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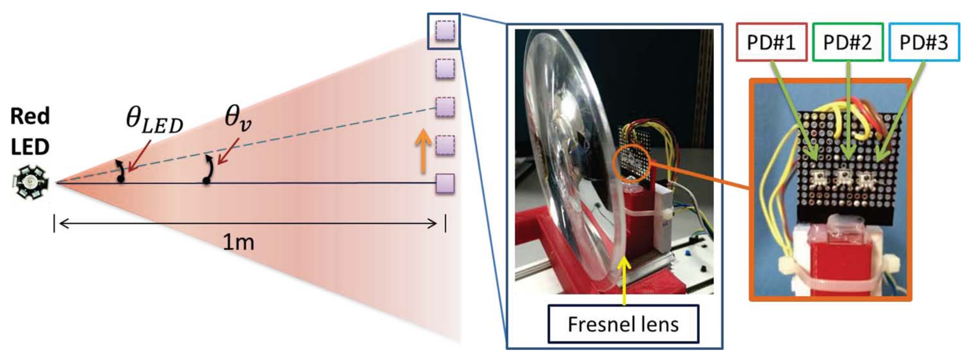

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Experimental Demonstration of VLC-Based Vehicle-to-Vehicle Communications Under Fog Conditions

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Abstract: Vehicle-to-vehicle (V2V) communication using visible light communication (VLC) technology under fog conditions is presented. Fog is known as one of the most detrimental atmospheric conditions that causes outdoor optical wireless communications to be unreliable. The effect of the fog conditions is experimentally analyzed in the VLC-based V2V system. Recognizing the least attenuation coefficient and a taillight color of a vehicle, a red light-emitting diode (LED) was employed in the experiment. In addition, a Fresnel lens and multiple photodiodes are utilized to efficiently counteract the impairment caused by fog. The experimental results demonstrate that the proposed VLC-based V2V system offers a reliable V2V data transmission over the fog-impaired optical channel with a relatively high signal-to-noise ratio (SNR), even under a heavy-fog condition.

Index Terms: Visible light communication (VLC), vehicle-to-vehicle (V2V) communication, atmospheric turbulence, multi-photodiode.

1. Introduction

Visible light communication (VLC) is a wireless data transmission technology using luminance to transmit data. The VLC uses light emitting diodes (LEDs) as a light source, which gives rise to some inherent advantages: low power consumption, a long lifetime, and rapid blinking speed [1]–[3]. For these reasons, LED-based VLCs have recently drawn much attention as a means of short-range wireless communications. The visible light is not harmful to human body, highly secure and offers vast unregulated frequency spectrum. In fact, the LED-based VLCs can fulfill many wireless communication needs in various applications, such as indoor lighting, outdoor billboard, street lamps, vehicle lamp, etc. [4]. VLC is primarily considered to provide indoor short range communications and illumination simultaneously.

Recently, the VLC has been proposed to provide VLC-based vehicle-to-vehicle (V2V) communications in automotive applications, exploiting the popularity of LEDs in vehicles for illumination [5]. A few reports on V2V communications, known as dedicated short range communications (DSRC) based on radio frequency (RF), were documented in the literature [6], [7]. Considering that the RF based DSRC entails a complex structure and special requirements, the LED-based V2V offers various advantages such as lower cost and complexity in view of popular installation of LED lamps in vehicles. In addition, an accurate positioning can be obtained from the LED-based V2V, due to the directional line-of-sight (LOS) propagation characteristics of light. It is true that the LED-based V2V technologies can reduce the positioning error up to tens of centimeters, which is more accurate than the RF-based positioning technology [8], [9]. As a consequence, the LED-based V2V can be a potential candidate for future V2V communications.

In the LED-based V2V, however, the transmission is strongly subjected to weather conditions over the optical channel, such as rain, snow and fog, because LEDs are often prone to severe transmission quality drop. In particular, a foggy weather causes either poor or no visibility on the road, thus making LED communications impractical. This is because fog is a type of vapor which is composed of water droplets. Even when the size of water droplets is merely a few hundred microns in diameter, it can deviate and completely disturb the passage of light through a combination of absorption, scattering and reflection [10]. The fog impaired channel is comparatively more severe than rain and snow [10]–[13]. Therefore, it can be said that fog is one of the most significant factors influencing the VLC link in terms of atmospheric attenuation. For this reason, a rigorous study under fog conditions needs to be conducted for the VLC based V2V technology to be viable as an alternative to the RF based V2V.

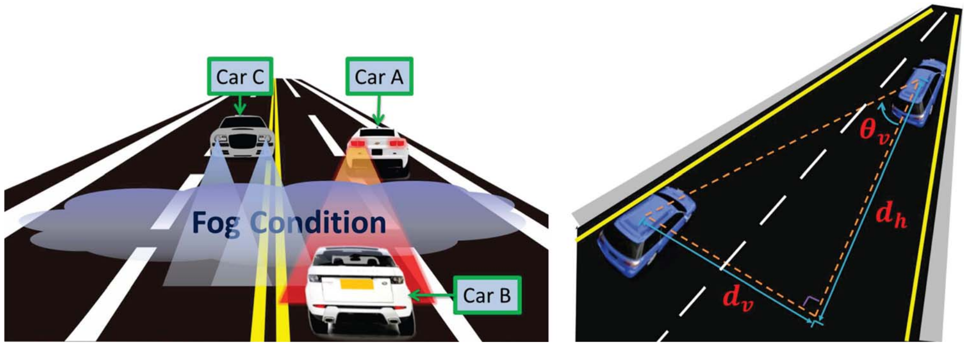
Luo *et al.* presented an analytical performance of a car-to-car visible light communication system under different communication geometries during the daytime [14]. This study treated weather conditions as reflection on non-line-of-sight (NLOS) transmission. Unfortunately, it failed to provide the effect of weather conditions on the VLC channel and, moreover, presented simulation based results only. By contrast, Hossain *et al.* reported fog attenuation on a free space optical link, using multiple TX/RX systems with travelling wave semiconductor optical amplifiers, in order to eliminate the effect of fog attenuation on free space optics (FSO) [10]. In view of using taillights as transmitters in the V2V, it appears to be less attractive to employ a large number of transmitters and receivers in the V2V, because it would cause high power consumption as well as increased complexity. Therefore, an experimental demonstration of a realistic and efficient LED-based V2V under fog conditions still needs to be documented.

In performing the LED-based V2V, there are two types of receivers to be used: image sensor and photodiode (PD). Image sensor is a device which produces electrical image signal converted from reading object information in the form of light [15]. Meanwhile, PD is a device which converts light into electrical voltage levels from its surface area [16]. Thus, the image sensor based method has an advantage over the PD based method, because it offers a wider detection area by using a wider angle sensor. However, this image sensor based method would incur high cost, high power consumption and low processing speed, whereas the PD based method provides low cost, low power consumption and faster processing speed [16]. With this consideration taken into account, the present study employs the PD based method for the proposed V2V under fog conditions.

Based on the notion that the fog condition is considered most detrimental in the outdoor V2V, this paper analyzes the effect of fog on the V2V transmission. Experiments were conducted to investigate this fog effect and an efficient detection technique with a Fresnel lens applied is proposed. The experimental results show that the proposed LED based V2V system under fog conditions is robust and reliable. In Section 2, the VLC experiment with fog conditions applied is described. Both the experimental results and the analysis of the proposed system are explained in Section 3. Conclusions are drawn in Section 4.

2. LED-Based V2V Experiments

The V2V communications play an important role in enhancing vehicle safety and should be reliable and efficient in transmitting traffic related information under various weather conditions on the road. We focus on investigating the effect of fog, which is one of the most significant factors in the V2V as noted previously. It affects the VLC link by influencing its range and reliability on



(a) (b)

Fig. 1. VLC-based V2V transmission model. (a) Fog condition in the V2V. (b) Diagram of transmission model.

the V2V communications [10]. Fig. 1 shows the VLC-based V2V model. That is, when drivers face fog on the road, the driver will usually turn on headlights, fog lamps, or both. As a consequence, Car A sends data using a red LED from the taillight to Car B equipped with PDs under the fog condition. Car C can also transmit the data using a fog lamp or the headlight to Car B. For simplicity and easiness, the present study considers transmitting data through taillights only.

2.1. Non-Line-of-Sight Transmission Model

Fig. 1(b) shows the transmission model of the LED-based V2V communication. In Fig. 1(b), d_h denotes safety distance. Safety distance is defined as spare distance providing *space cushion* against rear-end collision. d_v denotes the distance between two vehicles present in both lanes. We assume that the vehicle's width is 1.7 m and that the lane width is 3.5, although the lane width would vary from country to country. θ_v denotes the angle between the two vehicles. The primary challenge in this scenario would be when two vehicles are located at each edge of the road. For the present investigation, we consider this most unfavorable scenario.

In the proposed transmission model, we first computed a potential range of the angle, θ_v, by considering the safety distance d_h and the horizontal distance d_v. In other words, assuming the maximum d_v (the farthest separation), θ_v will change according to the safety distance, i.e. d_h. As the vehicle speed (v) increases, drivers would increase the safety distance in a usual situation. Since safety distance relative to vehicle speed can be computed in various ways, we used a simple formula, which is calculated as $v^2/100$ [17]. Therefore, by drawing a relationship between the vehicle speed and the corresponding safety distance, a realistic range of the underlying angle was found. Fig. 2 shows the relationship between these three parameters. With the assumption of a maximum vehicle speed of 80 km/h, the maximum angle we found was approximately 20°. The experiments were conducted for the angles of up to 22.5°.

2.2. Effect of Fog Condition

Prior to evaluating the effectiveness of the proposed V2V scheme, attenuation coefficients for different colors of LEDs under fog conditions were investigated. In general, the penetration of light is associated with the wavelength of light source used for transmission. Therefore, the attenuation coefficient is given by [18], [19]

$$\gamma(\lambda) \cong \frac{17.35}{V}\left(\frac{\lambda}{550}\right)^{-\varphi} \tag{1}$$

where $\gamma(\lambda)$ is the attenuation coefficient (in dB/km), V is the visibility range, i.e., atmospheric path distance for a transmission of 2%, and λ is the wavelength (in nm) of transmitted LED light. The

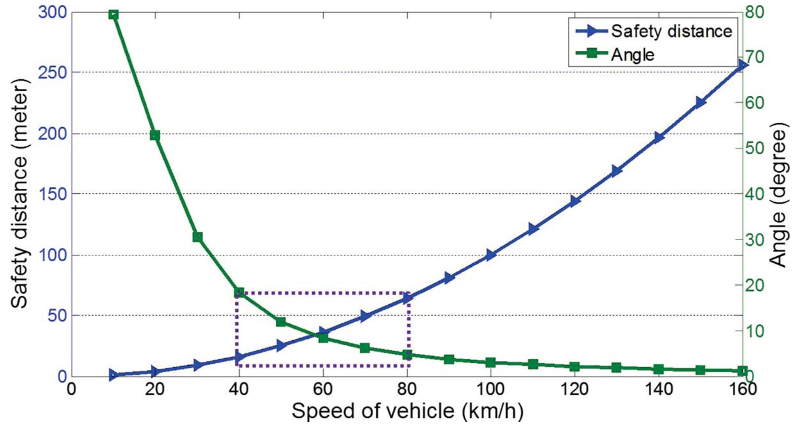


Fig. 2. Relationship between vehicle speed, safety distance, and vehicle angle.

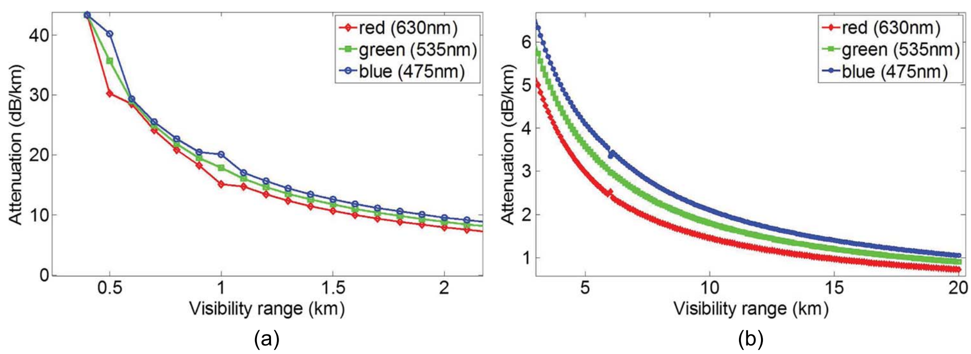


Fig. 3. Attenuation coefficients. (a) Low visibility. (b) High visibility.

parameter φ depends on the visibility distance range and is given by [18], [20].

$$\varphi = \begin{cases} 1.6, & \text{V} > 50 \text{ km} \\ 1.3, & 6 \text{ km} < \text{V} < 50 \text{ km} \\ 0.16V + 0.34, & 1 \text{ km} < \text{V} < 6 \text{ km} \\ V - 0.5, & 0.5 \text{ km} < \text{V} < 1 \text{ km} \\ 0, & \text{V} < 0.5 \text{ km}. \end{cases} \tag{2}$$

Based on the relationship between the attenuation coefficient and the visibility range [see (1)], the three most widely used LEDs, i.e. red, green and blue LEDs, were simulated under different fog conditions. Fig. 3 shows the computed attenuation coefficients of red (630 nm), green (535 nm) and blue (475 nm) color LEDs, according to both (1) and (2). It is found that the red color LED exhibits the lowest attenuation coefficient as compared with other color LEDs. Hence, the proposed scheme employs red taillights to transmit data under fog conditions. The usage of the red LED is also justifiable as the taillights of most vehicles are usually in red color. Table 1 shows some typical values of terrestrial short-range path attenuation for a red LED wavelength of 630 nm with corresponding visibilities provided. For the present study, the two worst conditions of both light fog and heavy fog only are considered in the experiments.

3. Experimental Setup

To evaluate the proposed scheme, an experimental setup was established with the proposed detection methods.

TABLE 1

Typical values of attenuation with visibilities

Climate	Visibility (km)	Attenuation (dB/km)
Clear	20.00	0.73
Haze	2.00	7.93
Thin fog	1.50	10.69
Light fog	1.00	15.15
Heavy fog	0.50	30.29

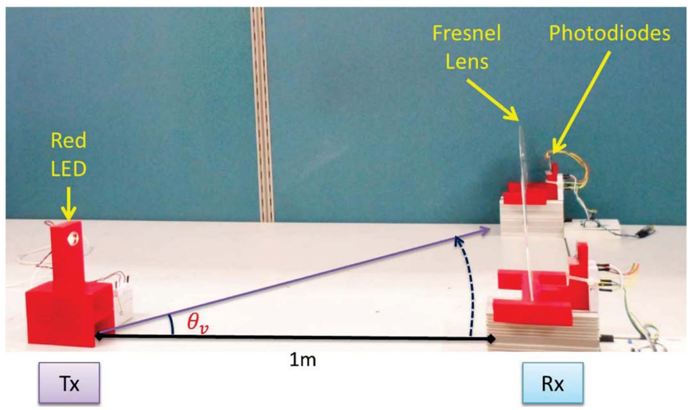


Fig. 4. Experimental setup.

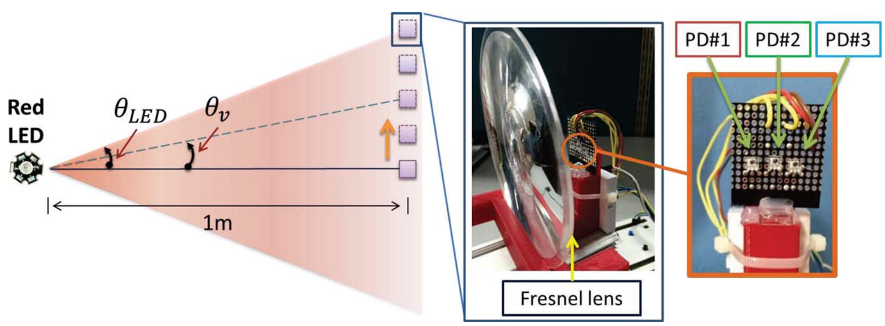


Fig. 5. Diagram of experimental setup.

3.1. Receiver Structure

The experimental setup is composed of transmitter and receiver units. Fig. 4 shows the experimental setup. The transmitter unit includes a 1-W red LED, representing a vehicle's taillight lamp and LED lens. The receiver unit consists of a Fresnel lens with three PDs. The LED lens at the transmitter serves to adjust the field of view (FOV) of the LED that is determined by the angle between two vehicles, θ_v. That is, the value of θ_{LED} is equivalent to the maximum value of θ_v. On the other hand, the Fresnel lens at the receiver focuses the incoming light onto any PDs positioned behind the Fresnel lens.

Fig. 5 illustrates the conceptual diagram of the experimental setup. Experiments were conducted by changing θ_v, while keeping θ_{LED} fixed. The θ_v values vary from 0 to θ_{LED} while

TABLE 2

Experiment parameters

Parameters	Values
Transmission Bit Rate	1000 bits/s
Link Distance	1 m
Modulation Type	On-Off Keying (OOK)
Wavelength of LED	625 nm
Power Dissipation of LED	1 watt
Viewing Angle of LED	45 °
Irradiance Responsivity of PD	10.2 mV/($\mu W/cm^2$) at λ_p = 635 nm
Intergrated PD Active Area	$0.26mm^2$

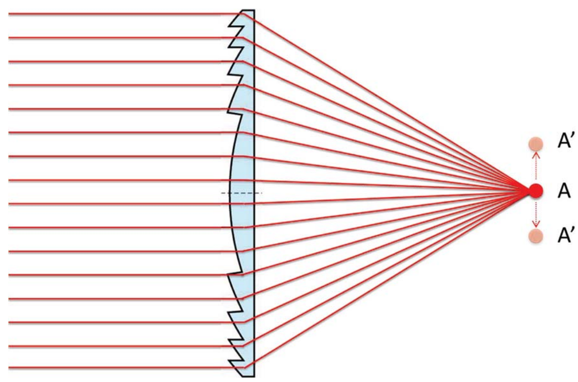


Fig. 6. Effect of Fresnel lens.

keeping a distance of 1 m for a 1-W LED. Obviously, the distance can further be increased with higher power LEDs. Although the experiments were conducted over a 1 m distance, the strength of the proposed scheme would still prevail at a larger distance. A detail of the experiment parameters is presented in Table 2.

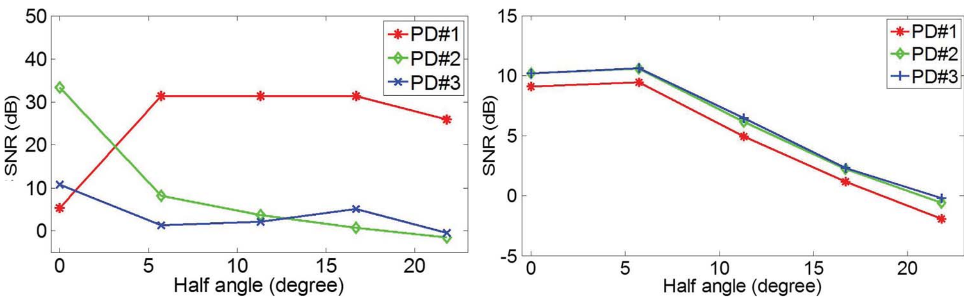
In practice, moving vehicle with the NLOS transmission under fog conditions would pose a major challenge for practical and efficient V2V communications. As an example, when the signal from an LED reaches a PD through the Fresnel lens at the LOS condition, the focus will clearly be placed at *A* as shown in Fig. 6. As the vehicle moves away, however, this focus will deviate from the point *A*, thus moving progressively to *A*′. This would constitute a NLOS condition in the V2V. Under this circumstance, it is important to devise an efficient solution to accurate and reliable detection of the signal. To this end, the present scheme performs the detection in the receiver by measuring the highest received intensity value among three candidates of the PDs. In regard to the position of the PDs, it is assumed that the PDs are installed around the middle of the front part of a vehicle. It should be noted that this solution is based on the fact that the Fresnel lens focuses the incoming light onto one of the three PDs, even when this focus moves away.

3.2. Design of Fog Simulator

The current experimental setup is designed to conduct the LED-based V2V under fog conditions, The experimental generation of fog for the investigation was made from a fog generator [21]. In order to have a different level of fog density, we used an atmospheric chamber where the generated fog is contained inside the chamber for the experiments. Inside this chamber, the

(a) (b)

Fig. 7. Chamber structure. (a) Without fog. (b) With fog.



(a) (b)

Fig. 8. Received SNR. (a) Three PDs with Fresnel lens. (b) Three PDs without Fresnel lens.

LED transmission was performed as described earlier. Fig. 7 shows the chamber with and without fog. Fog density is controlled by the fog generator that injects a controlled amount of fog, ranging from light to heavy.

4. Result and Analysis

The experiments were conducted in such a way that a data stream modulated by on-off keying (OOK) was first transmitted from an LED, and then, signal-to-noise ratio (SNR) values were measured in foggy conditions. Prior to this measurement, a clear weather condition was experimented as a reference for subsequent measurements. It is worth noting that although a simple OOK modulation scheme was employed, more advanced modulation schemes under thermal constraint, such as PWM, PPM and their variants, can be considered for improved performance. In order to investigate the effect of the lens at the receiver, the experiments were conducted both with and without the lens. Fig. 8 shows the results in the clear condition with and without the Fresnel lens by varying the receiver positions, i.e. the half-angle. As θ_v increases as depicted in Fig. 5, the SNR would vary due to changing light intensity. When the Fresnel lens is applied, however, the received SNR maintains a SNR value of approximately 25 dB. In other words, the Fresnel lens significantly contributes to maintaining a certain level of SNR. By contrast, it can be observed that the scheme without the Fresnel lens degrades SNR values sharply. Clearly, this is because the illuminated area of the receiver from the LED beam becomes dimmed as θ_{PD} increases.

In addition, the SNR variation relative to different fog densities with reference to the clear condition was observed. Fig. 9 shows the results of the SNR variation. It was found that the received SNR values decrease as the fog density increases. It should be noted, however, that the received SNR is still adequate even under the heavy fog condition. That is, it offers a

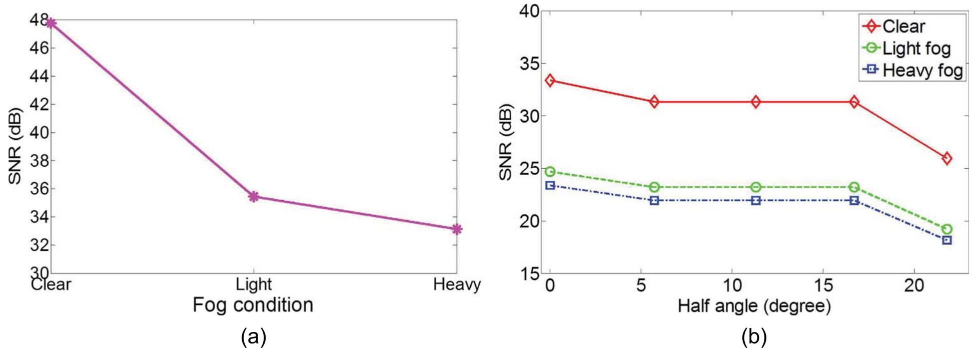


Fig. 9. Received SNR variation. (a) LOS transmission with different fog densities. (b) NLOS transmission with different half-angles and fog densities.

satisfactory level of SNR with which efficient and reliable V2V communications can be provided. Over the NLOS condition, a similar observation can also be made that the received SNRs decrease as θ_v and fog density increase. Therefore, it can be concluded that the proposed scheme with the Fresnel lens and multiple PDs ensures a robust and adequate performance, even under the heavy fog condition.

5. Conclusion

The LED-based V2V communications under fog conditions are presented. We employed the Fresnel lens to focus the incoming light effectively and multiple PDs to detect the highest intensity over the NLOS conditions among three candidates of the PDs. It was found that the fog conditions severely impair the V2V transmission. It was also observed that the proposed Fresnel based receiver unit yields a significant SNR performance gain even under the heavy fog condition. Therefore, it can be said that the proposed LED-based V2V scheme presents a potential candidate for future V2V communication systems with the robust and efficient detection method to counter the adverse effect of fog.

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