Empirical Characterization of the NLOS Component for Vehicular Visible Light Communication

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***Abstract*—We investigate the influence of Non Line Of Sight (NLOS) components on the performance of Vehicular VLC (V-VLC). Given the steep rise of Intelligent Transportation Systems (ITS) for road safety applications, the need for reliable technologies for Vehicle-to-Vehicle (V2V) communication rises. Among others, V-VLC turned out to be a promising candidate to enhance vehicular connectivity, which nicely complements Radio Frequency (RF)-based technologies. V-VLC is supposed to be a Line Of Sight (LOS) communication technology, nevertheless, there is also a NLOS component caused by reflection on the road surface. In this paper, we investigate this influence in a real-world measurement campaign for different ground surfaces. Our results are very interesting as they (a) confirm a huge impact, and (b) indicate such reflections being actually helpful as they improve the received signal strength.**

I. Introduction

Recent technological advances in the automotive industry have contributed to the reduction of fatalities on roads. However, road traffic accidents remain one of the leading causes of death. To address traffic safety and efficiency issues, many governments and organizations worldwide have put forward the idea of Intelligent Transportation Systems (ITS). ITS applications aim to improve traffic safety and efficiency by taking advantage of the capabilities of information and communication technologies for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication.

Radio Frequency (RF)-based wireless communication technologies, like IEEE 802.11p [1] and Cellular Vehicle-to-Everything (C-V2X) [2], have been mainly considered for ITS applications. However, different applications have different communication requirements [3] that might not be satisfied by a single technology, but rather by a combination of multiple communication technologies. Such technologies can complement each other to form a reliable heterogeneous communication system. This is particularly important for safety-critical ITS applications, like *platooning* or *intersection collision avoidance*, which typically require frequent transmission of messages with high reliability and minimum delay.

Since the signal of aforementioned RF technologies is spread in a wide area, if deployed in high traffic density scenarios, the communication channel can be saturated quickly, resulting in the loss of time-critical information. As a result, one could take advantage of Line Of Sight (LOS) technologies, like Visible Light Communications (VLC) [4]. VLC is enabled by LED-based headlight and taillight modules in modern vehicles, the light intensity of which can be modulated using Intensity Modulation and Direct Detection (IM/DD). Photodiodes (PDs) or camera image sensors can be used as receivers, thus vehicles can communicate with each other via Vehicular VLC (V-VLC). As a LOS technology, VLC has a directional collision domain and, therefore, smaller probability for collisions. In addition to this, resilience against security attacks can be improved, as the interception of a LOS is easy to notice compared to (omnidirectional) RF communications. On the other hand, VLC can be heavily impacted by environmental conditions, including bad weather (e.g., fog, rain, snow) and strong ambient light from artificial light sources and the sun. The communication range of VLC is also limited as the design of the automotive lighting modules is governed by international standards which impose limitations in terms of average optical power and shape of radiation pattern [5], [6].

As a relatively new technology, the Vehicular VLC channel has been studied in detail in recent publications [7]–[13]. Compared to RF-based solutions, particularly optical approaches turned out to be helpful for spatial multiplexing [14] and noise reduction [15]. Another specific characteristic of the V-VLC channel is its strong LOS component, and the typically weaker Non Line Of Sight (NLOS) component, which is often considered negligible in the literature. The difficulty with characterizing the V-VLC NLOS link comes from its dynamic and highly variable nature. In V-VLC scenarios the main source of reflections is the road. Therefore, the main factor impacting the strength of the NLOS link is the road surface material, which determines the roughness, hence, the reflection characteristics of the road; and the surface conditions (e.g., wet or dry), which usually depend on the weather conditions [7].

In spite of the low signal strength concentrated in the NLOS link, it needs to be characterized in order to accurately model V-VLC. In this work, we take an empirical approach to investigate the characteristics of the NLOS component in V-VLC.

Our contributions can be summarized as follows:

- We investigate the influence of the NLOS component in two scenarios with very different ground reflection characteristics, emulating dry asphalt and wet road;
- we analyze the path delay in the aforementioned scenarios using a geometric approach; and
- we estimate the influence of the different road conditions and path delays on the communication performance.

II. Related Work

As a novel technology, it is crucial to understand the channel characteristics of V-VLC in order to design actual systems that can be deployed in the real world. One of the main characteristics of the V-VLC channel is the directionality and the asymmetry property deriving from the nonuniform radiation patterns of the headlights, and the difference in illumination between them and taillights, respectively [16].

Due to the irregular surface of the road pavement, the ground reflections in V-VLC have a mixed (diffuse and specular) profile [7]. Luo et al. [7] present a comprehensive V-VLC channel model which considers the NLOS component besides the LOS link. To model the NLOS link from the headlights, they use a Bidirectional Reflectance Distribution Function (BRDF) [17] from the field of photometry. Luminous coefficients (calculated as a function of the angles of incidence and observation) are used to describe different road surface conditions. Based on analytical results, the optical power for the NLOS component is stronger in wet road conditions (for lower PD mounting heights), while the power for the LOS does not change regardless of the road conditions. Moreover, the authors conclude that the optical power for the NLOS link is 10 % of that of the LOS link.

Another approach for modeling the V-VLC channel, and the NLOS link thereby, is by means of simulations. Lee et al. [8] use commercially available Computer Aided Design (CAD) tools to model V2V and V2I scenarios, including the reflection characteristics of the buildings, cars, and other objects present in the environment. Power Delay Profile (PDP) obtained from ray tracing simulations for several metropolitan and intersection scenarios show that metropolitan scenarios have a more dispersive channel due to reflections of diffuse light from the objects in the environment. This work assumes that all of the objects in the environment have Lambertian reflection profile. Miramirkhani [9] use similar technique to model the V-VLC channel, but unlike in [8], objects' coating (i.e., concrete, aluminum, steel, asphalt, car paint), corresponding reflections (i.e., purely diffuse, specular and mixed), and different weather (i.e., clear, rainy, foggy) and road conditions are considered. Channel impulse responses for the V2V VLC scenario show that there are little reflections for the road, which is modeled with slightly specular reflection characteristic.

In [11], we presented a V-VLC simulation model based on realistic vehicle radiation patterns and a pure LOS channel. Results from our measurement campaign showed that our model was consistently underestimating the received signal strength as the NLOS was not considered.

The low signal strength in the V-VLC NLOS link combined with the complexity of the scenarios and parameters that need to be considered for its characterization has lead to little interest for their investigation in the literature. Whereas, the limited existing literature often lacks empirical validation. We fill this gap, characterizing the NLOS link for V-VLC scenarios conducting a series of measurements campaigns.

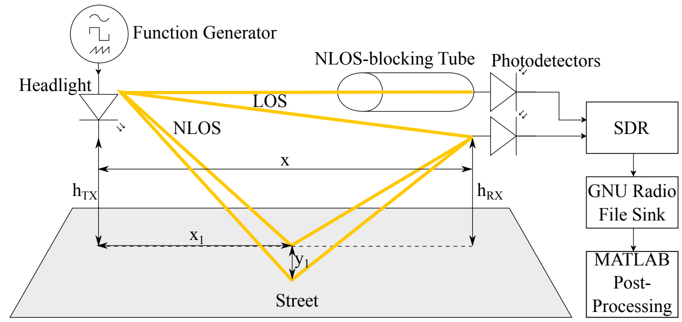

Figure 1. Illustration of the measurement setup.

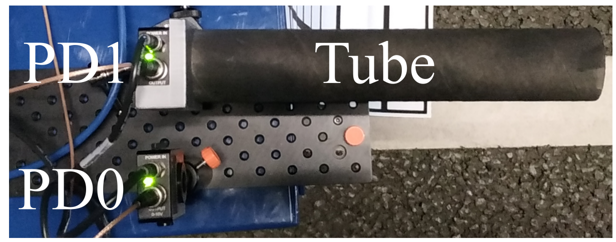

Figure 2. Top-view photo of the NLOS-blocking tube.

III. Measurement Setup

Studying the NLOS of V-VLC in isolated fashion is difficult due to high variation of existing reflection paths. Therefore, to study the NLOS component, we take a practical approach to extract it from the combined LOS and NLOS signal.

Figure 1 shows our measurement setup, which consists of two PDs which measure the Received Signal Strength (RSS). One of the PDs is left as it is, to detect both the LOS and NLOS component. The other PD is used to isolate the LOS signal from the NLOS signal. This is achieved by attaching a non-reflective black tube in front of one of the receivers (cf. Figure 2). The tube is pointing in the direction of the transmitter and its function is to block all reflection paths. Afterwards, the RSS for the NLOS component can be extracted by subtracting RSS measurements of both receivers.

Both PDs were mounted as close as possible to each other, with 3 cm separation. The PDs were mounted on a cart while the distance was varied for each measurement point. The cart was in alignment with the headlight at all times. The PD was placed 45 cm lower than the headlight, which would be the case if a PD is at 20 cm height, which the lowest allowed point to mount a license plate, while the headlight is at a typical height of 65 cm.

As the signal source out-of-the-shelf headlights of a truck, respectively of a passenger car, are used. Both, with radiation patters designed for right sided traffic in Europe. To distinguish the signal and ambient light, the headlight is modulated with a 100 kHz rectangular signal. The output voltage signal of the PD was converted from analog to digital with an Ettus USRP X310 and recorded with GNU Radio with a sample rate of 3 MSamples/s for 10 s at each position.

The measurements were performed at two different locations. One is the *Lichtkanal* facility of HELLA GmbH & Co. KGaA,

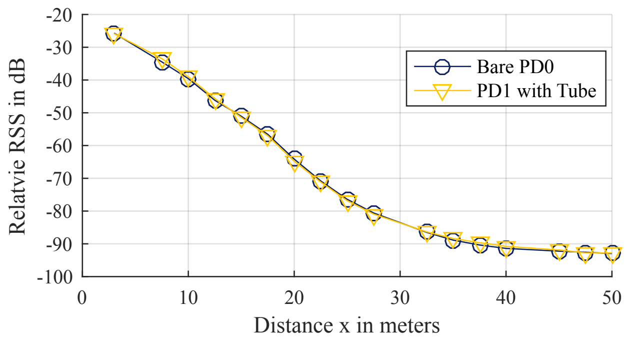

Figure 3. RSS of LOS and LOS+NLOS with dry asphalt.

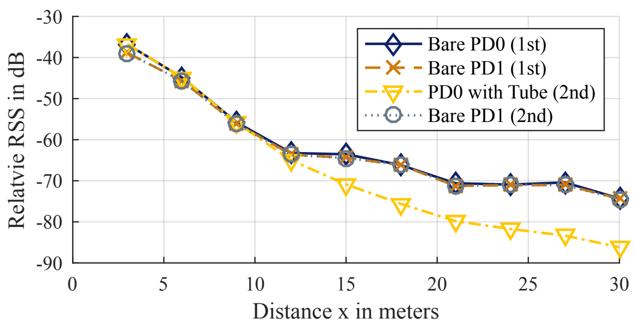

Figure 4. RSS of LOS and LOS+NLOS with a highly reflecting floor.

which is a 140 m long roofed asphalt road build for evaluating headlights. The walls at the Lichtkanal are painted with a special light absorbing paint to suppress any reflections. The second measurement location is in the basement of Heinz Nixdorf Institut (HNI) with a highly reflective linoleum floor, emulating the wet or icy road conditions.

IV. Evaluation

A. Signal Strength

If we examine the scenario with the dry asphalt in the Lichtkanal in Figure 3, it can be seen, that there is almost no difference between the measurement with and without tube. This means that the NLOS component is small and negligible compared to the effect caused by increasing the distance between the transmitter and the receiver. There are small variances between the signals which follow no particular trend and are most probably caused by expected measurement error misalignment between the transmitter and the receiver.

With higher reflectivity of the ground surface, a completely different behavior can be observed. Figure 4 contains three measurements of the bare PD and one measurement with the NLOS-blocking tube. First, both PDs were measured without the tube installed, to verify that the small displacement of the two PDs is negligible. It can be seen that there is just a small difference between PDs, which decreases with higher distances. In a subsequent measurement, the NLOS-blocking tube is attached to PD0 to measure the isolated LOS component. PD1 measures the same signal again in a bare configuration verifying that there is no change over time. In this scenario, a NLOS component, given as the difference between the

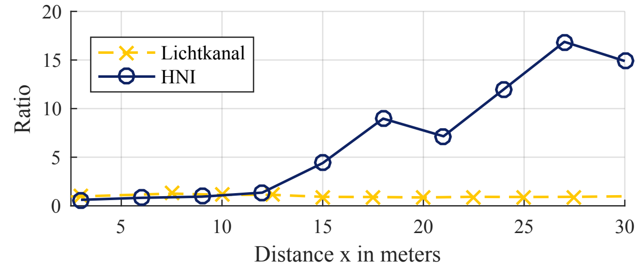

Figure 5. Ratio of RSS of LOS+NLOS to LOS for increasing distances.

measurement with and without the tube can be observed. While for measurements smaller than 15.5 m distance of Transmitter (TX) and Receiver (RX) the graphs are close to each other, they separate from each other for higher distances. This behavior is caused by two main reasons: First, since the low beam of the headlight was used, at roughly 12.5 m the PD passed the cut-off-line of the radiation pattern which results in a big drop of signal strength of the LOS component, so, the relative weight of the NLOS component increases. Secondly, the angle of reflection decreases, which in turn increases the reflection. Note that, the absolute RSSs of Figures 3 and 4 differ. This is because, due to technical reasons, slightly different transmitters were used for the two measurement locations. In the Lichtkanal, a truck headlight with an full range on-off-driver was used, while in the HNI a passenger car's headlight with a linear driver was used. The radiation patterns and luminous intensities are very similar for both headlights, but the drivers have an impact. Because the linear driver only uses the linear range of the LED, the signal from the HNI measurements is lower when we look at the absolute values. However, it is safe to ignore this when studying the relation between LOS and NLOS components.

If we look at the ratio of the NLOS+LOS sum divided by the isolated LOS component (cf. Figure 5) the decreasing RSS caused by increasing distance is compensated. Compared to the LOS component in the scenario of dry asphalt, it can be seen even more clearly that the NLOS component is negligibly small, but is of main importance in the case of highly reflecting floor. In a certain region the RSS of the NLOS component was around 15 times larger than the RSS of the LOS component, as shown in Figure 5.

B. Path Length Difference

Besides the a difference in RSS itself, the NLOS component could cause fading depending on the frequency of the signal and the path length difference, resulting in delay. In V-VLC the main reflection will occur on the street. The path lengths can be calculated analytically by geometric analysis. The path length difference Δs of the reflection on the line between RX and TX can be calculated as

$$\Delta s = \sqrt{x_1^2 + h_{TX}^2} + \sqrt{(x - x_1)^2 + h_{RX}^2} - x \;\forall x_1 \in [0; x] \,, \tag{1}$$

where x is the distance between TX and RX, x_1 the point of reflection, h_{TX} and h_{RX} the heights of TX and RX,

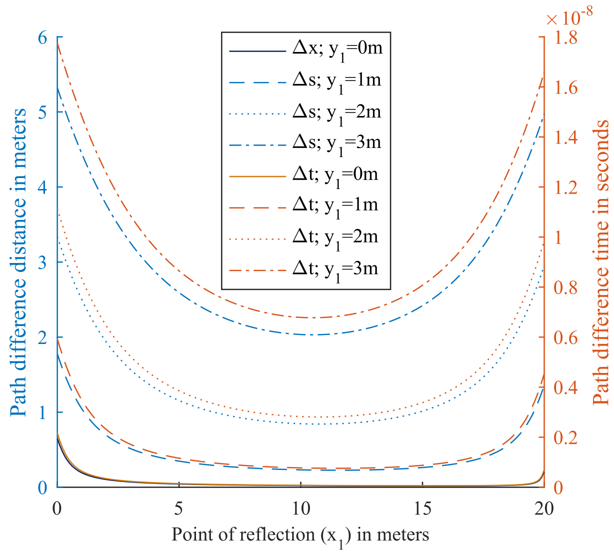

Figure 6. Length of reflection Path in time and distance

respectively (cf. Figure 1). With the speed of light c, the delay τ can be calculated as

$$\tau = \Delta s \times c\ . \tag{2}$$

Figure 6 shows the path difference in time and space domain for a communication distance of x =20 m. The reflection on the line between RX and TX (y_1 =0 m, solid line) contains a very small path difference of less than 80 cm. While increasing the lateral shift (y_1) of the point of reflection the delay increases. Note that this consideration does not take into account the signal strength, which has been shown to decrease with lateral displacement [12]. Nevertheless, in current implementations, the symbols last far longer than the maximum delay, due to the low pass behavior of LEDs. This is in line with Turan et al. [13], who measured multiple vehicular light sources with a maximum 3 dB bandwidth of 2.311 MHz. Utilizing the full bandwidth would result in a symbol duration of 0.432 µs, which is much longer than τ_{max} = 18 ns. Therefore, no frequency selectivity is expected in typical traffic scenarios.

V. Conclusion

In this paper, we studied the impact of the NLOS component of V-VLC, which basically consists of the road reflection path in common traffic scenarios. A strong dependency on the ground condition was observed. While the NLOS component in a dry asphalt scenario was almost negligible, the NLOS component was the main component in the scenario with highly reflecting ground surface. This is in line with observations of Köhler and Neumann [12], where a wet road has caused a forward reflection three orders of magnitude higher than that of a dry road. By analytically comparing the path lengths and the delay assuming systems with typical modulation frequencies, we show that the NLOS component has a constructive impact and enhances the signal. For this reason, in many cases it is sufficient to model the V-VLC channel as a pure LOS channel. By doing so, either the error is rather small or the channel quality is underestimated.

Based on observations from this paper, in future work we plan to focus on the impact of rain on V-VLC. On the one hand, raindrops in the LOS can attenuate signal strength of the LOS component due to scattering and absorption. On the other hand, however, the signal strength of the NLOS component can increase because of the stronger reflection, therefore, compensating the decrease in signal strength to some extent.

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