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Comparison of Radio Frequency and Visible Light Propagation Channels for Vehicular Communications

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ABSTRACT Recent research has shown that both radio and visible light waves can be used to enable communications in highly dynamic vehicular environments. However, the roles of these two technologies and how they interact with each other in future vehicular communication systems remain unclear. Understanding the propagation characteristics is an essential step in investigating the benefits and shortcomings of each technology. To this end, we discuss salient properties of radio and visible light propagation channels, including radiation pattern, path loss modeling, noise and interference, and channel time variation. Comparison of these properties provides an important insight that the two communication channels can complement each other's capabilities in terms of coverage and reliability, thus better satisfying the diverse requirements of future cooperative intelligent transportation systems.

INDEX TERMS Vehicle-to-vehicle (V2V), dedicated short range communications (DSRC), visible light communications (VLC), measurement.

I. INTRODUCTION

Reducing road traffic accidents and alleviating traffic congestion is widely recognized as one of the most pressing societal challenges. Exchanging information among moving vehicles and roadside infrastructure is seen as the most promising new technology for achieving the goals of accident and congestion reduction. To that end, spectrum has been allocated in many countries for the purpose of enabling Cooperative Intelligent Transportation System (C-ITS) applications. Spectrum allocation for C-ITS ranges from 700 MHz band (e.g., in Japan) to the 5 GHz band (e.g., 5.9 GHz in the U.S. and in Europe).

Candidate radio technologies for C-ITS in radio frequency (RF) spectrum are IEEE 802.11p-based Dedicated Short Range Communications (DSRC) and Cellular V2X specified by 3GPP. DSRC is specified by the IEEE 802.11p and IEEE 1609.x set of standards. Its physical layer is based on the popular IEEE 802.11a/g (WiFi) standards, modified to increase the tolerance to multipath in the high-speed outdoor environments.The waveforms are scaled down to use 10 MHz instead of the 20 MHz used in the IEEE 802.11 a/g standard. 3GPP started standardizing Cellular V2X solution in Release 14 of its standards, with initial vehicle-to-vehicle (V2V) standard finalized in September 2016 and V2X (in case of 3GPP, Vehicle-to-Infrastructure/Pedestrian/Network) in June 2017 [1]. The evolution of the Cellular V2X system – in both microwave and millimeter-wave – will continue as part of the future fifth generation (5G) systems, which are expected to explore different radio access technologies (cellular, DSRC, VLC) to provide enhanced C-ITS services [2].

Visible Light Communication (VLC) recently emerged as an interesting alternative to provide optical communication among vehicles using low-cost Light-Emitting Diodes (LEDs) and photodiodes. Given the fact that LEDs have been commonly adopted in vehicle lighting systems, vehicular VLC offers a low-cost solution to implement Vehicle-to-X Communications [3]–[7]. Operating at the (unlicensed) visible spectrum between 400 THz and 790 THz, the transmitter could modulate LEDs at very high frequencies to appear invariant as perceived by human eyes, which leads to the attractive dual usage of the LED light sources on vehicles - illumination/signaling and communications. In this paper, we therefore focus on exploring the properties of the LED-to-photodiode vehicular VLC channel.

Compared to RF, VLC implies several technology-specific characteristics. Although high level comparisons have been reported in [8] and [9], assessing the potential of VLC as a complement or an alternative to RF requires a deeper understanding of the transmission schemes with their channel and propagation characteristics. To the best of our knowledge, in the current literature there does not exist a comprehensive qualitative and quantitative comparison of RF and VLC communication channels in the context of vehicular communications. Therefore, the objectives of this article include: i) discuss the working mechanisms and characteristics of the two channels in relation to the constraints imposed by the outdoor environments and the vehicular traffic; and ii) compare and address the unique capabilities and limitations considering the requirements of vehicular applications. We concern ourselves with four specific properties of the radio and visible light channels: physical waves, radiation pattern and path loss modeling, noise and interference, and performance modeling. These properties are by no means exhaustive, but they help to understand the similarities and differences for these two channels in the context of C-ITS applications.

The rest of the paper is structured as follows. Section II compares radio and light waves. Section III compares the RF and VLC radiation patterns and path loss. Section IV compares the noise and interference characteristics. Section V looks into the coherence time and link duration. Section VI summarizes and discusses the results while Section VII concludes the paper.

II. RADIO VS. LIGHT WAVES IN THE COMMUNICATION CHANNEL

In vehicular communication systems, radio waves operate near the earth's surface, making the transmission medium linear and homogeneous. While traveling on established roadways, there will be obstructions with related attenuation, diffraction, reflection, and scattering from buildings, terrain, other vehicles, other human-made structures, etc. Their presence alters the homogeneity of the channel. Reflections, diffraction and scattering cause multipath propagation, thus introducing dispersion in the medium. For example, since the wavelength of the assigned 5.9 GHz bands is about 5 cm, diffraction can occur off many objects, as the wavelength is of the same magnitude as leaves, traffic signs, etc. The channel is also time-varying owing to the mobility of the transmitting and receiving vehicles, and of other moving objects in the environment.

In contrast, VLC features the unlicensed, free of charge optical band with potentially *much larger available bandwidth*. This makes very high data rate communication possible. Since the optical band does not overlap with existing radio frequency bands, there is no electromagnetic interference. Compared to their RF siblings, light waves cannot penetrate through opaque objects such as walls, but travel with limited attenuation through transparent objects such as glass. Dark objects absorb light waves, while diffused reflections are expected for light-colored objects. Unlike traditional RF systems, vehicular VLC systems largely rely on the unobstructed LOS link owing to the absence of fixed reflecting surfaces. Additional considerations for outdoor operating environments for vehicular applications include ambient light interferences, such as the background solar radiation and possible artificial light interference [4].

Different from RF systems with frequency modulation and coherent detection, many short range vehicular VLC systems utilize intensity modulation / direct detection method, owing to the nature of optical carriers generated by LED transmitters. Optical carriers generated from these devices may lack a determined phase or frequency, and often come in the shape of incoherent light waves with a certain optical bandwidth. The receiver side often features large-area square-law detectors. Together with its much shorter carrier wavelength than RF's, it could lead to efficient spatial diversity to prevent multipath fading, as opposed to the case of its RF siblings where large fluctuations in received signal magnitude and phase are expected in the link. One shortcoming of VLC might be the limited path loss it can handle, as the *square of the received optical power* largely determines receiver's signal to noise ratio (SNR). This observation naturally leads to the next section, where we discuss more details on path loss modeling.

III. RADIATION PATTERN AND PATH LOSS COMPARISON

Having discussed the physical waves that connect a data source to a data sink, we now turn our attention to the radiation pattern and path loss comparisons.

A. RF RADIATION PATTERN AND PATH LOSS

The radiation pattern is one of the transmitter's basic properties since it shows how the transmitter distributes its energy in space. It is mainly determined by the radio antenna in the RF case. Existing two-way radio and mobile telephone antennas on current vehicles may not be the best choice, since most of them are either collinear antennas with phasing coils or vertical monopoles. Besides providing nearly omnidirectional radiation patterns, the finite size of their ground plane formed by the metallic car surfaces makes the direction of maximum gain to be tilted above the horizontal. If we use these antennas in vehicular communications, the upward tilt of the antenna beam can easily increase the link loss by 6 to 12 dB [10], which could translate to significant range deduction (e.g., resulting in half of the original range if the signal power falls off as $1/r^2$).

Path loss is one of the most important metrics to quantify wireless channels. Owing to the highly dynamic nature of vehicular communications, a deep understanding of path loss of both RF and VLC systems is critical for many aspects of analysis, from link budget to scalability. For RF channels, many narrowband and wideband measurement campaigns were conducted in different parts of the world in various environments; Matolak [11] provides a recent review with pointers to all the relevant references. One conclusion from the reported literature that addressed path loss for the vehicular channels is that path loss modeling is highly dependent on the type of environment. Examples include urban [12], suburban [13], rural [14], and highway [11] environments.

One of the most widely used models is the log distance path loss model: $P(r) = P(d_0) - 10\gamma \log_{10}(r/d_0) + X_\sigma$, where $P(r)$ is the received power in decibel at distance r, $P(d_0)$ is the power in decibel at reference distance d_0, γ is the path loss exponent, and shadowing is modeled using the random variable X_σ, typically a zero mean Gaussian.

Another commonly used model is the dual-slope piecewise-linear model, which might be more suitable for comparison with VLC systems, owing to the different regions of the Lambertian radiation pattern (see section III-B). For RF systems, we characterize the dual-slope piecewise-linear model by a path loss exponent γ_1 within a critical distance d_c. Beyond this critical distance, the signal strength falls off with another path loss exponent γ_2, as shown in the formula below.

$$P(r) = \begin{cases} P(d_0) - 10\gamma_1 \log_{10}\left(\frac{r}{d_0}\right) + X_\sigma & \text{if } d_0 \le r \le d_c \\ P(d_0) - 10\gamma_1 \log_{10}\left(\frac{d_c}{d_0}\right) - & \text{if } r > d_c \\ 10\gamma_2 \log_{10}\left(\frac{r}{d_c}\right) + X_\sigma & \end{cases} \tag{1}$$

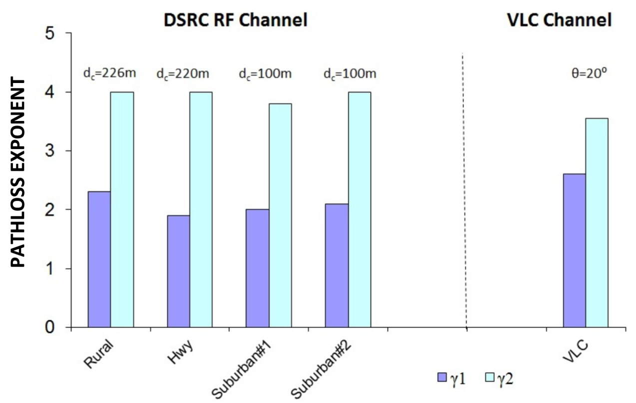

FIGURE 1. Example path loss model from empirical measurements.

As an example, Fig. 1 shows the dual-slope path loss parameters extracted from measurement campaigns conducted by Cheng *et al.* [13], [14] and their collaborators from four datasets: two suburban datasets, one highway and one rural dataset [13], [14]. Please note these results serve only as an example, whereas there exist many other works for RF path loss extracted from different regions of the world (e.g., [11] contains a summary of relevant studies). In general, the path loss parameter values have a structure similar to the two-ray propagation model, except that the suburban environments tend to have smaller critical distance d_c values than the classic two-ray model. One possible reason is the obstruction of the ground reflection (e.g., heavily traveled suburban roads) and contributions from many other scattering objects including dense structures along the road. In the rural environment, on the other hand, the two-ray structure is evident.

B. VLC RADIATION PATTERN AND PATH LOSS

While designing directional RF antenna patterns requires special care, many existing LEDs are by design directional light sources. A large number of LEDs in today's market are surface-emitting LEDs, which are optical sources following Lambert's cosine law, with an intensity directly proportional to the cosine of the angle from which it is viewed [4].

It should be noted that the dimensions of the transmitting light module is much larger than the usual dimensions of an RF antenna. Given the range of VLC of several meters to tens of meters, there exists a *near-field effect* in most cases, which shows irregular change of optical received power as the transmitter-receiver distance increases. Thus it is preferred to jointly consider radiation pattern and path loss in a single model.

One Lambertian model parameter directly related to channel modeling is the half power angle, $\phi_{1/2}$, of the transmitting LED. This is the angle where the effective transmission power is half of the maximum power. For a constant transmission power, the range of vehicular VLC systems depends on relative positions of nearby vehicles; in particular, the irradiance angle ϕ, i.e., the angle between the axis perpendicular to the LED surface and the direction to the receiver, and the incidence angle θ, i.e., the angle between the axis perpendicular to the photo-detector surface and the direction to the transmitter. Referring to measurements using scooter taillights, the red line of a 20° irradiance angle in Fig. 2 shows good agreement with safety regulations of scooter lights, which suggests that the optical channel parameters should be estimated separately for cases with greater and with less than 20° irradiance angle. In other words, a piecewise model with separate sets of parameters can more accurately describe the path loss behavior for VLC.

To obtain a piecewise path loss model, we start with the DC channel gain $H(0)$. When the transmitter-receiver distance is much larger than the size of the photo-detector A, the received irradiance can be approximated to a constant over the detector surface. We can derive the DC channel gain $H(0)$ according to Komine and Nakagawa [15]:

$$H(0) = \frac{(n+1)A}{2\pi D^\gamma} cos^n(\phi) cos(\theta), \tag{2}$$

where n is the order of the Lambertian model and is given by $n = -\frac{\ln 2}{\ln cos(\phi_{1/2})}$, where $\phi_{1/2}$ is the half power angle as defined previously. γ is the path loss exponent, ϕ is the irradiance angle, θ is the incidence angle, and D is the standoff distance between the transmitter and the receiver. If the heights of the LED transmitter and receiver are very similar

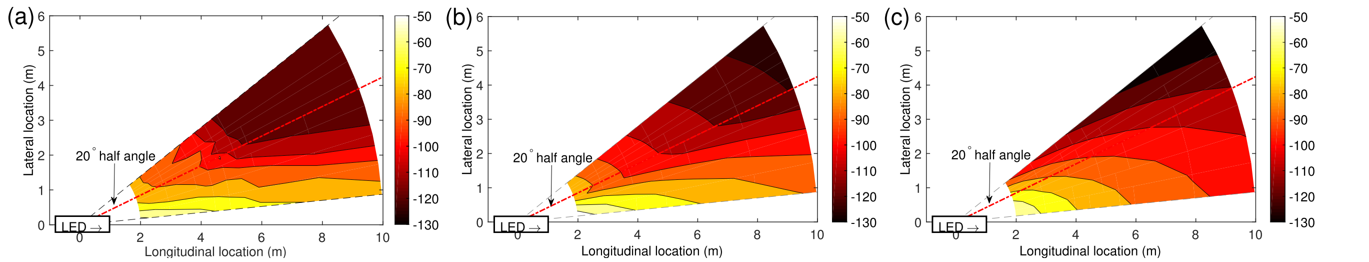

FIGURE 2. Contours of received power in dB: (a) empirical measured data; (b) predictions by the piecewise model; (c) predictions by the original Lambertian model; using a scooter taillight as transmitter [16].

(for example, communication between two passenger cars of similar heights), and the two vehicles have the same heading, i.e., $\phi = \theta$ (both referred as alignment angle in the following), the path loss exponent γ can be obtained by relating the received power P_R to the transmission power P_T as follows:

$$\ln\left(\frac{P_R}{P_T}\right) = \ln(A) - \ln(2\pi) + \ln\left(1 - \frac{\ln(2)}{\ln\left(\cos\phi_{1/2}\right)}\right) + \left(1 - \frac{\ln(2)}{\ln\left(\cos\phi_{1/2}\right)}\right)\ln(\cos\theta) - \gamma\ln(D). \tag{3}$$

Once we are given the transmitter with a particular half power angle $\phi_{1/2}$ and a photo-detector area A, all the terms in equation (3) except the last two will be constants, so one can use the measured P_T, P_R values and the alignment angle to obtain the path loss value experimentally. After performing least-square fitting, we arrived at a dual-angle model based on linear least-square fitting from the measured data: a path loss exponent of 2.597 when θ is less than 20° and a path loss exponent of 3.551 when θ is greater than 20° [16]. They are included in Fig. 1 for comparison purposes.

To validate the accuracy of the piecewise Lambertian model, Fig. 2 depicts the received power estimated from the dual-angle model based on Lambertian theory to compare with the empirical measurement data. The figures show that the piecewise model provides better estimates than the original Lambertian model.

Comparing this scooter piecewise dual-angle model with the dual slope model for RF, we observe that the VLC's dual-angle model is very similar to the dual-slope piecewise-linear model we described based on channel measurement at 5.9 GHz, as shown in Fig. 1. They are however caused by different factors. In the RF case, the path loss parameter values vary based on the distance, due to the two-ray propagation mechanism. On the other hand, in the VLC case, these values vary based on the alignment angles, due to the radiation patterns (which is somewhat regulated).

Path loss modeling between vehicle headlights and taillights is a complex problem. We used the data collected by Tseng *et al.* [17], where the authors conducted empirical measurement using a 2015 Toyota Corolla to characterize the loss in optical links. Fig. 3(a) depicts the measuring locations for the headlight radiation pattern measurements. The hardware setup is similar to the scooter taillight measurement, and the details are described in [17]. Since the height of the receiver is likely to have a significant impact on the measured radiation pattern, the measurements were performed at three different heights for the headlight (Fig. 3(b)-(d)) to mimic the three scenarios: receiver positioned at the same height, slightly above, and slightly below the height of the transmitting light module. Measurements were conducted for the left headlights.

Fig. 3 shows a clear asymmetry in the radiation pattern for a single headlight. For example, the left side appears to obtain significantly less received power than the right side. This is likely owing to the design to prevent strong light from blinding the drivers on the other side of the road. The asymmetry is more pronounced at larger receiver height. We also observe a cut-off angle between 0° and 3.75°.

While the received power decreases with larger transmitter-receiver distance, Fig. 3 shows that the dependence on irradiance angle cannot be overlooked. This result implies that even small relative lateral movements between the VLC transmitter and receiver may impose significant variation in terms of the received power. An ideal path loss should be able to model all of these effects. However, due to quite different headlight and taillight designs, including number of LEDs, reflection shield and plastic lens configuration, etc., it is unlikely that a comprehensive model can be designed so that it is applicable for all vehicle makes and models. A measurement based approach, such as the one outlined above, is preferred for link planning purposes.

From a link budget perspective, while radiation pattern and path loss can be treated separately in the RF case, *it is challenging to decouple the VLC link budget into light patterns and path loss exponent*. Moreover, while the revised piecewise Lambertian model works for the case of scooter VLC, it would be more difficult to build path loss models for other types of vehicles, as there exists a large number of parameters due to the more complex radiation pattern.

IV. NOISE AND INTERFERENCE

Besides the large scale signal attenuation modeled by the path loss, one cannot ignore other channel factors affecting signal

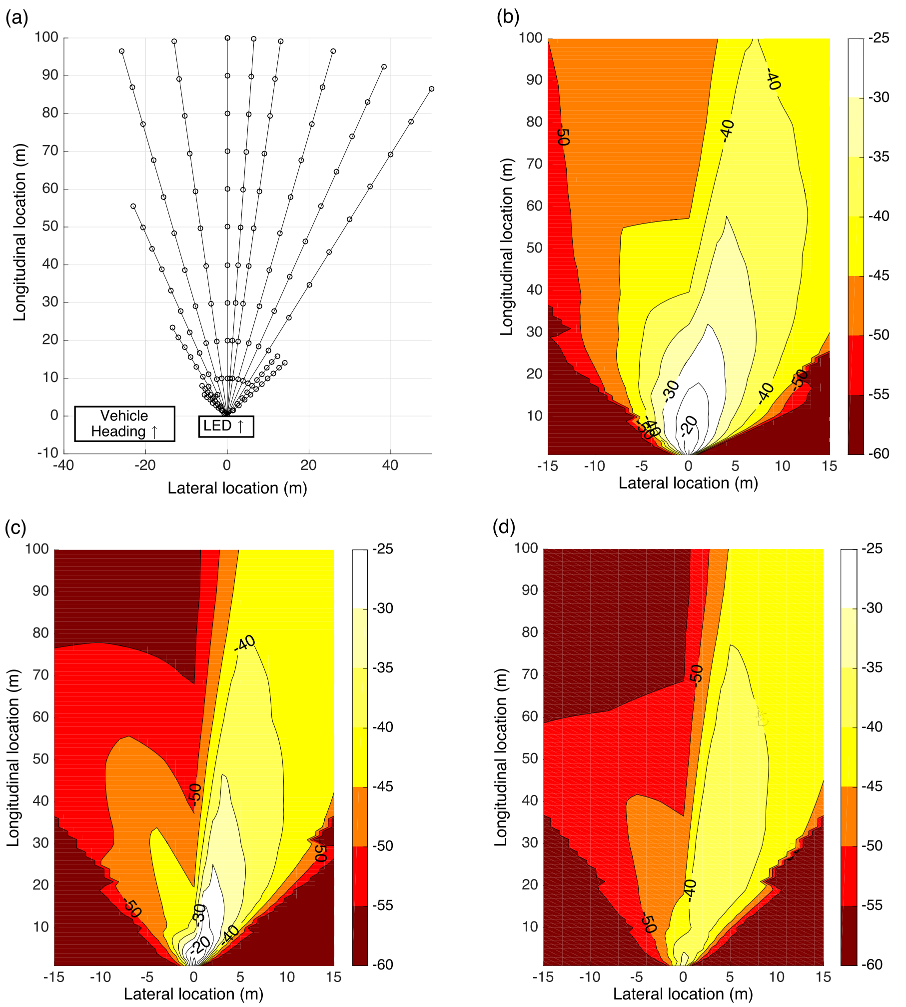

FIGURE 3. Vehicle headlight radiation patterns from empirical measurements [17]; (a) Measuring locations and data obtained with (b) receiver height at 55 cm (slightly below TX), (c) receiver height at 70 cm (same height as TX) and (d) receiver height at 85 cm (slightly above TX). The values in the plots represent the received optical power and are in decibel; the contour lines have 5-dB increments.

quality, such as noise and interference. RF communication in the 5.9 GHz frequency band has virtually no atmospheric or cosmic noise/interference sources; the main contributors are thermal noise at receiving antenna and the interference by other simultaneous transmissions. The power of thermal noise depends on temperature and bandwidth. An example calculation at 300 Kelvin and for a 10 MHz bandwidth yields a thermal noise value of -104 dBm. Common causes of interference by other simultaneous transmissions include the following:

- **Inter-Carrier Interference.** Most RF transmission schemes are based on Orthogonal Frequency-Division Multiplexing (OFDM), where the spacing between sub-carriers is designed such that each carrier experiences flat fading, even if the whole OFDM spectrum might experience frequency selective fading. Owing to the high mobility of vehicles, potential inter-carrier interference may occur when a Doppler spreaded signal leaks into the neighboring sub-carrier. The problem can be addressed by ensuring that there is sufficient spacing considerably greater than the maximum Doppler spread between neighboring sub-carriers.
- **High power interference from adjacent channel**. Since OFDM is a multi-carrier scheme, large power variations are possible among sub-carriers. High peak power may induce power leakage and interference into adjacent sub-carriers.
- **Interference due to imperfect receiver filters**. Imperfect receiver filters may also lead to interference, for example if the receiver is not tuned accurately to the desired frequency.
- **Interference due to random channel access**. Interference is also caused by the effects of random medium access control. For example, the DSRC standard employs CSMA/CA mechanism, which decides on transmission or back-off according to the perceived

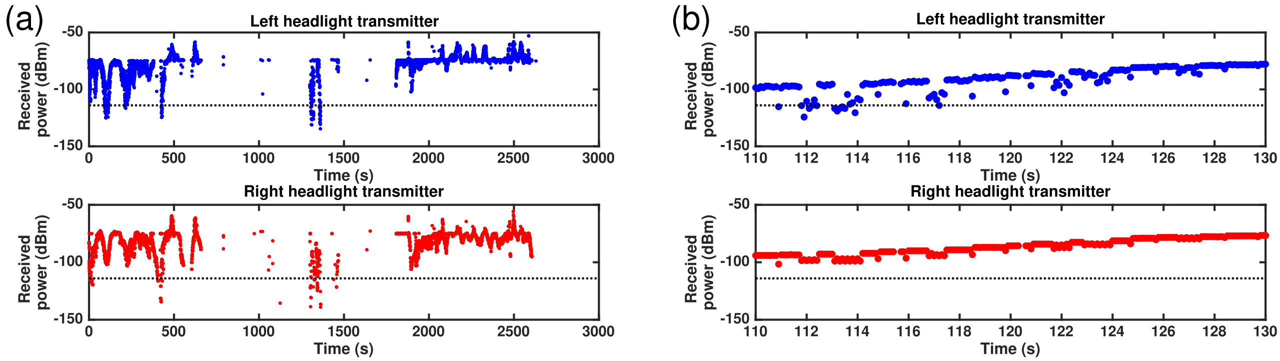

FIGURE 4. VLC received power for a set of vehicle mobility traces collected on A28 highway near Porto, Portugal. (a) plot for a period of 2600 seconds. (b) zoomed-in plot on a 20-second period.

interference and channel load, a design parameter. Interference from far-away transmitters in the same channel, while non-negligible, is often characterized as tolerable enough to initiate parallel transmission on the same resource, thus generating interference.

Related to the last point above is the impact of path loss on RF interference. If the separation distance between the transmitting and receiving vehicles is large, the high path loss will cause the receiver to be more sensitive to a nearby interferer vehicle. Known as the near-far effect, the Signal-to-Interference ratio (SIR) at the receiving vehicle may become too low that the receiver cannot decode the precise information from the radio waves.

In contrast to RF channels, vehicular VLC channels suffer from ambient light interference. Examples include solar radiation and artificial light interference.

- **Solar radiation** is one of the biggest interference sources during the day, which can easily saturate the detectors. One model of the background solar irradiance is SPCTRAL2 [18] based on weather and location related parameters. The background solar radiation can indeed be greater than the anticipated signal optical power (at microwatt level), so we need an effective way to isolate the signal from the intense background solar interference. SPCTRAL2 and other measurement based studies have demonstrated that photo-detectors usually capture mostly the DC component of solar radiation, often less than 200 Hz. A bandpass filter can help to eliminate their effect. The remaining part is the photo-detector shot noise induced by the intense solar radiation, because it behaves like white noise and cannot be mitigated by a bandpass filter. This remains a challenge for VLC system designs.
- **Artificial light interference** comes from light sources on the street (neon lamps, fluorescent lamps, light-based advertising boards, etc.) and is a major source of interference, particularly during nighttime. These interference sources cannot be avoided, especially in urban areas. In contrast to solar radiation, interferences from many of these sources are modulated. For example, a flashing advertising board may produce an electrical power spectrum extending to a certain frequency to interfere with the signal of interest. These modulations vary so much that it is hard to build general models to capture them, so the strategy to eliminate the interference often falls into separating the signal and interference in the modulation frequency band.

V. COHERENCE TIME AND LINK DURATION

In this section we compare RF and VLC channels with respect to coherence time and link duration, two metrics describing the temporal characteristics of the channel. Coherence time describes behavior of the channel in relative short term, which is useful for e.g., pilot design and channel estimation. On the other hand, link duration describes the availability of communication between the transmitting and receiving vehicles, which provides insight into the use cases that can be supported by each technology.

We describe below how we obtain the VLC received power data for the study presented in this section. We used GPS traces collected by Boban *et al.* [19] to compute VLC received power for a pair of vehicles on highway trailing each other as follows. Vehicles were traveling on a 20 km stretch of A28 highway near Porto, Portugal. We collected GPS traces and interpolated the mobility of vehicles so that each vehicle's location was recorded every 100 ms. We then calculated the received power by looking up the headlight results from Fig. 3 based on the relative angle and distance between vehicles as they traveled on A28. The resulting plots are shown in Fig. 4 for the transmitter in the rear (i.e., transmitting with its headlights) and the receiver in front with the photo-detector at its back bumper. The figure shows that the received power differs significantly between different transmit-receive pairs; this is the result of i) asymmetric transmit patterns of the headlights; and ii) the non-negligible difference between angles of arrival of different pairs. Furthermore, Fig. 4 shows there are "gaps" in the received power, which are a result of either distance above 150 m between the vehicles or the angles between the headlight and taillights that are large enough to result in insignificant amount of power at the receiver.

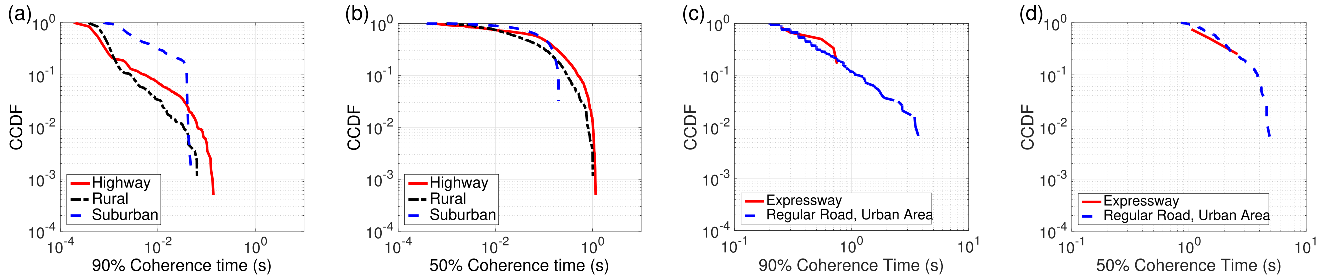

FIGURE 5. Coherence time comparison: (a) Example 90% Coherence time for RF channels; (b) Example 50% Coherence time for RF channels; (c) Measured 90% coherence time for VLC channels; (d) Measured 50% coherence time for VLC channels. Note that the X scale of the sub-plots for RF and VLC is different.

A. COHERENCE TIME

Coherence time describes the time duration that the channel's response is highly correlated (i.e., remains largely unchanged over time). From the measured received envelope of narrowband signals, one can calculate the autocorrelation function $\rho(\Delta t)$ to specify the correlation between the channel's response to a narrowband signal sent at a time t and the response to a signal sent at $t + \Delta t$. The commonly used 90% and 50% coherence time are then estimated from the 90% and 50% threshold level of the autocorrelation function [20]. Besides describing channel variations, the autocorrelation function is also useful for determining space diversity design parameters.

To analyze the coherence time of VLC channels, we combine the LIDAR trace collected in Taipei [17] and the measured received power of headlight transmitters shown in Fig. 3 to calculate how the received power changes over time, which is then used to calculate the 90% and 50% coherence time. To calculate coherence time for RF channels, we use the narrowband channel measurements reported by Cheng *et al.* [13].

TABLE 1. Coherence time comparison.

V2V Channel	Freeway		(Sub) Urban	
	90%	50%	90%	50%
RF, DSRC [13]	0.629	99.4	3.6	103
VLC (video) [21]	-	-	33	300 $\sim$ 333
VLC (measurement) [22]	120.3	2656.7	46.8	164.7

All numbers are in milliseconds and represent medians.

Fig. 5 and Table 1 compares the coherence time of vehicular RF and VLC channels. We observe that, for both 90% and 50% coherence time, the values of the VLC channels are at least an order of magnitude larger than that of the DSRC channels. The main reason for this result is that VLC has significantly less multipath effects, as its effective path loss component is larger and the received power predominantly arrives through line-of-sight (LOS). We can also observe that, compared to the freeway scenario, the DSRC channels of the suburban scenario stay invariant longer. This is due to the increase of relative speed between the transmitter and receiver vehicle causing severe Doppler spread and fast received power variation in the former. However, the opposite trend is observed for VLC. Due to more stable vehicle behavior on freeways, the changes of surrounding environment and relative vehicle positions are less frequent compared to the urban scenario, resulting slower time variation. These show that in the challenging freeway scenarios VLC could complement DSRC to provide a more stable and reliable communication link.

B. LINK DURATION

For a transmitter and a receiver, we define the link duration as the time during which the largest message inter-arrival time (time between two successfully received messages) is smaller than some predefined period t. In this paper, we use $t = 1$ second. In other words, the link is considered as active if at least one message is correctly received within each time period t. VLC communication is highly directional, which limits the applicability of VLC to car-following scenarios, where relative mobility between transmitter and receiver is low and the direction of their travel is the same. For those applications, the connection duration of VLC can be on the order of minutes. Conversely, for scenarios where vehicles are moving in opposite directions or on perpendicular roads, VLC link duration is orders of magnitude shorter than in the car following scenarios. For this reason, we compare the connection duration for VLC and RF in terms of car following scenarios only.

We calculate the link duration for VLC based on i) a set of LIDAR traces collected in Taipei [17]; and ii) GPS traces described earlier in this section, with vehicles traveling in highway and urban scenarios in Porto, Portugal (Fig. 4). Note that for both traces, we assume the ambient noise of -114 dBm according to [17]. If the computed received power is below the ambient noise level, we assume that the link is broken. We use DSRC (IEEE 802.11p) measurements described in [23] to calculate RF connection duration. Fig. 6(a) shows the connection duration for RF in same-direction urban and suburban Pittsburgh during both daytime (high vehicular density) and nighttime (low density) conditions. In both cases, the duration is in the order of seconds, with urban scenario having longer duration due to frequent stops at traffic lights and lower average speed.

TABLE 2. Average VLC link duration from car-following traces.

Traces	Type of data	Link duration (s)
Downtown Taipei, Taiwan	LIDAR	13.49
Highway scenario, Porto, Portugal	GPS	18.84
Urban scenario, Porto, Portugal	GPS	10.12

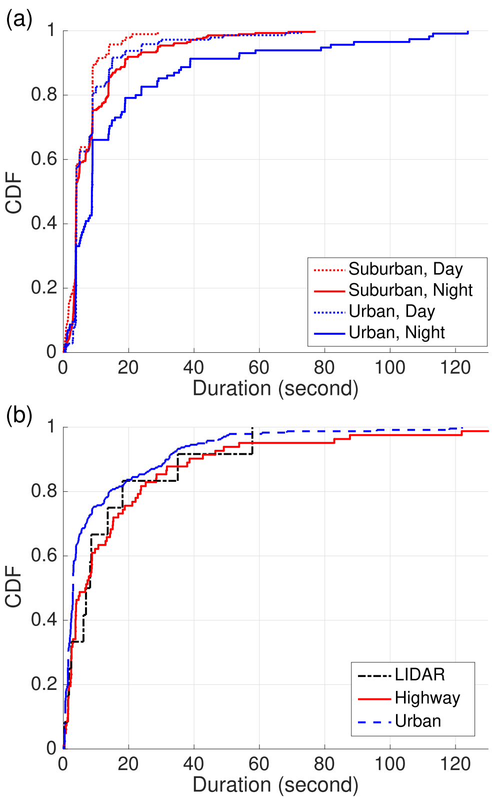

FIGURE 6. Link Duration: (a) RF (DSRC) and (b) VLC.

Table 2 and Fig. 6(b) shows that VLC link duration in highway is on average longer than in urban environment. The main contributor to prolonged link duration on highway is same-direction motion of vehicles at similar speeds. In urban environment, the most significant contributors to longer uninterrupted links are low average speeds and frequent stops at intersections, which result in frequent bumper-to-bumper communication.

Comparing results for VLC (Table 2 and Fig. 6(b)) and RF (Fig. 6(a)), we can see that they result in similar link duration. Note that this comparison assumes somewhat different configurations of links; in case of VLC, the links are purely LOS, whereas RF links can be both non-line-of-sight (NLOS) and established over a larger distance (up to 500 m, compared to 150 m by VLC). Therefore, we conclude that VLC can provide comparable link duration to RF, in specific case of LOS, same-direction, and short-distance scenarios. In all other situations (e.g., non car-following scenarios and same distance ranges), RF links will exhibit longer link duration than VLC.

VI. DISCUSSION

A. SUMMARY OF FINDINGS

In this paper, we presented a comparative study of vehicular communication channel delivered by RF and by visible light. The findings obtained from the study are summarized below:

- **Coherence time**: in all relevant environments, VLC coherence time is *an order of magnitude larger* than RF coherence time. Since the channel stays stable for longer period of time, VLC requires less frequent channel estimation and results in an overall more stable link. This is particularly relevant for use cases such as platooning and C-ACC (ETSI [24]), which require continuous and stable V2V links; combined with inherently directional motion of vehicles in a platoon, high coherence time ensures that VLC link is robust enough to support these use cases. Additionally, higher coherence time implies that VLC is a good technology for ensuring fault tolerance, since it can act as a ''fall-back'' solution when RF channel is congested or otherwise disrupted. More details can be found in Section V-A.
- **Link duration**: we show in Section V-B that VLC link duration is (considerably) shorter than RF when vehicles are not following each other. However, in car-following scenarios, VLC link duration is maintained for a long period of time, again indicating that VLC can be used for V2V communication in use cases that happen in car-following situations: platooning, emergency braking, overtaking, etc [24].
- **Interference**: the interference patterns for VLC are quite different than that of RF: while RF can suffer from interference from far-away concurrent transmissions, the number of interferers in case of VLC is reduced due to LOS and directional communications. However, other kind of interference sources affect VLC: weather, sunlight during the day and artificial light sources at night. While these interference affect the channel and thus the system performance, the impact of these effects is insignificant for radio channels below 6 GHz. It is worth noting that some VLC interference sources (e.g., solar radiation and artificial light) can be limited by using a camera-based system [25] that can spatially filter out areas which are not occupied by the transmitting light. In addition, since due to being completely blocked by opaque objects, the interference for optical channel is reduced to LOS-only transmissions.

B. IMPLICATION TO C-ITS APPLICATIONS

In previous section, we have discussed different characteristics of RF and VLC channels in the context of vehicular communications. A very important insight from these results is that radio and optical channels can serve as *complementary transmission media* that greatly improve coverage and reliability for many C-ITS applications. Instead of viewing VLC as a competing technology, we argue that it is a complementary technology to RF communication technologies; combined with RF technologies, VLC has the potential to reduce interference and improve overall system throughput. The following points summarize the most important observations for applications stemming from propagation channel perspective.

- **Range**: For range dependent applications, one might favor radio channel for longer range and optical channel for shorter range applications.
- **Data rate**: While radio channel works better than optical channel for applications that need to support link duration in case of high user mobility, *optical channel has the potential to deliver a high per-link bit rate and can even sustain long link durations in some scenarios (e.g., red light or slow traffic)*.
- **Complexity**: Owing to the intensity modulation / direct detection scheme, *the receiver signal-processing complexity of vehicular VLC is much lower than its RF counterpart*, and the optical channel may be favored for applications to maximize the aggregated system capacity with minimal receiver complexity.
- **Coverage**: since it is highly directional, VLC communication ensures coverage of only a small area. Therefore, it is less suitable for use cases which require omnidirectional transmission, such as cooperative awareness or other broadcast-based applications.
- **Cost**: Radio-based solutions have a higher initial deployment costs. Vehicular VLC has lower initial cost as LEDs are common in vehicles today and additional electronics to enable VLC is inexpensive. In addition, since VLC transmitter may modulate LEDs at very high frequencies to appear invariant as perceived by human eyes, dual usage of LED light sources for lighting and vehicular VLC purposes is possible.

C. APPLICATIONS EXAMPLES

In addition to the above discussions, we also study a few application use cases.

1) PLATOONING

In platooning applications, a lead vehicle is followed by a group of vehicles that can adjust their positions automatically. This application relies heavily on efficient data exchange, as the United State Department of Transportation (USDOT) recommends a transmission latency of 20 ms in platooning applications [26].

While RF based V2V communications can provide the range and data rate needed for platooning transmissions, the solution can suffer from interference especially in dense traffic scenarios, which can cause unwanted long transmission delays for platooning, and get into performance issues due to the broadcast storm problem, disrupting real-time information dissemination. On the other hand, VLC links depend on the existence of uninterrupted LOS, so high car density scenarios would result in an increased number of optical links between vehicles, which could improve data delivery since multiple paths become available. VLC's immunity to electromagnetic interference can serve as a good complementary technology. In addition, since VLC is highly directional, spatial reuse is possible for VLC to accommodate a larger number of vehicles without interference compared to the RF case. It should be noted that there are security vulnerabilities of IEEE 802.11p and visible light communication based platoon as discussed in [27] and [28].

2) SCENARIOS REQUIRING ACCURATE RELATIVE POSITIONING

Due to its ability to provide precise relative positioning between vehicles [29], VLC can be used to enhance any use case that relies on estimating accurate relative position of the involved vehicles. Some examples of such use cases are: platooning [30], C-ACC [24], Left-Turn Assist,[1] and Vulnerable Road User (VRU) use cases [30]. Most V2X use cases rely on satellite based systems (e.g., GPS) for positioning. Positioning error of these systems is of the order of meters in open space and tens of meters in case of urban multipath environment [31]. This makes lane-level precision difficult and any use case relying on relative position between vehicles hard to achieve without additional sensors. While enhancements can be made by using camera [31] or radar/LIDAR systems, VLC provides a cost-effective positioning system that can be used in conjunction or as an alternative to these systems.

VLC can improve on the positioning estimate of satellite based systems (e.g., GPS) in situations where: i) vehicles are near each other; ii) there are a large number of vehicles in proximity of each other; and iii) where the precision of satellite based systems is impaired (e.g., urban areas). For example, VLC can be used to estimate and adjust the inter-vehicle distance in a platoon or assist in vehicle merging in case of C-ACC. Furthermore, it can enhance Vulnerable Road User (VRU) use cases [30], where it can help determine the precise trajectories of VRUs (e.g., motorcycles or bicycles) in relation to the car, particularly in situations where there is a multitude of VRUs in vicinity and false positive notifications occur easily.

3) SCENARIOS WITH RELATIVE MOBILITY

As we discussed, VLC does not perform well for NLOS scenarios. The relative mobility between vehicles is likely to disrupt LOS links for VLC, and it is likely to pose an effective limit on the communication range. Published results, both experimental [4] and theoretical [32], have mostly shown that reliable communications take place only with a range no farther than 50 meters. For cases requiring farther range, VLC-based solutions could be used as a complementary technology.

[1] http://www.nhtsa.gov/staticfiles/rulemaking/pdf/V2V/Readiness-of-V2V-Technology-for-Application-812014.pdf

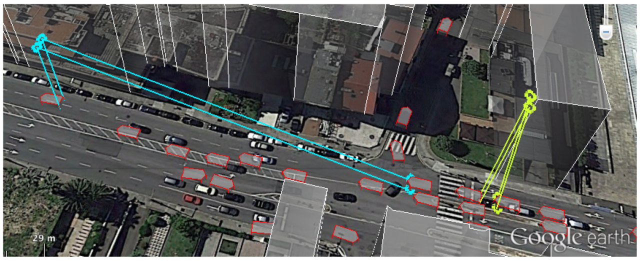

FIGURE 7. Visualization of received power for VLC communication (transmitters: headlights; receivers: located at taillights) as implemented in GEMV^2 simulator [23]. Warmer line colors and receiver circles positioned higher represent higher received power.

D. IMPLEMENTATION OF VLC CHANNEL MODELS IN A LARGE SCALE PROPAGATION SIMULATOR

In order to study the propagation-related aspects of VLC communication (e.g., connection duration and coherence time) in a repeatable manner and on a large scale, we implemented the received power calculations of VLC channels in GEMV^2, a geometry-based, efficient propagation model for V2V and vehicle-to-infrastructure (V2I) communication simulator [23]. Specifically, the code[2] implements received power calculations via two approaches:

- According to the Lambertian model shown in eq. 3, with an option to vary the half power angle and path loss exponent (e.g., according to the measurement-based parametrization).
- According to tabulated data lookup, with the data collected during the measurement campaign reported in [17] and depicted in Fig. 3. Both headlight and taillight measurements were collected and tabulated. The received power is interpolated between measurement points shown in Fig. 3(a) and quantized to a square grid with 1 m resolution with rounding to the nearest dB value.

Each of the two approaches has its advantages: while the code implementing eq. 3 gives flexibility to test received power for a range or parameters, the lookup based approach provides a more realistic calculation of received power for links similar to those analyzed in measurements (i.e., headlights and taillights of passenger cars of specific radiation and elevation). Irrespective of the approach to calculate received power, the simulator implements VLC channels so that they depend on both the distance between transmitter and receiver and the angle between them. Fig. 7 shows the visualization of power at the receiver located near the taillight, with the headlights as transmitters, for two pairs of transmit-receive vehicles. The simulator implements the blockage of VLC links by other vehicles, buildings, or trees, rendering the power in non-LOS cases insignificant, thus allowing for a time- and space-consistent deterministic analysis of VLC link behavior.

[2]The source code shall be available free of charge and openly distributed at http://vehicle2x.net at the time of publication of the manuscript.

VII. CONCLUSION

We highlight the significant role the propagation channel plays in communication systems. While there exist many excellent studies on RF channel modeling [11], there are many exciting opportunities for VLC channel characterization in the outdoor, vehicular context. Comparing the different channel properties helps us to gain a deeper understanding of both channels. By examining the RF and VLC systems through the lens of the propagation channel, we can better appreciate the two complementary transmission methods in their ability to serve the diverse application needs for future intelligent transportation systems.

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