Experimental Investigation of the Effects of Fog on Optical Camera-based VLC for a Vehicular Environment

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***Abstract*— The widespread increase in the use of light emitting diodes in vehicle's head and taillights and also the use of dashboard cameras provides great prospects for the optical camera based visible light communications (VLC) technology in intelligent transport systems. In this paper, we experimentally investigate the impact of fog on the optical camera based VLC technology for vehicle-to-vehicle (V2V) communications. A range of meteorological visibilities between 5-120 m is considered based on realistic inter-vehicle distances in practical vehicular environments and using a real car taillight as the transmitter. We show a reduction in the index of modulation of the signals from 1 to 0.75 and 0.5 to allow for tracking purposes of the light source when sending '0' symbols. The results show that, the link is error-free up to 20 m meteorological visibility for the three modulation index scenarios and degrades considerably below 10 m meteorological visibility.**

Keywords*— *Optical camera, intelligent transport system, VLC technology, meteorological visibility, fog

I. Introduction

Visible light communications (VLC) is a wireless technology for the transmission of data by the use of light emitting diodes (LEDs). This emerging technology uses luminance for data transmission, therefore LED based VLCs can be implemented wherever LED light fixtures are installed. For this reason, the VLC technology has drawn much attention for indoor wireless communications [1-2]. Recently, VLC has been proposed in vehicular applications as part of intelligent transport systems (ITS) where vehicles can exchange safety information with each other and the roadside infrastructures such as traffic and street lights. Consequently, the provision of safe traffic information and warnings to drivers will give additional capabilities for enhancing traffics on the roads and improving safety through the exchange of real-time data between vehicles and road infrastructure.

The currently established ITS communication technology in a vehicular environment is the dedicated short-range communications (DSRC), which is a 5.9 GHz radio frequency (RF) technology [3-5]. The DSRC technology renders several applications in vehicular environments such as emergency braking warning and intersection collision warning [5]. However, communications in vehicular environments using the RF technology often experience low packet reception rates on dense roads where the number of vehicles is high [3-6]. Furthermore, using the RF technology, which is usually omnidirectional, for vehicular communications include the difficulty in visually recognizing the position of the Txs [3]. To deal with such issues, the VLC technology emerges as a potential candidate for vehicular connectivity. Furthermore, several automotive manufacturers and in fact individual car owners are now replacing their headlights, taillights, brake lights etc. with LEDs as they have longer life spans, dissipates less heat and are brighter for illumination than halogen bulbs widely adopted in the past [7]. Consequently, cars with LED-based head and tail lights and cameras can communicate with each other.

Indoor communications based on VLC have been studied intensely [8-9] while its application to outdoor communications such as vehicular environments is still relatively new [10-11]. Therefore in such a developing subject for vehicular communications, channel modelling is very essential in order to ascertain the performance limits placed by the outdoor channel conditions. The research works in the area of VLC for vehicular applications have been reported in the literature. Prior works built upon the indoor line of sight channel models with a Lambertian pattern, which is not applicable for high beam and low beam vehicular headlights with asymmetrical intensity distribution patterns (for VLC based PD systems). In addressing this, in [12-14] a measured headlamp beam pattern model was employed and the relationship between system bit error rate (BER) performance and the communication span was developed.

The type of road surface as well as the weather condition may also influence the performance of the VLC based vehicular links. In [13-15], a V2V VLC channel model based on measured headlamp intensity patterns and road reflection properties was proposed. Moreover, the results obtained showed received power plots for different types of road surfaces and using both clean and dirty headlamps during the daytime.

Importantly, a major issue for VLC based vehicular channels represent the atmospheric weather conditions, which influences have been sparely reported in literature. In [16], the effect of weather conditions was quantified based on an infrared LED point to point outdoor communication link. This cannot be applied directly to vehicular VLC links employing the visible wavelength and with limited light intensities (in order to control glare for other road users and eye safety regulations). Also in [1], the effect of two fog conditions (light and heavy fog) was experimentally demonstrated, employing a single red LED as the Tx (used to represent the taillight of a vehicle) and the PD as the Rx. The fog conditions demonstrated did not relate to specific visibility figures. *Elamassie et al.* in [17] carried out a comprehensive simulation-based channel modelling study to measure the effect of rain and fog on V2V links using an advanced ray tracing software employing a high-beam headlamp as the Tx and a PD as the Rx. However, experimental investigations are always necessary to verify simulation studies.

In LED-based vehicular links, two types of Rxs may be employed: a PD and a camera. However, based on the fact that, new cars generally come with camera(s), we consider this Rx in this study. Importantly, all previous works based on vehicular VLC links under fog conditions as outlined earlier have reported results based on the use of PDs as the optical Rx and no works, to the best of our knowledge, have been reported on the use of a camera as the Rx. In this paper, we carry out experimental investigations of the effects of fog on camera-based VLC link by considering a range of visibility levels and inter-vehicle distances. We employ a real car taillight as the Tx and a camera as the Rx, the use of which has not been reported in the literature under atmospheric weather conditions in outdoor VLC systems. Consequently, we investigate a reduction in the modulation index (MI) of the signal from 1 to 0.75 and 0.5 considering applications for a vehicular environment where tracking the light source is indispensable due to mobility and we present the transmission success rates for a range of visibilities.

The rest of the paper is organised as follows: In section II the vehicular based OCC link system under fog conditions is described. Results and discussion are presented in section III. Finally, conclusions are given in section IV.

II. SYSTEM

The schematic block diagram of the proposed V2V VLC link is shown in Fig. 1. It is composed of a real LED-based taillight (i.e., Nissan 26550 4EA0A model) as the Tx and a camera (Canon Rebel SL1 EOS 100D) as the Rx. An indoor laboratory fog chamber is used to simulate the outdoor foggy channel as proposed in [18-20]. At the Tx, an on off keying (OOK) data stream $s(t)$ is used for intensity modulation of the taillight. The data stream (a short traffic message) is a packet with a header and payload of 21 and 175 bits, respectively. The intensity modulated light $x(t)$ is transmitted through the clear channel (i.e., no fog). At the Rx side, the signal is captured using a camera.

For the line of sight (LOS) link, the received signal is given by [21]:

$$y(t) = \eta x(t) \otimes h(t) + n(t), \tag{1}$$

where η 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 signal and dark current related shot noise sources and the thermal noise.

The channel DC gain for the LOS link can be expressed as [21]:

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

where D_{T-CAM} is the distance between the Tx and Rx, A_{IMAGE} is the size of the projected illuminated light source on the IS of the camera. $T_S(\varphi)$ and $g(\varphi)$ are the gains of the optical filter and optical concentrator, respectively. φ is the incidence angle, ϕ denotes the irradiance angle, Ψ_{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 [21]:

$$m = -\frac{\ln 2}{\ln\left(cos\theta_{\frac{1}{2}}\right)}, \tag{3}$$

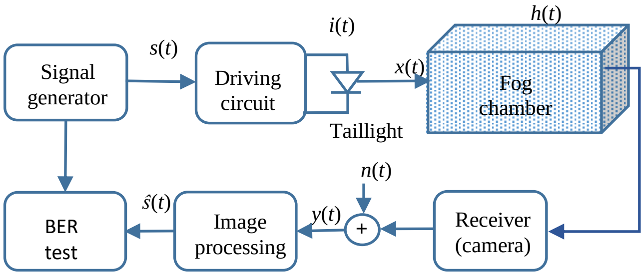

Fig. 1. The schematic block diagram of a V2V based OCC link.

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

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

The average received optical power for the LOS link at the Rx under clear weather is given by [17]:

$$P_{R\_LOS} = P_T\, H(0)_{LOS} + n(t), \tag{5}$$

where P_T is the transmit power.

A. Fog attenuation

The attenuation of a light beam in the atmosphere is described by Beer's law [22]. Visibility is usually used to characterise fog attenuation in optical systems. Using Mie scattering model [23] to reflect the attenuation, the link visibility is obtained from the fog attenuation as:

$$A_{FOG} = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}, \tag{6}$$

where V is the meteorological visibility in km, $\boldsymbol{\lambda}$ denotes wavelength in nm and parameter q is the distribution size of scattering particles given by Kim's model [24]:

$$q = \begin{cases} 1.6 & V > 50 \text{ km} \\ 1.3 & 6 \text{ km} < V < 50 \text{ km} \\ 0.16V + 34 & 1 \text{ km} < V < 6 \text{ km}. \\ V - 0.5 & 0.5 \text{ km} < V < 1 \text{ km} \\ 0 & V < 0.5 \text{ km} \end{cases} \quad (7)$$

The channel coefficient for fog H_{FOG} can be determined by applying Beer's law [22] describing light scattering and absorption in a medium as:

$$H_{FOG} = e^{-A_{FOG} D_{T-CAM}}. \quad (8)$$

Consequently, applying the channel coefficient for fog to Eq. (5), the average received optical power for the LOS link at the Rx under fog is expressed as:

$$P_{R\_FOG} = P_T \, H(0)_{LOS} \, H_{FOG} + n(t). \quad (9)$$

B. *Inter-vehicle distance*

It is important to know the allowable inter-vehicle distances on roads for safe driving so as to correctly investigate practical scenarios for V2V communications. Typically [25], a two seconds rule was recommended whereby a driver maintains a minimum of two seconds behind the vehicle in front for perfect weather conditions, which is doubled to four seconds in bad weather. In some other driving rules three, six and nine-second rules are recommended for good, average and bad weather conditions [26]. Fig. 2 shows the inter-vehicle distance for both the 2 s and 3 s rules for good to bad weather conditions. Moreover, there are different speed limits in adverse weather conditions; however the European Commission regarding mobility and transport gives a speed limit of 50 km/h in fog conditions (i.e., visibility <50 m) [27]. Therefore, for the worst-case scenario i.e. using the 3s rule for bad weather and 50km/h speed limit, the inter vehicle distance is at least 125m as can be deduced from Fig. 2. Consequently, considering the inter vehicle distance for the worst-case scenario, we carried out measurements within the visibility range from 5-120m.

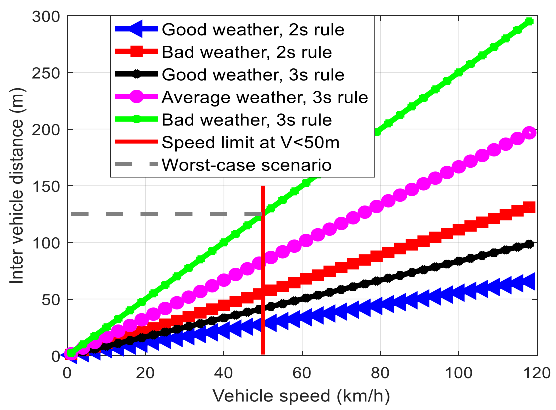

Fig. 2. Driving distances between vehicles at different speeds using the 2 and 3 seconds rules.

III. Results and Discussions

The experimental setup of the OCC based V2V system under fog is shown in Fig. 3. The outdoor fog condition is simulated using a laboratory fog chamber. The link visibility was measured simultaneously along the length of the fog chamber at 550 nm wavelength (using the A_{FOG} parameter from Eq. (6)). The bit error rate (BER) of OCC link was measured for clear and fog channel conditions. Furthermore, for each visibility condition, measurements for three modulation indexes (1, 0.75 and 0.5) were carried out. This is due to the fact that, for vehicular communications, the position of the Rx, constantly changes with respect to the Tx as vehicles are moving around. Consequently, it is necessary during communications to be able to track the light source in order to maintain the communication link. This is very important particularly when a '0' symbol is transmitted, in which the taillight is off if a MI of 1 is used and it is therefore difficult to track the light source in the camera image. The key parameters of the experiment are shown in Table 1.

TABLE I.: KEY PARAMETERS OF THE EXPERIMENT

Parameter	Value
Shutter speed	1/800 s
International Standard Organisation (ISO) of camera	6400
Camera focal length (*f*)	18 mm
Camera aperture	*f*3.5
Meteorological visibility *V*	5-120 m
Camera frame rate	60 fps
Camera resolution	1280 ×720
Transmission bit rate	30 bps
Number of start bits	21 bits
Number of data bits	175 bits
Length of the fog chamber	7.5m

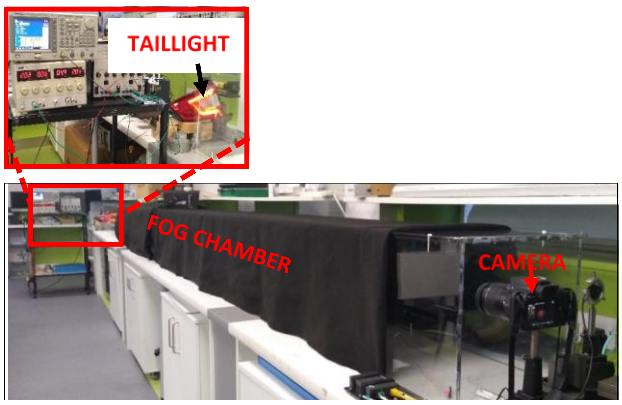

Fig. 3. Experimental setup for investigating the effect of fog on the V2V based OCC link.

The percentage success of received bits versus the meteorological visibility is shown in Fig. 4. The data transmission over the fog channel is error-free for the MIs of 1 and 0.75 up to a meteorological visibility of 10 m while for the of MI of 0.5 the success rate is reduced to 98.47%. Below the meteorological visibility of 10 m, the success rate of the data transmission has decreased considerably with the MI, with the lowest success rate of 63.27% achieved at a MI of

0.5. From the results obtained, the proposed OCC based V2V link shows high reliability even under the fog condition up to a meteorological visibility of 20 m (for all the 3 MIs employed) as against the results reported in [1], where under light and heavy fog conditions, the communication link was severely impaired while employing a PD as the Rx.

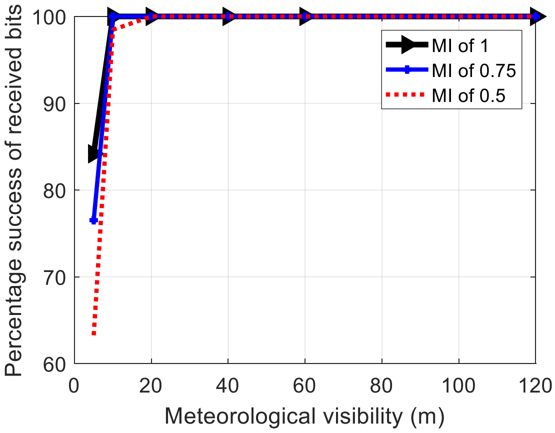

Fig. 4. Success rate of data transmission with fog for a range of MIs.

Furthermore, the normalized received light intensities of the taillight captured by the camera for MIs of 1 and 0.5 for transmission under fog conditions are shown in Fig. 5. Note that, the received light intensities under fog conditions were normalised with reference to the clear weather condition for each MI. The results show that there is a continuous decrease in the received light intensities with decreasing visibility as demonstrated by captured images of the car taillight in Fig. 6(a-d). At the meteorological visibilities of 10 and 5 m, for both MIs of 1 and 0.5 the percentage of received light intensities is decreased to about 30% and < 0.5% respectively (Fig 5.), with the latter been the worst case scenario and the taillight is not visible in the captured image as shown in Fig. 6(d). Table 2 provides the values of the percentage loss in the received light intensities of the taillight at the corresponding meteorological visibilities with reference to the clear weather.

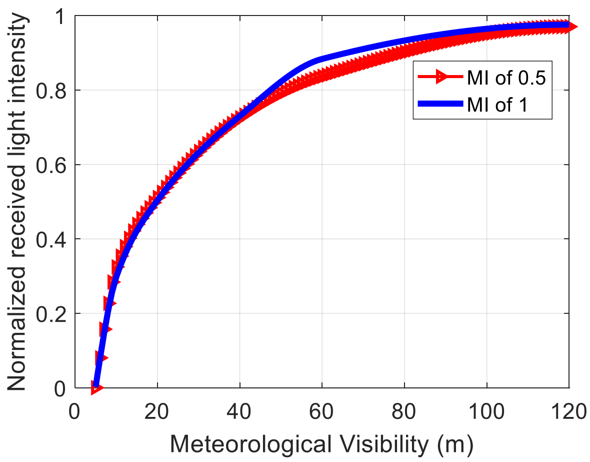

Fig. 5. Meteorological visibilities versus normalized received light intensity of the car tail light by the camera at MI of 1 and 0.5.

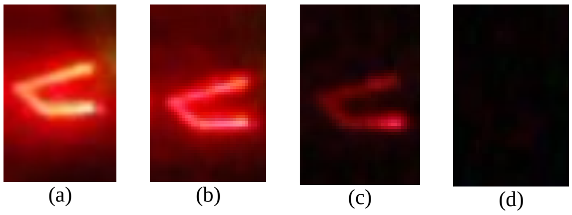

Fig. 6. Captured images of the car taillight for a MI of 1: (a) clear weather, (b) 40 m, (c) 10 m and (d) 5 m meteorological visibilities

TABLE II. PERCENTAGE LOSS IN RECEIVED LIGHT INTENSITY OVER METEROLOGICAL VISIBILITY

Experiment	**Meteorological visibility *V* (m)**	**Percentage loss in received light intensity for MI=1**	**Percentage loss in received light intensity for MI=0.5**
1	Clear weather	0.0	0.0
2	120	2.5	3.0
3	60	11.7	16.3
4	40	27.0	27.5
5	20	49.7	48.9
6	10	70.2	67.6
7	5	99.7	99.9

IV. Conclusions

We investigated the effect of varying visibility levels due to fog on the proposed OCC based V2V link following realistic inter vehicle distances in practical vehicular environments and using a real car taillight. The results obtained showed that the link was reliable (error free) up to 20 m meteorological visibility for a MI of 0.5 and even up to 10 m meteorological visibility for MIs of 1 and 0.75. Thereafter, the link degraded considerably below the 10 m meteorological visibility for all three values of MIs.

Acknowledgment

The work is supported by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement no 764461 (VISION).

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