Dual Channel Visible Light Communications For Enhanced Vehicular Connectivity

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***Abstract*—Visible Light Communication (VLC) has recently been proposed as a low-cost and low-complexity technology for vehicular communications. In this paper, we propose the usage of dual channel VLC with the goal of providing enhanced vehicular connectivity to disseminate safety-critical messages and perform an experimental study to determine the spatial and angular limits of an off-the-shelf automotive Light Emitting Diode (LED) fog light. Single channel VLC refers to the independent transmission of different data packets from each LED fog light, while the dual channel VLC offers the concurrent transmission of the same data packet from both lights. There is a trade-off between increasing the angular limitation and the performance of dual channel VLC, which needs to be experimentally evaluated to identify its efficient usage. We first show the dependency of the received optical power of single channel VLC on the angle and distance, and demonstrate that Lambertian model does not represent the automotive LED fog light radiation pattern accurately. We then demonstrate that dual channel usage increases the angular limitation by up to 10°compared to the single channel VLC. We also show that dual channel improves the packet delivery error rate performance at only short distances due to the photodiode (PD) saturation led by light intensity overlapping at higher distances.**

I. Introduction

The enhanced connectivity among vehicles in Intelligent Transportation Systems (ITS) aims to reduce traffic accidents by providing timely and efficient data dissemination about events like accidents, road conditions and traffic jams beyond the driver's knowledge. Current vehicular communication architectures mainly adopt Dedicated Short Range Communication (DSRC), Long Term Evolution (LTE) or a hybrid of both [1]. Recently, as an alternative to DSRC and LTE, the usage of VLC technologies has been investigated. VLC uses modulated optical radiation in the visible light spectrum to carry digital information in free space. LED has become very common in automotive lighting due to its long service life, high resistance to vibration, and better safety performance. LEDs are used in the stop lamps, brake lights, turn signals, and headlamps of many vehicles. VLC provides a low cost alternative to the radio frequency (RF) based wireless communication. Moreover, VLC communication is robust to malicious attacks such as intentional jamming from surrounding, and does not cause any electromagnetic interference.

Vehicular VLC has been investigated for its channel characteristics [2]–[5], handover capabilities [6], requirements [7]–[10] and feasibility in a hybrid architecture together with DSRC [11], [12]. Proposed vehicular VLC schemes are studied either experimentally [2]–[4], [7], [9] by using a single LED light or via computer based simulations [5], [6], [8], [10]–[12] using Lambertian property of LEDs. However, in [2], it is demonstrated that Lambertian property does not hold for the off-the-shelf scooter tail light. Also, none of the studies have experimentally analyzed the single automotive LED light usage limitations for separate channel usage and dual automotive LED light utilization for extended connectivity.

It is foreseen that remote controlling of vehicles in closed formations such as platoon will efficiently reduce traffic jam and fuel consumption [13]. However, one of the key challenges in highly autonomous platooning is to provide a secure communication robust to intentional jamming from surrounding, where VLC is a strong candidate technology for the solution [8]. Despite its jam-free nature, the limited range of angles over which PD can collect data, known as field of view (FOV) limitation, is a debated topic regarding the VLC suitability for platooning. Thus, few studies investigated VLC FOV limitations [10]–[12]. [10] studied methods to enhance FOV for platooning by using the Lambertian property of LEDs and employing optical arms in a simulation environment. Authors in [11], [12] considered complementing VLC with RF based technologies, ending up with a hybrid framework to overcome FOV limitations and increase communication reliability. None of the proposed studies, nevertheless, performed outdoor experimental evaluations. Moreover, the mechanisms proposed to improve FOV require additional hardware such as optical arms and RF front-end.

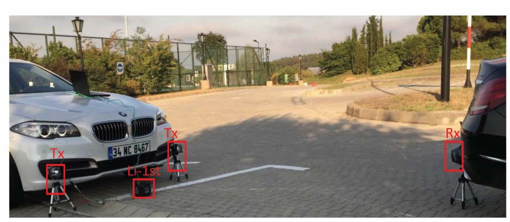

Fig. 1: Vehicular VLC Experimental Setup

The goal of this paper is to experimentally evaluate the dependency of the single channel received optical power on angular and spatial variations, and compare dual channel VLC with single channel VLC performance to determine vehicular VLC limitations by using LED fog lights in varying road

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curvature conditions. The original contribution of this paper is threefold. First, the characteristics of the VLC link in line of sight (LoS) is investigated and compared with its Lambertian model. Second, the usage limitations of single LED fog light are defined for separate channel use cases. Third, the effect of the dual channel usage of VLC in varying inter-vehicular distances and angles is analyzed. We demonstrate that dual channel usage can improve the angular limitation and reliability of VLC in certain scenarios.

The rest of the paper is organized as follows. Section II describes the experimental setup for VLC communication. Section III introduces the Lambertian model and the switching limit calculation from single to dual channel VLC. Section IV presents the experimental results. Section V discusses the on-going work for an alternative switching methodology. Finally, conclusions and future work are given in Section VI.

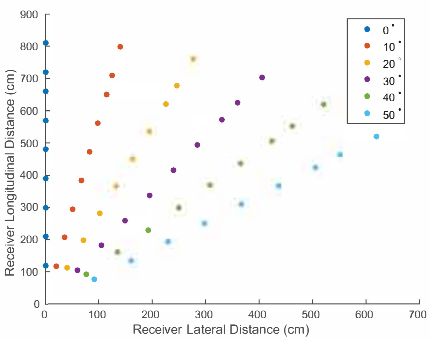


Fig. 2: Receiver Locations

II. Experimental Setup

In the experimental setup, two symmetrical LED fog lights [14] are connected to Li-1st [15] transmitter unit (TU) and PD based receiver unit (RU) as shown in Fig. 1. Dual symmetrical LED fog lights are mounted on tripods with 36 cm height and 150 cm separation distance. Automotive fog lights are preferred to provide reliable communication from the following vehicle to the leading vehicle under degraded visibility conditions since they have wide and flat illumination pattern to minimize reflection by fog. Li-1st TU is used for driving LED fog lights in order to illuminate and transfer custom created 150 byte length data packets. As TU is able to provide more voltage but less current required to operate fog light properly, it is terminated with 20 W 50Ω power resistor, decreasing the nominal light intensity by 8 dBm. Despite this intensity degradation, transmission pattern of the LED fog light did not show any deviation when compared to nominal intensity. TU utilizes Pulse Amplitude Modulation (PAM) scheme along with Reed-Solomon coding operating at a sample rate of 2.5 Msps, allowing 5 Mbps data rate with 4PAM.

Received power is measured via OMM-6810B Optical Power Meter using OMH-6703B Si power head. Transmitted data is captured with Li-1st RU. Both TU and RU are connected to computers for evaluating communication performance. Night time outdoor measurements are executed to compensate shot noise, sourced by diurnal variations. RU and Si-power head of optical power meter is mounted on tripods with 36 cm height at the center of the leading vehicle's bumper. Both fog lights and RUs are placed between vehicles in an outdoor environment to take into account the reflections from vehicles and road. Measurements emulated the following vehicle disseminating safety critical message (i.e. slip, lane change intention) with LED fog lights, to the leading vehicle proceeding on a curved path. Thus, receiver distance is changed from 1.2 to 8.1 meters, with varying angles from $0°$ to $50°$, as shown in Fig. 2, while LED fog lights are fixed.

Two different use case scenarios are considered. In the first single channel VLC scenario, one of the LED fog lights is turned on. This corresponds to the case where two separate LED fog lights transmit different messages on different channels simultaneously. In the second dual channel VLC scenario, both LED lights transmit identical messages at the same time to overcome single LED fog light limitations for enhanced connectivity. Hence, optimal switching limits between single and dual channel VLC depending on inter-vehicular distance and angle are defined for sustaining safety critical message link.

III. Communication Model

A. Lambertian Model

A single LED light usually has the Lambertian radiation pattern [16]. The optical channel DC gain $H(0)$ in this model is given as

$$H(0) = \begin{cases} \frac{(m+1)A_{pd}}{2\pi d^{\Gamma}} cos^{m}(\varphi) T_s(\Psi) g(\Psi) cos(\Psi), & 0 \leq \Psi \leq \Psi_c \\ 0, & \text{elsewhere} \end{cases} \quad (1)$$

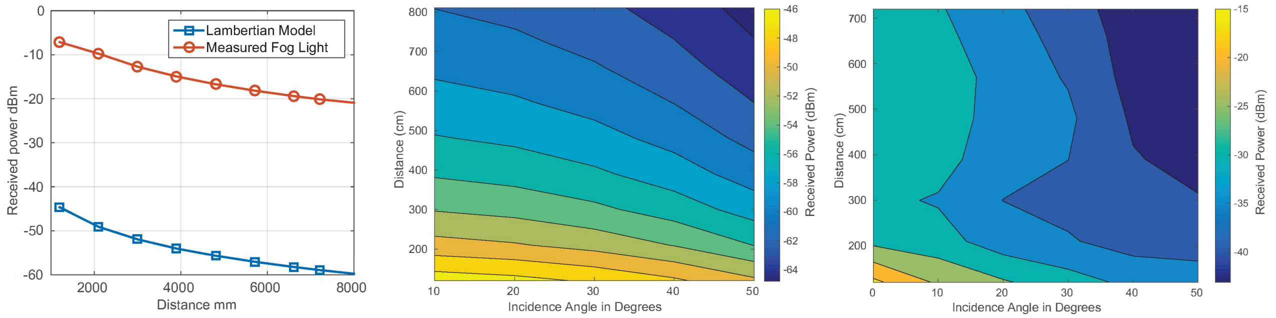
where d is the inter-vehicle distance; φ is the irradiance angle; Ψ is the incidence angle; Ψ_c is the PD FOV; A_{pd} is the active receiver area of the PD; Γ is the path loss exponent; $T_s(\Psi)$ is the filter gain of value 1; $g(\Psi)$ is the gain of an optical concentrator calculated by,

$$g(\Psi) = \begin{cases} \frac{n^2}{sin^2(\Psi)}, & \text{if} |\Psi| \leq \Psi_c \\ 0, & \text{if} |\Psi| > \Psi_c \end{cases} \quad (2)$$

in which n is the internal refractive index of PD; m is the order of Lambertian model specifying the directivity of the transmitter and computed by $m = -\frac{ln2}{ln(cos\hat{\phi})}$, in which $\hat{\phi}$ is the half-intensity beam angle of LED. The coverage range and radiation pattern of single LED light is affected by the half-intensity beam angle $\hat{\phi}$ such that narrower $\hat{\phi}$ increases the illumination range. The average received optical power P_r is calculated by

$$P_r = H(0) P_t \quad (3)$$

The half-intensity beam angle and path loss exponent values are estimated by using linear least square methods based on the measured received power with varying distances up to 8.1 meters and incidence angles from 0 to $50°$ [2]. A_{pd} and n values are 28 mm^2 and 1, respectively. $\varphi = \Psi$ as both RU



(a) (b) (c)

Fig. 3: (a) Lambertian vs. Off-The-Shelf Fog Light (b) Estimated Lambertian Pattern (c) Single Channel Fog Light Pattern

and TU are located at the same height, while P_t is 8 dBm for each LED fog light.

B. Usage Limitations Calculation

The receiver sensitivity levels for the received optical power are determined to be -33 and -30 dBm for single and dual LED fog lights, respectively, depending on the RU characteristics. As overlapped light intensity causes PD saturation and optical automatic gain control (AGC) is not utilized due to the complexity of gain characterization under various road lighting conditions, receiver sensitivity level using dual LED fog lights is considered 3 dBm higher to ensure reliable reception. The received optical power measured at the optical power meter is first compared to these thresholds to calculate the spatial and angular limitations of single and dual LED lights. Then the data packet delivery ratio (DPDR) metric is inspected for validation purposes. DPDR is defined as the ratio of the number of successfully received data packets to the total number of transmitted data packets.

IV. Performance Evaluation

A. Single Channel VLC

Fig. 3 shows the comparison of the Lambertian model to the single channel experimental data. The path loss exponent and half-intensity beam angle of the LED fog light are estimated to be as 1.8319 and 50.66°, respectively. Lambertian radiation pattern with estimated parameters is evaluated and compared with the measured model. We observe that Lambertian model is not appropriate for link modeling, as depicted in Fig. 3 (b) and (c). Even though the received power decrement patterns match for both models, actual model provides more intensity due to the reflector and lens, as shown in Fig. 3 (a). Collimating and diffusing optics (i.e. reflector and lenses) are widely used on automotive LED lights to shape radiation pattern and achieve homogeneous lighting. Thus, despite its common acceptance, Lambertian radiation pattern is inaccurate to model vehicular VLC link.

Fig. 4 shows the received power at different distances and angles. We observe that received power exhibits similar degradation pattern with the increasing angle at all distances, which is consistent with the vehicle fog light regulation [17]. Results indicate that knowing the distance and angle from the leading vehicle with road curvature, following vehicle can decide switching from single to dual channel usage in order to ensure efficient safety critical message dissemination.

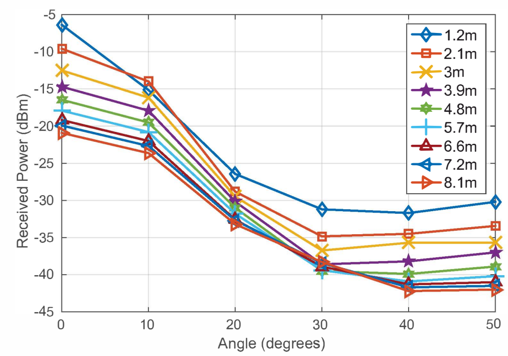


Fig. 4: Received Power With Varying Angle and Distances

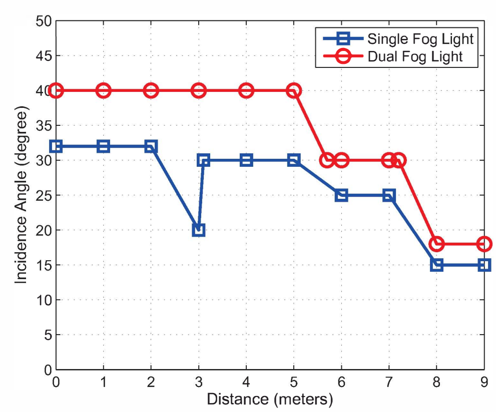


Fig. 5: Single and Dual LED Fog Light Usage Limits

B. Dual Channel VLC

Fig. 5 shows the angular limits for single and dual channel VLC based reliable data transmission at different distances. The usage of dual channel VLC increases the angular limitation by up to 10°. This slight improvement in the angular limits can be used for optimal switching between single and dual channel usage depending on the inter-vehicular distance and road curvature. Moreover, the angular limit of VLC communication decreases with the increasing distance for both single and dual channel communication. On the other hand, dual channel usage compensates for the 20° incidence angle limitation regarding 3 meters inter-vehicular distance which is mainly due to the collimation optics of single fog light.

Fig. 6 shows the DPDR performance of single and dual channel VLC as a function of distance at 0° incidence angle. Up to 6 meter distance, the dual channel VLC improves the DPDR performance due to the increase in Signal-to-Noise Ratio (SNR) by the simultaneous dual fog light usage for data transmission. For distances greater than 6 meters, PD reaches saturation due to the overlapping of fog lights, resulting in degraded efficiency. Thus, increased receiver sensitivity is considered for defining dual fog light reliable link limitations.

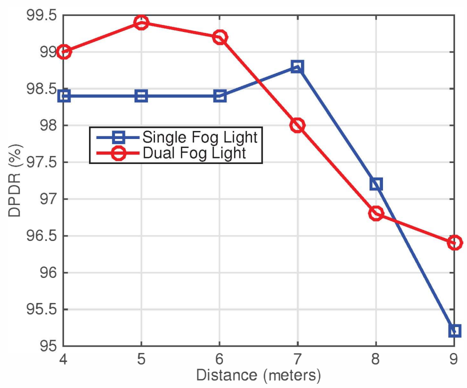


Fig. 6: DPDR performance of single and dual channel VLC

V. On-Going Work

Off-the-shelf equipment has been used to define automotive LED fog light efficient utilization limits for vehicular VLC. We are currently working on frequency selective thresholding for switching, detailed as follows. Switching on the transmitter side can be realized by predefining and interchanging two different carrier frequencies for both LED fog lights. While the single LED usage is feasible, each light can disseminate data using different carrier frequencies, enabling separate channel usage. Whenever the single LED usage is not feasible, both fog lights can transmit the data at the same frequency in order to extend safety-critical message dissemination.

VI. Conclusion and Future Work

VLC offers low cost, directional and jam-free LoS communication scheme viable for platooning. Due to their wide and flat illumination pattern, LED fog lights are good candidates for VLC data transmission under degraded visibility conditions. Considering the requirement for increased data transmission rates and enhanced link availability, we analyzed the limitations of reliable vehicular communication in single and dual channel VLC. Based on the outdoor experiments, we demonstrate that the dual channel usage increases the angular limitation up to 10° compared to the single channel VLC. We also show that dual channel improves the packet delivery error rate performance at only short distances due to the PD saturation sourced by light intensity overlapping at higher distances. Future work will concentrate on determining the efficiency of LoS and non-LoS communication at different light, temperature and humidity conditions for high speed data communication with automotive LED lights.

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