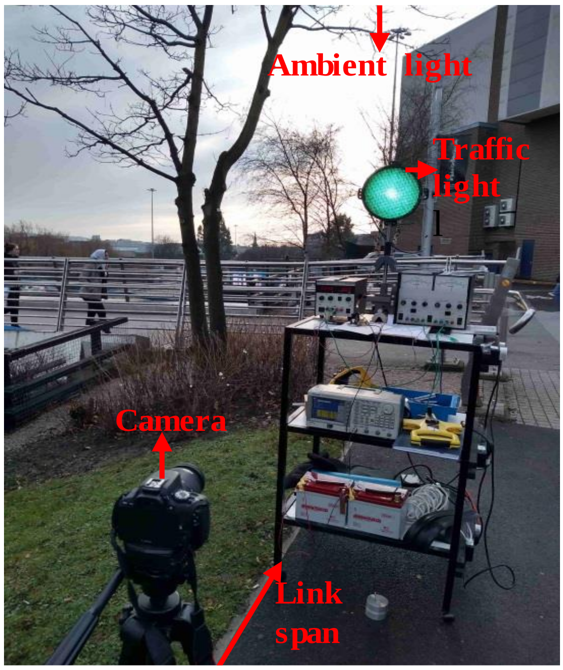


Fig. 5. The experimental setup for theV2I VLC system

TABLE I.: KEY PARAMETERS OF THE EXPERIMENT

| Parameter | Value |
|---|---|
| Shutter speed | 1/4000 s |
| International Standard Organisation (ISO) of camera | 1600 |
| Camera focal length (*f*) | 18 mm |
| Camera aperture | *f*5.6 |
| Vertical height difference between Tx and Rx | 0.77 m |
| Link span | 5-80 m |
| Camera frame rate | 60 fps |
| Camera resolution | 1280 ×720 |
| Camera horizontal FOV | 60° |
| Transmission bit rate | 30 bps |
| Number of start bits | 21 bits |
| Number of data bits | 175 bits |
| Average driving current for traffic light | 250 mA |
| Maximum measured Tx illuminance | 7211 lx |

This is in contrast to the focused mode whereby the size of the image of the traffic light decreased exponentially with the increased link span as shown in Fig. 6. Note that, the normalised diameters of the traffic light image presented in Fig. 6 are with respect to the defocused mode. Therefore, defocusing the camera made the light source appear with the same size of the circle of confusion (CoC) even for longer distances, which makes it simpler to find the region of interest in the image [19].

Fig. 7 shows the success rate of the data transmission against the link span for two MDs of 50% and 100% under focused and defocused camera modes. The communication was error free up to 70 m. At a link range of 80 m, the success rates in receiving correct bit from the traffic light was reduced to 98.5% only for the defocused mode with 50% MD as depicted in Fig. 7. This is due to the fact that, the received power is spread over a number of pixels, hence lower SNR. Consequently, at the MD of 50% symbols became more prone to errors.

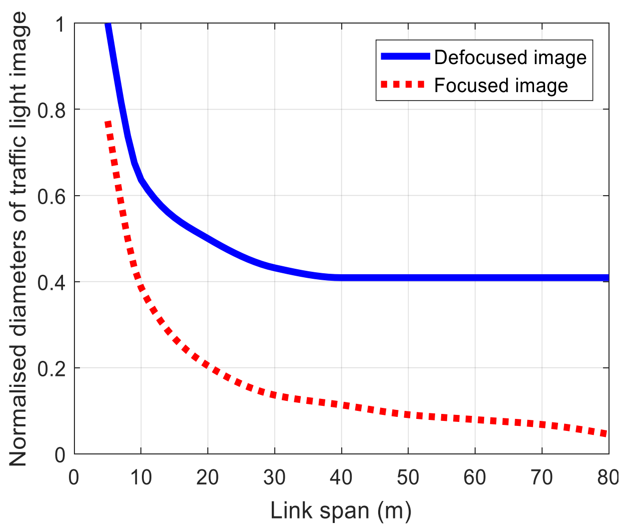


Fig. 6. The normalised diameter of traffic light image with reference to the defocused mode versus link span

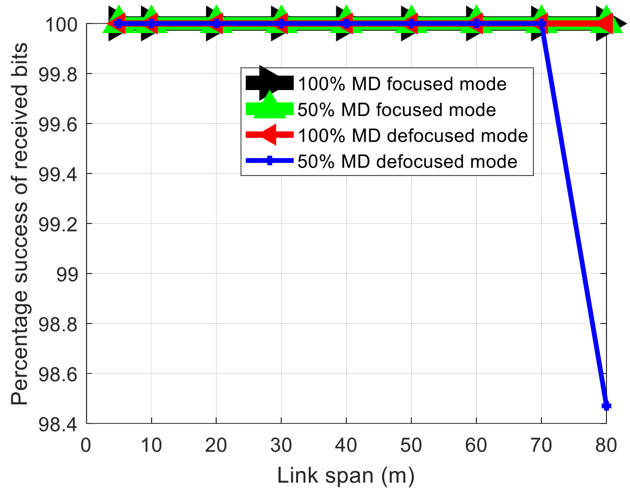


Fig. 7. Success rate of the data transmission over a link span for the focused and defocused camera modes

## IV. Conclusion and Future Work

We have reported the investigation of a VLC V2I system using a real traffic light under outdoor conditions. It was demonstrated that a reduction in the MD from 100% to 50% in order to track the light source when sending '0' symbols did not introduce any additional errors for a link span of up to 70 m. Moreover, using the defocusing camera made it easier to detect the traffic light in the captured images for longer transmission distances of greater than 30 m. Further investigations will be carried out for a range of MDs and over a much longer transmission link spans.

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