such as error control, device association and disassociation, channel access etc [9]. As far as channel access is concerned, in essence, the standard utilizes random access with simple backoff or random access based on CSMA/CA. A comprehensive analysis of IEEE 802.15.7 can be found in [5], [10].

There is a small number of analytical and simulation studies in the literature providing insights into the MAC-related metrics for VLC. For prototype implementations this number is even smaller, as those studies rarely go beyond the PHY in order to reduce complexity and the associated costs [5]. Speaking of analytical studies, Nobar et al. [9] use a Markov chain model and MATLAB simulation to investigate the performance of the CSMA/CA in the IEEE 802.15.7 standard with respect to various metrics, under saturated traffic. As expected, their results show that the collision probability increases with the number of the nodes in the network. Another study dealing with collisions in VLC has been conducted by Ley-Bosch et al. [11]. The authors inspect the implications of the hidden terminal problem in a star topology scenario. They reported that in a network with just four nodes packet loss reaches almost 100 % under 20 % channel load.

The papers mentioned above investigate wireless personal area networks based on VLC. As such, their findings may not apply to the vehicular environment. Liu et al. [12] simulate a V-VLC network of 30 vehicles driving in a three lane road. The MAC layer of the vehicular nodes is based on an ALOHA protocol. The ratio of colliding packets was at least 24 % for inter-vehicle distances between 0–100 m; and the collisions have a decreasing trend for distances larger than 30 m. Yu et al. [13] consider V-VLC for safety applications on the road. One of their findings is that the number of the nodes in the collision domain of a vehicle ranges between 5–8, depending on the detection accuracy. Generally speaking, this estimation is correct. However, at specific times and in certain geometric setups, this number can be much larger as we show in this paper, thus, requiring more sophisticated access control.

III. CRITICAL INTERFERENCE SCENARIO FOR V-VLC

Based on the findings of the aforementioned papers, one can argue that due to the small collision domain of V-VLC, there is no need for coordinated access to the channel, or for a MAC layer altogether. However, because of the dynamic nature of the vehicular environment, we hypothesize that a driving vehicle will frequently encounter situations where multiple LOS links exist to a single receiver. Such a scenario is illustrated in Figure 1 showing a section of *Boulevard d'Avranches* in the city of Luxembourg. The lines represent the LOS links between the headlight of the transmitting vehicle $\mathrm{V_{TX}}$ (colored gray) and the other vehicles in the road. In this example, we see 11 LOS links in total; three towards the vehicles moving in the same direction as $\mathrm{V_{TX}}$, and eight towards the vehicles moving in the opposite direction of $\mathrm{V_{TX}}$. These numbers are substantially larger than the ones reported in the literature and require further attention. Additionally, if all of the vehicles in this scenario transmit concurrently via VLC, the number of the links detected at a receiver might be large enough to disturb the communication between the different parties. These are undesirable situations, especially if V-VLC is used for safety-related applications, and they indicate that there are cases where we can benefit from a MAC layer in V-VLC. In the following, we quantitatively investigate such situations and also look at the potential impact on V-VLC in terms of interference-based collisions.

Figure 1. Illustration of a typical scenario with a large number of Line Of Sight (LOS) links. This example shows a 160 m section of *Boulevard d'Avranches* in Luxembourg. The transmitting vehicle $\mathrm{V_{TX}}$ is colored in gray.

IV. QUANTITATIVE ASSESSMENT OF V-VLC INTERFERENCE SITUATIONS

A. Models and Scenario

To investigate the recurrence of LOS links in V-VLC scenarios, and assess the severity of the interference caused by them, we base our study on realistic simulations comprising two main components, i.e., the vehicle mobility model from the LuST scenario and the V-VLC simulation model [14] for the Veins vehicular networking simulator [6]. The LuST scenario [7] is a well-known simulation model of the road traffic in Luxembourg. It provides an accurate representation of the road topology of the city, including highways, arterial and residential roads. Also, it models the location of the buildings, which is relevant to calculate signal shadowing conditions. Most importantly, the scenario provides 24-hours of traces modeling the traffic demand and mobility patterns of vehicles in microscopic level.

To simulate the communication between the VLC-equipped vehicles in our scenario, we rely on our Open Source VLC model for Veins [14]. The VLC model is based on empirical measurements of the optical power emitted from the LED-based light modules of a vehicle. It consists of radiation patterns for the headlight and the taillight of a vehicle. The model calculates the Received Signal Strength (RSS) at a receiver, if the receiving vehicle is in the communication range of the transmitting VLC module. Model fitting was used to extrapolate the RSS beyond empirical measurement samples.

B. Investigating V-VLC LOS Links

In a first set of simulation experiments, we investigate the potential number of receivers of a VLC transmission. We run the LuST scenario for the whole 24 h interval. The maximum number of the vehicles in the scenario was about 5000 during rush hour periods. All of the vehicles in the scenario are equipped with VLC-enabled lighting modules. Every second, one randomly (uniformly distributed) selected car performs a VLC transmission, resulting in 86400 samples in total. This guarantees that there is no other interfering communication. We also simulate obstacle shadowing, meaning the buildings

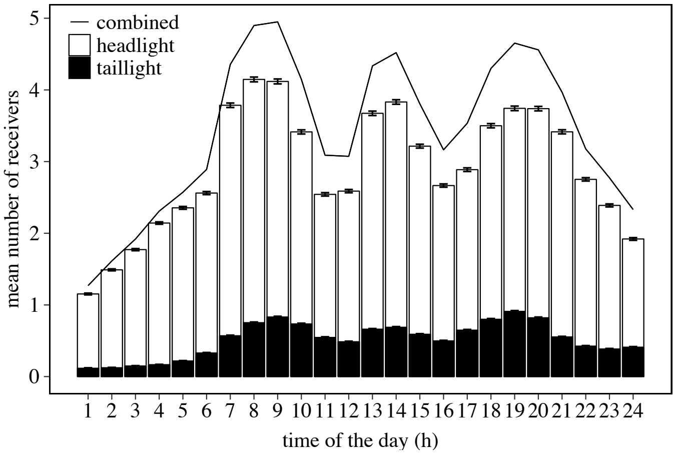

Figure 2. Mean number of receivers of a V-VLC transmission differentiated by the transmitting light module. The error bars (often indistinguishable due to their small size) indicate the 95 % confidence interval.

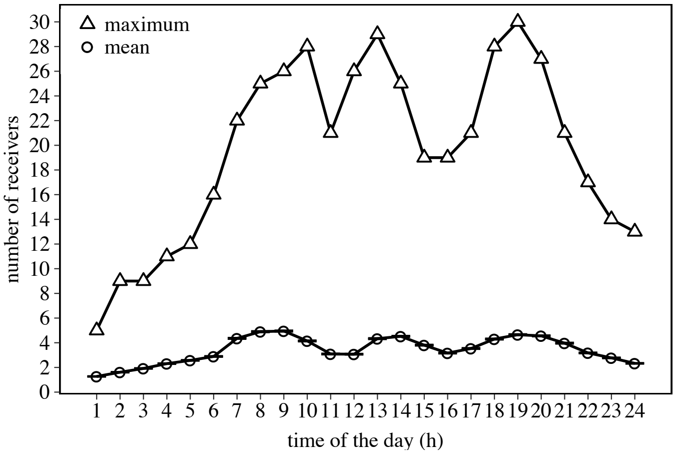

Figure 3. Mean and maximum number of receivers of a V-VLC transmission. Similar to Figure 2, the error bars indicate the 95 % confidence interval for the mean.

and the vehicles intercepting the LOS will fully attenuate the signal. Lastly, to ensure statistical confidence, each simulation setup is repeated 10 times

In Figure 2, we show the mean number of recipients of VLC transmission in our simulation. As expected, the number of the recipients is higher during rush hours at 8–9 AM and 7–8 PM. If we look at the mean number of recipients differentiated by the headlight and the taillight, we see that for the packets transmitted by the headlight there are more recipients compared to the transmissions by the taillight. This is due to the asymmetrical communication ranges of the headlight and the taillight [15]. Since the headlight has higher optical power, its radiation pattern is larger and, thus, has more recipients in its range. Furthermore, the total number of recipients indicated by the black line in Figure 2 shows that a V-VLC transmission has at most five recipients on average. This makes for a small collision domain compared to the omnidirectional RF communications, and is in the range of the values presented in [13].

However, further investigation on the recipients count shows that this number can be much higher than the mean values indicate. In Figure 3, we plot the mean and the maximum number of recipients of a VLC transmission for each simulated hour in the scenario. The mean value is the same as the one combining the means of the headlight and the taillight in Figure 2. Looking at the maximum values for each time of the day, however, we see that a VLC transmission has much more recipients than initially expected. In sporadic cases, the number of the LOS links from and towards a vehicle is indeed much larger than previously reported in the literature.

It is important to mention that the road topology has great influence on the occurrence of the LOS links. An example is shown in Figure 1. Here, V_{TX} is positioned at a slightly tilted angle. This positioning causes the headlight's radiation pattern to fully cover the road in front of it. This allows the light beams to reach receivers of many other vehicles. If in similar multiple LOS scenarios all of the vehicles transmit concurrently, the number of the overlapping links at the receivers can be quite large, i.e., being able to cause interference and affect the communication quality.

C. Impact of Multiple LOS Links in V-VLC

To investigate the impact of such interference scenarios, we designed a second set of simulations. Instead of using the whole city of Luxembourg, we only simulate the traffic in the section of *Boulevard d'Avranches* as shown in Figure 1. We now have every vehicle performing periodic safety *beaconing* at a frequency of 10 Hz (this corresponds to the typical 100 ms safety latency). The payload of the transmitted packets is parametrized to model different applications. One configuration has 350 byte packets as in Cooperative Awareness Messages (CAMs), whereas the other configuration has 8192 byte payload according to the maximum size allowed in the IEEE 802.15.7 standard, which corresponds to a relatively low data rate of 80 kB/s. The V-VLC channel was configured to On-Off Keying (OOK) modulation and a maximum data rate of 6 Mbit/s [14].

The road we simulate is approximately 160 m long and consists of five lanes. Looking from the intersection connecting *Boulevard d'Avranches* to *Boulevard de La Petrusse*, three of the lanes are incoming and three are outgoing lanes. Moreover, the maximum number of the vehicles in this scenario is about 35–40 during the morning rush hour, and 55–60 during the evening rush hour. In both cases, the number of V-VLC LOS links is slightly below three on average, whereas the maximum number easily reaches 15. This is a relatively large number regarding the length of the road.

We are primarily interested in the impact of multiple LOS links on the reception of the packets transmitted in the scenario. Our findings show that the ratio of the packets lost due to interference, i.e., packet collisions, was negligible for both packet sizes during non-rush hours. This is expected due to the low number of V-VLC nodes at these times. To further inspect the collisions, we consider packet transmissions under high-load conditions.

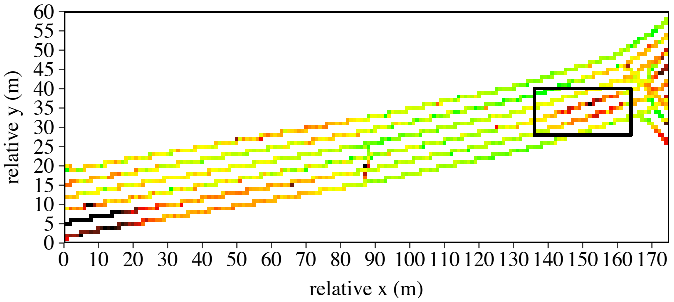

Figure 4. Two-dimensional heatmap of packet collisions occurring during the morning rush hour in the simulated section of *Boulevard d'Avranches*. The box indicates one of the hotspots with an overall high number of collisions.

Figure 4 shows the heatmap of the 8192 byte packets transmitted between 8–9 AM. The color-coding indicates the ratio of the packets lost due to collisions where darker colors represent more collisions and lighter colors the opposite. Looking at the plot, we notice *hotspots* in the scenario where more collisions occur, and that these hotspots are usually located close to the intersections. Presumably, as the vehicles approach an intersection the light beams emitted from the headlights of the vehicles on the other approaching lanes interfere with each other, which in turn contributes to more collisions.

We thus assessed the collisions in one of such hotspots (cf. Figure 4). Figure 5 shows the ratio of the packets differentiated by reception status for each time of the day for 8192 byte packets. Based on the reception status, a packet can either be received or lost due to collisions. We considered the ratio of receptions and collisions for the 350 byte packets as well. The number of collisions was below 1 % even during rush hours, thus, these results are not shown in Figure 5. On the other hand, for the larger packets this number is more critical. Because of the reduced traffic during the morning hours, there is not much interference, hence negligible packet collisions. However, at later times the number of collisions increases going up to 13 % during the rush hours. This is a substantial collision ratio, especially having in mind the still low data rate of the simulated application.

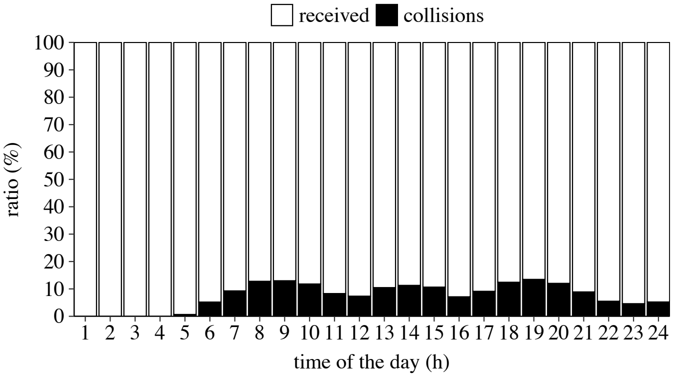

Figure 5. Ratio of the 8192 byte packets in the hotspot area differentiated by reception / collision status.

V. CONCLUSION

Our results confirm that Vehicular VLC (V-VLC) is a viable candidate for vehicular applications, particularly when using small packet sizes such as CAMs.

Based on our investigation, however, we conclude that, if V-VLC is to be used in applications with high throughput demand (such as look-ahead or entertainment applications), there is a high risk of substantial packet loss due to interference and collisions in certain geographical areas: In a realistic simulation setup using the Luxembourg mobility model, we are able to show that, at some intersections and gentle bends in roads, the number of transmitters seen at a single receiver can easily grow up to 30.

We thus argue that, contrary to the literature, the design of a dedicated MAC protocol for V-VLC is a must and can substantially improve the communication performance when successfully dealing with coordinated channel access.

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