A Location-Aware Cross-Layer MAC Protocol for Vehicular Visible Light Communications

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***Abstract*—Vehicular Visible Light Communications (V-VLC) has emerged as a technology complementing RF-based Vehicle-to-Vehicle (V2V) communication. Indeed, such RF-based protocols have certain disadvantages due to the limited radio resources and the, in general, omnidirectional interference characteristics. Making use of LED head- and taillights, V-VLC can readily be used in vehicular scenarios. One of the challenging problems in this field is medium access; most approaches fall back to ALOHA or CSMA-based concepts. Thanks to modern matrix lights, V-VLC can now also make use of Space Division Multiple Access (SDMA) features. In this paper, we present a novel approach for medium access in V-VLC systems. We follow a location-aware cross-layer concept, in which dedicated light sectors of matrix lights are used to avoid interference and thus collisions. We assess the performance of our protocol in an extensive simulation study using both a simple static scenario as well as a realistic urban downtown configuration. Our results clearly indicate the advantages of our location-aware protocol that exploits the space-division features of the matrix lights.**

***Index Terms*—Vehicular Visible Light Communication, V-VLC, Vehicle-to-Vehicle Communication, V2V, Medium Access, Spatial Multiplexing, Matrix Headlight**

I. Introduction

Traditionally, the majority of the Vehicle-to-Vehicle (V2V) communication systems in the literature rely on RF-based technologies [1], like IEEE 802.11p [2] or Cellular V2X (C-V2X) [3], [4]. However, RF-based technologies can impose certain disadvantages. For instance, if the communication is realized using typical omnidirectional antennas, the signals can interfere with each other due to the relatively large collision domain of such antennas. This, in turn, results in increased network congestion, affecting reliability and application performance [1].

On the other hand, stimulated by the wide adoption of LED-based lighting modules for exterior lighting in modern vehicles, Vehicular Visible Light Communications (V-VLC) has emerged as a viable communication technology for V2V communications [5]–[7]. V-VLC has a set of intrinsic properties which can overcome shortcomings of RF-based communication as a complementary technology [3], [8]. Namely, the LED-based headlights and taillights have optical components which focus the light beams in a certain direction. This directionality leads to a relatively smaller collision domain and also permits the spatial reuse of the modulation bandwidth. Furthermore, the physical characteristics of the light wave and its interaction with the objects in the environment impose that V-VLC is a predominantly Line Of Sight (LOS) technology. Hence, there is an increased resilience against multipath fading due to the typically weak reflections [5].

Besides the aforementioned characteristics, there are also hardware and system-level solutions that can be exploited to improve V-VLC's performance. For instance, many approaches in the literature deploy optical components in front of the receivers to improve signal reception at the Physical Layer (PHY) [9], [10]. Additionally, V-VLC can benefit from Adaptive Front-Lighting System (AFS) with LED matrix headlights [11]. These systems optimize road illumination by selectively turning on (or off) a subset of the LEDs based on sensory input from an on-board camera. The possibility to control a smaller group of LEDs with strictly separated illumination sectors can allow communication via more fine-granular, spatially divided channels. This reduces multiuser interference, increases bandwidth efficiency and can help medium access.

Actually, the combination of V-VLC's characteristics (e.g., directionality and LOS), the space-division feature of the LED matrix, and the possibility of learning neighboring vehicles' locations (e.g., via an on-board vision system, GPS, Vehicular Visible Light Positioning (V-VLP) [12], or another communication technology), provides a unique opportunity for designing simple but efficient Medium Access Control (MAC) protocols for V-VLC. In this regard, many works in the literature still assume simple ALOHA access schemes; The IEEE 802.15.7 standard [13], [14] supports CSMA/CA. While, there exist works that focus on specific optics and the LOS properties of the signal [9], [10], [15].

In this paper we present a location-aware cross-layer MAC protocol for V-VLC. Our MAC protocol exploits the Space Division Multiple Access (SDMA) feature of modern LED matrix headlights and uses location information of the potential communication partners to select the optimal subgroup of LEDs to transmit towards a communication partner. Moreover, it deploys a simple collision avoidance scheme to minimize collisions. We investigate the performance of our protocol in both a simple static scenario and in a dynamic realistic urban environment. In the static scenario, the collision avoidance protocol is able to mitigate collisions, whereas in the realistic scenario our approach reduces the number of collisions by roughly 50 %.

Our main contributions can be summarized as follows:

- We propose a novel, location-aware cross-layer MAC protocol for V-VLC communication;

- we discuss the advantages of SDMA-based V-VLC communication for improved spectral efficiency; and
- we present the results of an extensive simulation-based performance evaluation comparing our protocol to ALOHA and classical CSMA.

II. Related Work

As a relatively new technology, the most of V-VLC research so far has focused on physical layer aspects of V-VLC, such as channel characterization and modeling, as well as modulation and coding schemes [5]. However, as V-VLC is maturing, there is more research interest for higher layer protocols, in particular for medium access. The main reason why medium access for V-VLC has not drawn much attention from the research community is the assumption that, as a directional LOS technology, V-VLC has a small collision domain and a relatively small one-hop neighborhood [16]. However, it has been shown that in certain scenarios (e.g., close to intersections, where the vehicle headlights face each other), V-VLC can suffer from severe interference, and it can benefit from a dedicated MAC protocol [17], [18]. In the following, we briefly study some of the MAC-related publications from the V-VLC literature.

Liu et al. [7] simulated a V-VLC scenario with 30 vehicles driving on a three-lane road. The nodes make use of an ALOHA-based protocol for medium access. The simulation results show that for inter-vehicle distances between 0–100 m at least 24 % of the packets collide, whereas the collisions decrease for distances larger than 30 m.

In a similar study, Masini et al. [19] adapted the physical and medium access layers specified the IEEE 802.15.7 standard [13], [14] for V-VLC. By exploiting the reverse communication link for immediate feedback between two vehicles, they modify the original CSMA/CA to implement collision detection. As a result, they realize a full-duplex link. Their results show that the full-duplex CSMA/CD approach achieves significant collision reduction and improves packet delivery. However, it is unclear if the used model accounts for the transmit power asymmetry between headlights and taillights, which has a large impact on V-VLC. This effect is taken in consideration by Eldeeb et al. [20], who also investigated the performance of V-VLC based on the IEEE 802.15.7 standard [13]. They use more realistic models that account for headlight's asymmetric radiation pattern, different weather conditions and road reflections. The results show that the number of relaying nodes in the network and the size of the contention window has a profound impact on the system throughput, as do the weather conditions.

Apart from pure protocol-based solutions that address medium access for V-VLC, there are other approaches that benefit from the specific hardware, i.e., optics and lighting modules. For example, Shen [9] and Tebruegge et al. [10] propose the use of special optics in front of the receivers that can spatially filter out interference and noise sources. These receiver-side techniques can indeed help medium access for V-VLC, and substantially simplify protocol design.

Likewise, Tebruegge et al. [11] conceptually show the benefits of LED matrix headlights, and are able to reduce multi-user interference below the noise level, while increasing the signal strength accordingly. The advantages of this technology have further been demonstrated for a platooning application in straight and curved highway scenarios [15].

Neither of the aforementioned works, however, implement a MAC protocol that can take advantage of the space-division capability of LED matrix headlights. In the present work, we fill this gap by proposing a MAC protocol that, among others, takes advantage of LED matrix headlights to improve medium access for V-VLC.

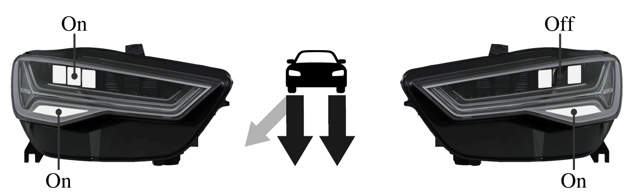
III. Cross-Layer MAC Protocol for V-VLC

In the following, we introduce the core concepts of our protocol. We first describe the concept of sectorizing the LED matrix headlights, and then the medium access algorithm.

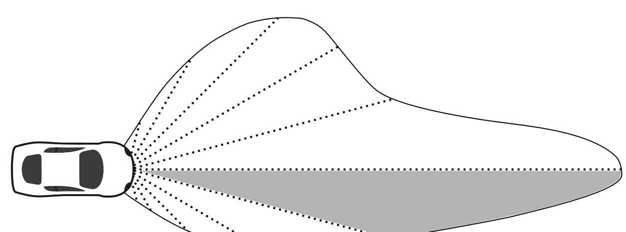
A. LED Matrix as a Sectorized Transmitter

The original function of a vehicle's headlights and taillights is to provide optimal forward illumination and signaling in all road and weather conditions. However, with the wide adoption of LEDs as the primary source of illumination, headlights and taillights can now be used for communication via Visible Light Communications (VLC), as long as their primary functionality is not hindered.

From the communication perspective, the lighting modules of a vehicle effectively serve as antennas, and their radiation patterns represent the antenna pattern. State-of-the-art forward illumination technologies, like LED matrix headlights, provide an opportunity for optimized communication. Figure 1a shows a pair of LED matrix headlights, where different groups of LEDs are turned on (or off) to realize different lighting functions.



(a) Turning on/off different groups of LEDs to realize different lighting functions. Image adapted with kind permission from HELLA GmbH & Co. KGaA. (Source: https://www.hella.com/techworld/ae/Technical/Automotive-lighting/LED-headlights/Audi-A6-Matrix-LED-Headlights-61322/)



(b) Sectors and corresponding service areas of an LED matrix headlight and its radiation pattern.

Figure 1. Functions of LED matrix headlights and the concept of LED matrix headlight as a sectorized transmitter.

We already mentioned that the LED matrix consists of many tiny LEDs with strictly separated radiation patterns, which in turn implies spatially independent communication channels. Taking advantage of this property, the lighting modules can be utilized as sectorized antennas (see Figure 1b). This space-division characteristic of the LED matrix headlight can improve bandwidth efficiency and reduce interference.

B. *Design of the Cross-Layer MAC Approach*

Generally speaking, the purpose of a MAC protocol is to coordinate nodes' access to the shared medium in a way that optimizes communication performance. In essence, this means that a node needs to be told *when* to transmit, and *how* to transmit – given that there is a way to dictate the former.

To answer these questions, our MAC protocol relies on certain information: It requires position information of the neighboring nodes, and a list of ongoing V-VLC transmissions from other nodes towards the desired destination. The former is required to infer the location of the desired destination, in order to transmit to it via the best fitting sector; the latter is needed to avoid collisions from concurrent transmissions to that destination.

Briefly, our layered protocol architecture works as follows: The application layer generates packets which are passed to MAC layer. At the MAC, if there is no ongoing transmission towards a desired destination within communication range, the MAC selects the appropriate sector for reaching that destination and passes the packet (along with the control information about the optimal sector) to the PHY. At the PHY, the packet is immediately sent to the channel. The operation of our MAC protocol is outlined in Algorithm 1.

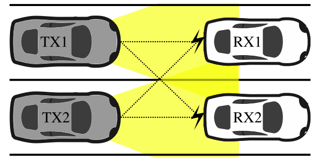
Algorithm 1 Location-aware cross-layer MAC protocol

Input: unicast message m_d for destination node d
Input: neighbor table storing position and heading information of neighboring nodes, including d's: pos_d
Input: $\mathbb{T}_d$, the set of ongoing transmissions from neighbors towards d
Input: sector table storing the service area $area_s$ of each transmitter antenna sector s

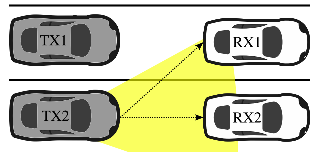
```
for all sectors s in sector table do
    if pos_d in area_s and T_d = ∅ then
        send(m_d) via sector s
    end if
end for
```

Output: (m_d, s) pair for transmission

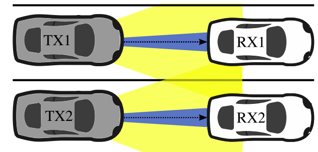
Note that, in the aforementioned protocol steps, we assume that important input information, like the location of the destination node, and the ongoing transmissions are readily available. This information can be collected using cooperative awareness messages (as defined in other V2V protocols) and communication technologies, such as the beaconing concept from both DSRC/IEEE 802.11p and C-V2X. Other techniques, like GPS, Vehicular Visible Light Positioning, or computer vision via an on-board camera can be used to extract location information, too. However, to test the feasibility of our protocol, at this stage we obtain this information from the simulation toolkit.



(a) Collision due to concurrent transmissions with full beam.



(b) No collision due to single transmission with full beam.



(c) Parallel transmission with sectors; no collision.

Figure 2. Simple static scenario with four nodes: two transmitters (TX1 and TX2) and two receivers (RX1 and RX2); Inter-vehicle distance along the vertical axis is set to a typical lane width of 3.75 m. Yellow cones represent the whole radiation pattern; Blue cones represent sectors.

IV. Performance Evaluation

In the following, we describe our performance evaluation setup for two different scenarios, and discuss obtained results. In both studies, we use Veins VLC [21] to simulate the V-VLC channel. For the purpose of this work, we extended Veins VLC with the capability to sectorize the radiation pattern of a lighting module.

A. *Static Scenario*

We first evaluate our protocol in a static scenario consisting of four nodes (see Figure 2). The transmitting nodes use their headlights to transmit VLC packets, whereas the receiving

Table I
Simulation parameters and corresponding measurements setup from [22].

Parameter	**Value**
Transmitter (low beam)	2015 Toyota Corolla Altis
Tx power	19 W
Receiver	Thorlabs PDA100A
Rx gain	0 dB
Sensitivity threshold (ambient)	−114 dBm
Headlight height	70 cm
Headlight measurement height	55 cm
Taillight height	90 cm
Taillight measurement height	70 cm
Packet size	9 kB
Bitrate	1 Mbit/s
Transmission rate	1 Hz
Modulation and BER model	OOK

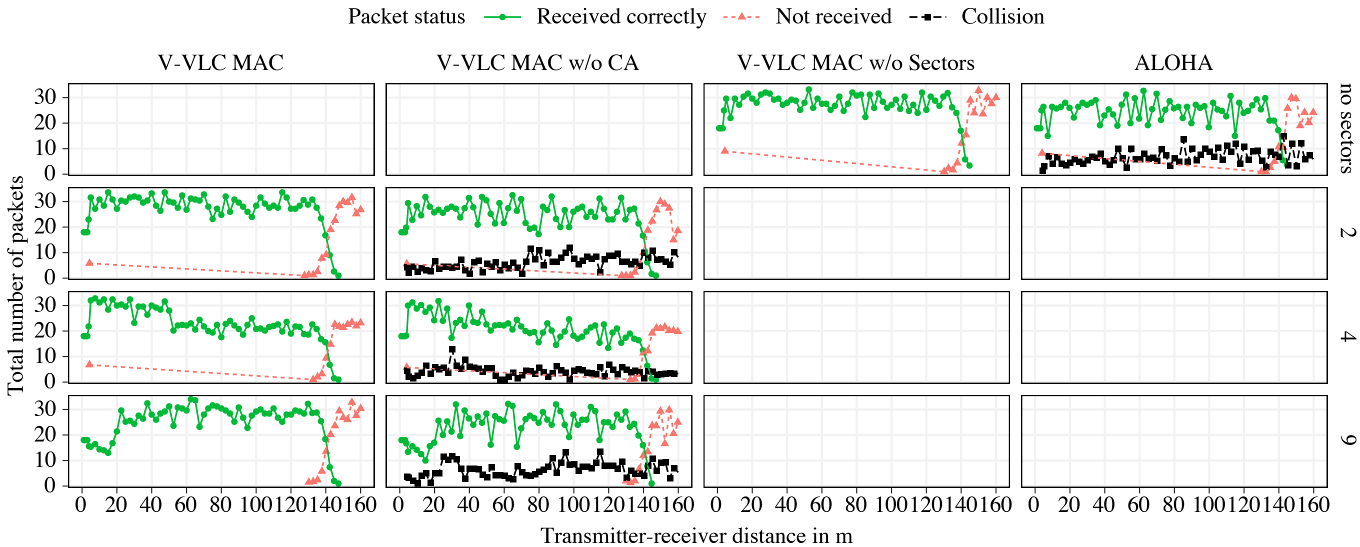


Figure 3. Total count of different types of packets over distance for each protocol and sector count configuration. Depending on the features of a protocol corresponding plots are shown, e.g., there is no data for the protocols that do not support multiple sectors. The *no sector* configuration refers to the case when the whole radiation pattern is used for transmission. In this configuration, V-VLC MAC essentially behaves like V-VLC MAC w/o Sector, and V-VLC MAC w/o CA behaves like ALOHA.

nodes receive the signals via the rear-mounted photodiode. To evaluate the performance of our protocol, the nodes are arranged in such a way that allows the transmissions to interfere with each other and packets to collide (see Figure 2a). However, if a MAC protocol is used, collisions can be avoided (see Figure 2b) and spectral efficiency can be maximized (see Figure 2c).

Since our nodes are static, to capture the impact of the distance, we vary the distance between the transmitting and receiving nodes between 1–160 m in each experiment. For statistical confidence, we conduct five repetitions per experiment. Moreover, we vary the number of the sectors that a headlight can have between one and ten, practically dividing the radiation pattern into sectors with equal central angle: the more sectors there are, the smaller the central angle of the sectors. The number of sectors is fixed for the duration of an experiment, i.e., nodes cannot dynamically adapt the sector angle (or sector count) to communicate with a destination, and a node cannot transmit with more than one sector at a time.

TX1 and TX2 each asynchronously transmit a unicast data stream of 9 kB, over a 1 Mbit/s channel, at a frequency of roughly 1 Hz[1], for a duration of 10 s. The destination node is randomly chosen from the set of neighbors (RX1 and RX2), if it is within communication range and LOS. At this stage, we intentionally pick a low network traffic scenario to better demonstrate the implications of our protocol. Table I outlines relevant simulation parameters.

In order to show the impact of the different features of our protocol, we implement multiple versions of it with collision avoidance and sectorization features enabled/disabled. We also compare our protocol against ALOHA. Hereafter, for simplicity we refer to our original protocol as V-VLC MAC. Table II shows the different protocol variations that we compare.

Table II
SIMULATED PROTOCOL VERSIONS AND CORRESPONDING FEATURES.

Protocol	Unicast	Collision Avoidance	Multiple Sectors
V-VLC MAC	✓	✓	✓
V-VLC MAC w/o Sectors	✓	✓	✗
V-VLC MAC w/o CA	✓	✗	✓
ALOHA	✓	✗	✗

Figure 3 is a matrix of plots, where a subplot shows the number of different types of packets observed at the physical layer by all receivers over varying distances for a specific protocol type and sector count. We mentioned previously that we simulated ten different configurations for the sectors, however as most of the effects recur, only four configurations are sufficient to show the more prominent trends.

We first focus on the physical layer aspects of the communication: As TX1 and TX2 transmit packets, at the physical layer these packets can either be received (green dots), not received (red triangles), or collide[2] (black boxes). Generally speaking, for distances of roughly up to 130 m, packets can be received or collide, while beyond that distance packets cannot be received due to insufficient received signal strength. On the other hand, for close TX-RX distances (i.e., between 1–4 m) there are no collisions observed for any number of sectors, because of the LOS characteristic of VLC: In such close distances the receiving vehicles can only "see" the packets transmitted from

[1] In certain scenarios, the actual transmission frequency can be lower than the nominal one due to blockage by the collision avoidance mechanism.

[2] A collision is registered when an ongoing packet reception is corrupted by one or more packets arriving within the packet duration. Packets causing the collision are not counted.

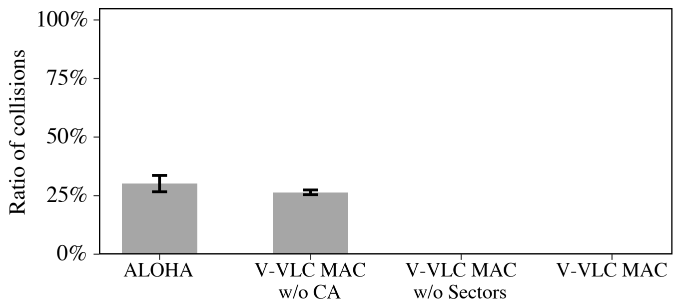


Figure 4. Collisions as a ratio of the total number of packets received at the PHY of each node, for different protocol configurations. The error bars indicate the 95 percent confidence interval around the mean.

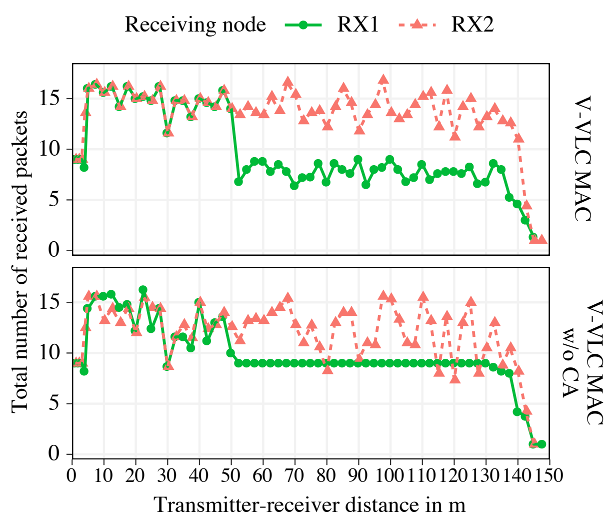


Figure 5. Received packets using the four sector configuration, differentiated by protocol and receiver.

the vehicle directly behind them, because the signal from the other transmitter is blocked completely due to shadowing by the other receiver vehicle, thus, no chance for collisions. As the TX-RX distance increases the service area of transmissions increases, therefore RX1 and RX2 can each “see” the signals transmitted from both transmitter. Hence, the total number of receptions at the physical layer can exceed the total number of transmitted packets by each transmitter. This also increases the probability for collisions.

Regarding collisions, in Figure 3 we notice that whenever we use the protocols with the collision avoidance feature, we can completely avoid the collisions in this scenario. This effect is shown also in Figure 4, where we can clearly see that regardless of the sector count or TX-RX distance, there are no collisions for the protocols with collision avoidance, whereas for ALOHA and V-VLC w/o CA, on average 25 % of the packets that reach a receiver are lost due to collision.

If we look at the impact of the number of sectors on the received packets, we notice that for the configuration with four sectors there is a sudden drop in receptions at a distance of roughly 50 m, and this drop persists for farther distances.

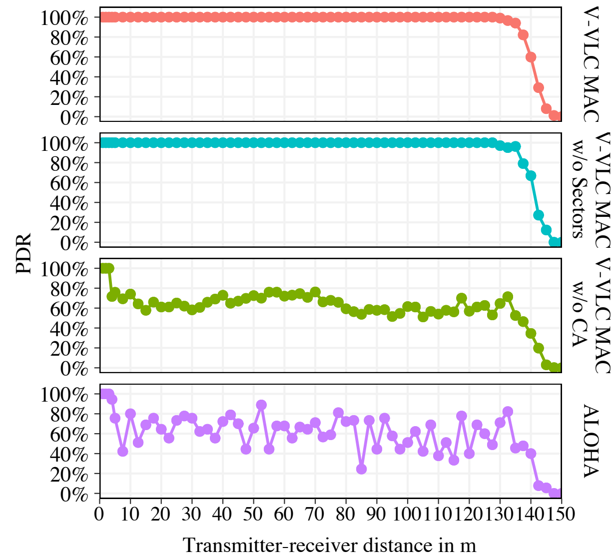


Figure 6. PDR for different protocol and sector size configurations.

This effect is better shown in Figure 5. This happens due to the sector layout (i.e., division of the radiation pattern by the sectors), and the asymmetric power distribution of the radiation pattern (cf. Figure 1b): In this configuration, when TX1 and TX2 transmit packets destined to the nodes directly in front of them, they use a sector on the right side (relative to their heading, cf. Figure 1b). Therefore, when TX2 sends to RX2, RX1 does not receive any packets (because it is on the left of the transmitter). For the diagonal transmission (TX1 → RX2), TX1 again uses a sector on the right, therefore both RX1 and RX2 can receive the packet. For the other diagonal transmission (TX2 → RX1), TX2 uses a sector on the left, hence TX1 does not receive the packet. In Figure 5, there is also a fluctuation of the received packets for RX1 in the V-VLC MAC scenario. This is because the collision avoidance protocol sometimes prevents the transmission of packets which otherwise could be received by RX1. The presence of collisions in the V-VLC w/o MAC also contributes to RX2 receiving less packets. Thus, the gap between the number of packets received by the different receivers is smaller than the one with V-VLC MAC protocol. Although the effects stemming from the sector configuration can be interpreted as simulation artifact, they also demonstrate that the configuration and choice of sectors can have a nontrivial impact on the communication.

Figure 6 shows Packet Delivery Ratio (PDR) for different protocol configurations. This confirms that indeed whenever we use the collision avoidance feature, we can achieve high PDR for the unicast transmissions in our simple scenario. Nonetheless, we also observe that using only multiple sectors without collision (i.e., V-VLC MAC w/o CA) avoidance can still improve the PDR compared to ALOHA. Note that, in Figure 6 in the subplots for V-VLC MAC w/o CA and ALOHA, we can see how communication in short distances with the receiver directly in front of the transmitter manifest with 100 %.

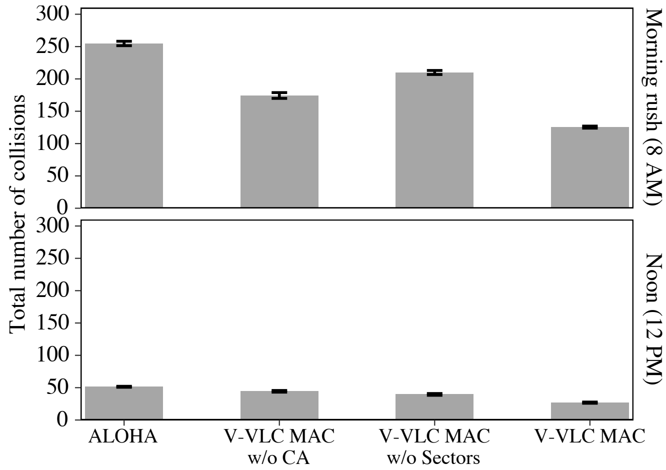


Figure 7. Total number of collisions at different times of the day grouped by protocol type. The error bars indicate the 95 percent confidence interval around the mean.

B. Realistic Dynamic Scenario

Next, we evaluate the performance of our protocol in a realistic scenario. For this, we use the well-known Luxembourg scenario [23]. We run our simulations in a region of interest which we have previously shown to be prone to interference [17]. In this setup the mobility of the vehicles is determined by the mobility traces of the scenario, therefore we do not have any means to control the inter-vehicle distance, as in the previous scenario (Section IV-A). However, we simulate different times of the day, when vehicle density is lower or higher: 8 AM, corresponding the morning rush with high density; and noon (12 PM), for lower density traffic. We simulate a period of ten minutes for each of the aforementioned scenarios. The remaining simulation parameters are the same as described in Section IV-A.

For this scenario, we study the total number of packet collisions as a cumulative metric to show the impact of the different protocols on communication performance. Figure 7 shows the total number of collisions for the 8 AM and the noon scenarios separately. In general, the number of collisions in the morning rush scenario is higher than the number of collisions in the noon scenario, because the vehicle density is higher, although the signals are attenuated due to shadowing from the presence of more vehicles. Remember that, in the static scenario, we observed no collisions whenever a protocol with the collision avoidance feature was used. This does not apply to the current setup, because the geometry and number of vehicles varies more dynamically, resulting in more interference and hidden terminal situations, which manifest as collisions. Looking at the different protocol versions, we see that all the V-VLC variants perform better than ALOHA in terms of collisions, whereas V-VLC performs best – almost halving the number of collisions compared to ALOHA in either scenario. Additionally, the impact of the different protocol versions is similar regardless of the time of the day, except for the V-VLC MAC W/O SECTORS: In this case, there are comparatively more collisions in the morning rush scenario than in the noon scenario. Here, not only differences in node density and geometry between the two scenario have an impact, but also the way how the transmission are carried out: When vehicles use the whole radiation pattern for a transmission and the scenario has relatively lower node density, there is less shadowing from neighboring nodes and more LOS links to unintended receivers. This causes more interference, hence more collisions for V-VLC MAC W/O SECTORS.

V. CONCLUSION

We presented a new concept for medium access for V-VLC based on a multi-layer protocol architecture and LED matrix headlights. Our approach relies on information exchange between the different protocol layers to decide when and how to transmit a V-VLC packet in order to improve communication performance. We take advantage of the space-division characteristic of LED matrix headlights, which offer the properties of a sectorized antenna: using positional information of the immediate neighboring nodes, we are able to select a subset of LEDs (i.e., sector) for optimal communication.

Our results clearly show the benefits of this approach when using collision avoidance and multiple sectors for communication. In a well-controlled static scenario, we were able to mitigate collisions and improve spectral efficiency; and in a realistic dynamic scenario our V-VLC MAC is able to reduce the number of collisions compared to simple ALOHA protocol by 50 %. Moreover, in the realistic scenario we see that node geometry (depending on traffic density at different times of the day) and LOS characteristic of light have profound impact on interference.

In future work, we plan to extend our approach to a heterogeneous vehicular network, where nodes' locations can be obtained by means of other radio-based V2V communication technologies, and assess the impact of information age on transmission decisions. In addition to this, we also plan to enhance our simulation model to capture different environmental conditions (e.g., sunlight, fog, rain) that can have a significant impact on system performance.

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