A Location-aware RF-assisted MAC Protocol for Sectorized Vehicular Visible Light Communications

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Abstract

Vehicular Visible Light Communications (V-VLC) has emerged as a viable technology complementing RF-based communication in automotive scenarios. This is mainly due to properties such as the large unlicensed spectrum and the intrinsic security due to the Line Of Sight (LOS) requirement. In this context, one aspect of V-VLC needs further attention given the current state of the art, namely medium access under multi-user interference. In this paper, we extensively study interference in typical vehicular scenarios. Based on the findings from this study, we propose a novel approach for medium access. We follow a location-aware cross-layer approach that exploits the Space Division Multiple Access (SDMA) feature of modern matrix lighting modules to avoid interference and thus collisions. Making use of heterogeneous communication concepts, in which vehicles share their positions via the Radio Frequency (RF) channel, V-VLC transmissions can be scheduled accordingly. In an extensive simulation study using a realistic urban scenario, we first identify critical interference scenarios and then assess the efficacy of our proposed solution. We also investigate the impact of position uncertainty due to, e.g., GPS errors. Our results clearly indicate the benefits of a location-aware protocol that exploits the space-division features of the matrix lights.

Keywords: Vehicular Visible Light Communication, V-VLC, Vehicle-to-Vehicle Communication, V2V, Medium Access, Spatial Multiplexing, Matrix Headlight

1. Introduction

The vast majority of the ITS applications in the literature are envisioned on top of RF-based technologies [1], like IEEE 802.11p [2] or Cellular V2X (C-V2X) [3, 4]. Nevertheless, RF-based technologies face certain challenges – particularly related to resilience of real-time applications, where efficiency and resilience represent two sides of the system characteristics [5, 6]. One such challenge, is the interference in the RF domain which is caused by the omnidirectional antennas, typically deployed in the aforementioned technologies. Omnidirectional antennas have relatively large collision domains that permit signal interference, in turn, this results in increased network congestion, affecting reliability and application performance [1].

In recent years, stimulated by the wide adoption of LED-based lighting modules for exterior lighting in modern vehicles, V-VLC has emerged as a viable communication technology for ITS applications [7, 8, 9]. Communication in Visible Light Communications (VLC) is realized by modulating information on the light intensity of the LEDs, whereas photosensitive devices (e.g., photodiodes or camera image sensors) are used as receivers to recover the original information from the generated photocurrent.

V-VLC has certain properties that, as a complementary technology, can help overcome the shortcomings of RF-based communications [3, 10]: The physical characteristics of the light wave and its propagation characteristics make V-VLC a predominantly LOS technology. Additionally, headlight and taillight modules in modern vehicles have optical components which focus the light beams in a certain direction. In terms of communication, this directionality can lead to a relatively smaller collision domain and also permits the spatial reuse of the modulation bandwidth.

Physical properties aside, there are also hardware and system-level solutions that impact V-VLC communication. For instance, some approaches in the literature deploy optical components in front of the receivers to improve signal reception at the Physical Layer (PHY) [11, 12]. Additionally, V-VLC can benefit from Adaptive Front-Lighting System (AFS) with LED matrix headlights [13]. These systems optimize road illumination by selectively switching a subset of the LEDs based on sensory input from an on-board camera. The possibility to control individual (or a subset of) LEDs with strictly separated illumination patterns can enable communication via more fine-granular, spatially divided channels.

The directionality and LOS characteristics of V-VLC, combined with the space-division capability of the LED matrix, and the possibility of learning the locations of the neighboring vehicles (e.g., via an on-board vision system,

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GPS, Vehicular Visible Light Positioning (V-VLP) [14], 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 [15, 16] for VLC supports CSMA/CA. While, there exist works that focus on specific optics and the LOS properties of the signal [11, 12, 17].

In this paper, we build upon our proof of concept protocol introduced in [18] as follows: We first conduct an extensive study to identify interference hotspots for V-VLC in a traffic scenario based on the real world. Then, we extend our location-aware cross-layer MAC protocol [18] with realistic positioning and heterogeneous communication capabilities. Our MAC protocol exploits the SDMA concept from modern LED matrix headlights, and uses GPS position information gathered via the RF channel to select the optimal subgroup of LEDs to transmit towards a desired destination. Next, we design multiple versions of our original protocol with different features, and finally examine their performance in a challenging dynamic intersection environment.

Our main contributions can be summarized as follows:

- We quantitatively investigate the problem of interference in a realistic urban scenario, and establish temporal and spatial hotspots for collisions in V-VLC;
- we extend our initial protocol with realistic assumptions regarding positioning and communication, and propose a novel, heterogeneous cross-layer MAC protocol for V-VLC communication;
- we present the results of an extensive simulation-based performance evaluation comparing different features of our protocol in a dynamic intersection scenario.

2. Related Work

As a relatively new technology, most of the V-VLC research so far has focused on physical layer aspects of V-VLC, such as channel characterization, channel modeling, and coding [7]. However, as V-VLC is maturing, a natural next step is to investigate 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 [19]. 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 [20, 21]. In the following, we briefly describe some of the MAC-related publications from the V-VLC literature.

Liu et al. [9] 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.

Masini et al. [22] modified the PHY and MAC layers specified in IEEE 802.15.7 standard [15, 16], meant for indoor VLC, and adapt it for V-VLC. By exploiting the reverse communication link for immediate feedback between two vehicles, they extend the original CSMA/CA with collision detection functionality. Thus, they realize a full-duplex V-VLC 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 has been taken in consideration by Eldeeb et al. [23], who also investigated the performance of V-VLC based on the IEEE 802.15.7 standard [15]. 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 protocol-only solutions that pertain medium access for V-VLC, there are other approaches that exploit specific hardware, i.e., optics and lighting modules. For example, Shen et al. [11] and Tebruegge et al. [12] deployed 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.

From a hardware perspective, Tebruegge et al. [13] conceptually showed the benefits of LED matrix headlights, and were 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 [17]. Neither of the aforementioned works, however, implement a MAC protocol that takes advantage of the space-division capability of LED matrix headlights. To fill this gap, in [18] we presented a proof of concept MAC protocol that improved medium access in V-VLC, which in the present work, we extend [18] with heterogeneous communication and more realistic assumptions.

3. Connectivity and Interference in V-VLC Scenarios

V-VLC has certain characteristics which inherently affect multi-user interference and node connectivity. Due to the restrictive regulations governing the shape and brightness of vehicle lighting modules, as well as the directionality and LOS characteristic of V-VLC, it is considered that

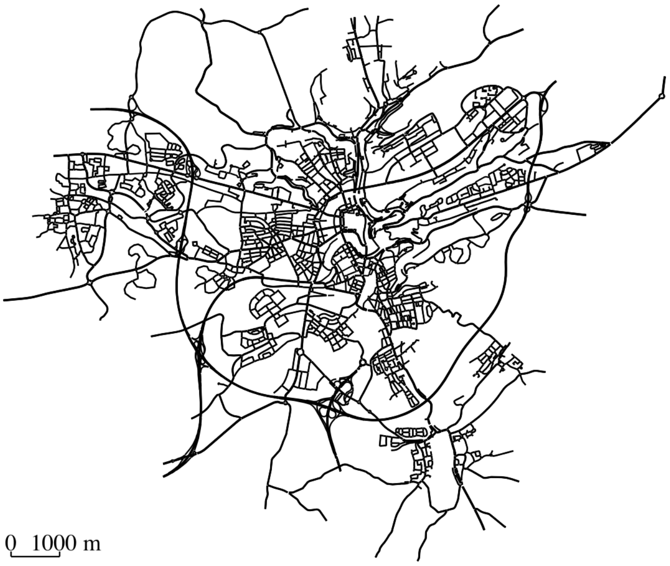


Figure 1: City of Luxembourg as modeled by the LuST simulation model [24], deployed in our simulation toolkit.

nodes do not suffer severely from multi-user interference, and the number of nodes that can communicate with each other is rather low.

To test these assumptions, we perform comprehensive experiments of a realistic V-VLC scenario. The goal of these experiments is to investigate connectivity and multi-user interference in V-VLC and identify corresponding hotspots. Furthermore, by means of these experiments we can quantify the severity of interference in the channel (manifested as packet collisions) and corroborate the need for a MAC protocol in V-VLC.

We base our study on realistic simulations of vehicles' mobility and V-VLC channel. For the former we use the LuST scenario [24] and for the latter *Veins VLC*[1] – our Open Source V-VLC simulation model for the vehicular network simulation framework Veins. The channel model used in our simulations is based on [25]. We deploy the radiation patterns for the headlights and taillights introduced in [25], and divide them in sectors (see Section 4.1). The LuST scenario simulates the road traffic in the city of Luxembourg. It provides an accurate representation of the road topology of the city and 24 hours of traces that model the traffic demand and mobility patterns of the vehicles at a microscopic level (cf. Figure 1).

In this first set of experiments, we simulate the complete LuST scenario. This allows us to capture all relevant V-VLC communication situations. In terms of time, we divide the simulation into multiple simulation intervals: Every 10 minutes all vehicles in the scenario transmit a 9000 Byte V-VLC message with their head- and taillights. Furthermore, to account for the LOS property, signals are fully attenuated when other vehicles are located between a transmitter-receiver pair. Attenuation by buildings is not considered, however.

[1] `https://www2.tkn.tu-berlin.de/software/veins-vlc/`

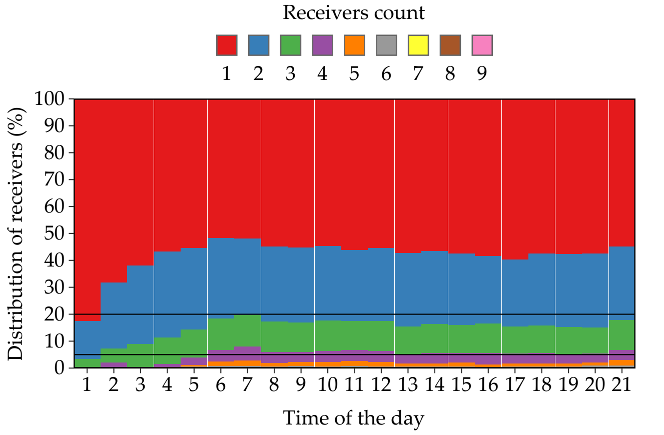


Figure 2: Distribution of the number of the receivers of a V-VLC message at different times of the day (i.e., Transmitter perspective).

Next, we focus on two relevant metrics: the number of recipients of a particular message, and the number of transmissions detected at a receiver during an ongoing reception (i.e., interference).

Figure 2 shows the distribution of the number of recipients of a V-VLC message at different times of the day in our scenario. Note that the transmissions without a recipient are not registered in this metric. As shown in Figure 2, in roughly 80 % of the cases a message is received by at most two other nodes. On the other hand, in less than 10 % of the cases a V-VLC message can be received by four or more nodes.

The number of the recipients of a message depends strongly on the simulated time of the day. This is because the traffic demand varies accordingly. For instance, messages transmitted at the earlier times of the day (e.g., midnight to 4 AM), can be received by at most three nodes, because the number of the vehicles in the scenario during those times is relatively low. Thus, there are not enough neighboring nodes to communicate with. The opposite holds true for the rush hour periods (e.g., 8–9 AM, noon, 7–8 PM), when we observe the highest value of nine receivers

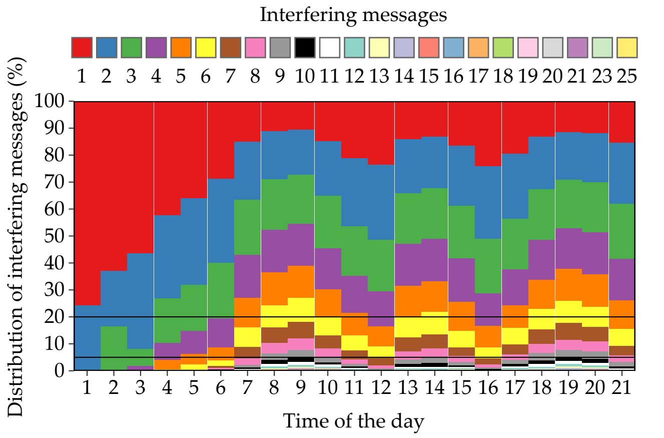


Figure 3: Distribution of the number of interfering frames for an ongoing V-VLC message reception (i.e., Receiver perspective).

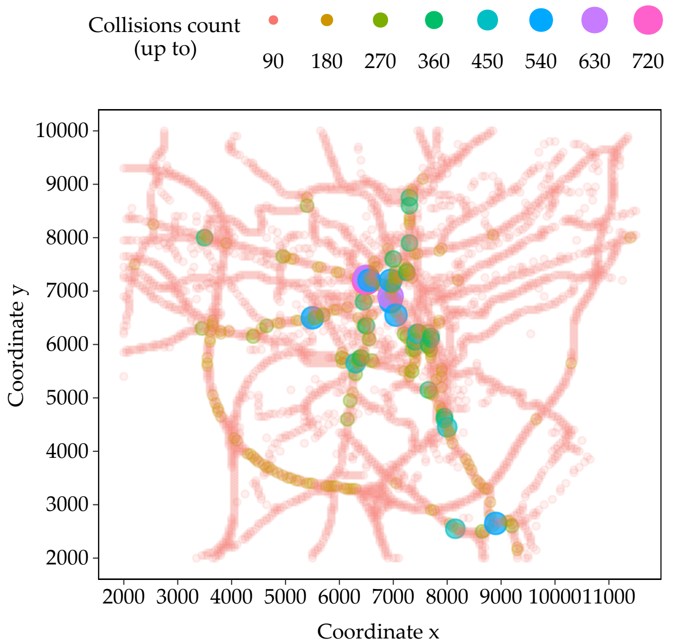


Figure 4: Two-dimensional density plot for the total number of collisions in the Luxembourg scenario. Size of the circle corresponds to the number of collisions.

for some messages in our scenario.

Note that, in our simulations in less than 3 % of the cases a message can have five or more recipients; However, in the literature we have previously reported that the number of receiving nodes for a message can go up to 20 in certain traffic demand and road situations (i.e., road curvature and intersections). Yet, such a large number of recipients for a single V-VLC message is very rare [20].

Figure 3 shows the distribution of the number of messages detected at the receivers at different times of the day. In essence, this metric allows us to quantify the amount of interfering transmissions for an ongoing reception. Here, we only account for the transmissions that are detected at the receiver as it is trying to receive a message; cases with no interfering transmissions are not registered.

As shown in Figure 3, the number of interfering messages at a receiver ranges between 1–25. Across all simulated times of the day, in at least 50 % of the cases there are between 1–3 interferers. Whereas in only 5 % of the cases there are more than 10 interferers. As in Figure 2, in Figure 3 also the highest values of the interfering transmissions (i.e., 20–25) occur during the rush periods in the scenario, despite the assumption that more vehicles in the scenario might reduce interference due to frequent shadowing of the LOS.

Heretofore, we quantified connectivity and interference in our scenario and established the temporal hotspots (i.e., critical times of the day). Next, we examine the spatial hotspots in the scenario. We focus on the number of colliding messages in the scenario as a by-product of interference (cf. Section 3). A collision is registered each time an ongoing frame reception yields unsuccessful due to one or more other interfering frames detected at the receiver.

Figure 4 shows a heatmap of the count of collisions mapped to spatial coordinates in the scenario. As seen in the figure, certain areas in the scenario are more pronounced relative to the rest. Based on Figure 4 (and upon further inspection of the map of Luxembourg) we can conclude that most of the collisions happen in intersections or in their close proximity.

Typically, intersections are busy locations where multiple vehicles cluster together waiting to drive further. In such situations, the vehicles face each other with a certain distance in between. The higher vehicle density, the relatively low mobility, and the larger communication range of headlights are reasons for more collisions at intersections. This has further been confirmed by our experiments, where the ratio of collisions in a subset of selected intersections (located along *Boulevard Royal* within the inner circle of the city of Luxembourg) was higher than collisions in the rest of the scenario. As such, interference is a challenge in V-VLC and a MAC protocol can be used to address this [20].

4. Heterogeneous Cross-Layer MAC Protocol for Vehicular VLC

In this section, we introduce the concept of space-division in LED-based matrix headlights and then we describe our heterogeneous cross-layer medium access protocol for V-VLC.

4.1. LED Matrix as a Sectorized Transmitter in V-VLC

The space-division technique in V-VLC can be realized using state-of-the-art headlight modules based on LED matrix technology [13]. These lighting modules consist of a large number of tiny LEDs arranged in a matrix formation, where subsets of LEDs can be controlled individually.

The technology to control different sets of LEDs individually is used to implement different lighting functions (e.g., low beam, high beam, bend lighting), but it also presents an opportunity for optimized communication. Namely, individual LEDs in a matrix lighting module have strictly separated radiation patterns, resulting in spatially independent communication channels; This allows the modulation of a selected subset of LEDs and the utilization of a lighting module as a sectorized antenna (see Figure 5).

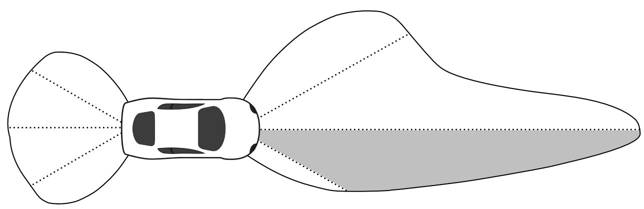
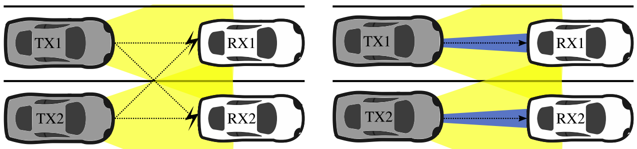


Figure 5: Illustration of the division of radiation patterns of lighting modules into multiple sectors.



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

(b) Parallel transmission with sectors; no collision.

Figure 6: Simple scenario with four nodes: two transmitters (TX1 and TX2) and two receivers (RX1 and RX2); Yellow cones represent the whole radiation pattern; Blue cones represent sectors.

The division of the radiation pattern into multiple sectors can improve spectral efficiency and reduce interference. To illustrate, in Figure 6 we show a simple two-by-two scenario where two vehicles transmit concurrently with their headlights and collisions occur in the vehicles upfront (Figure 6a). Figure 6b, on the other hand, shows that collisions can be avoided and spectral efficiency maximized if we take advantage of the lighting modules as sectorized antennas.

4.2. Design of the Heterogeneous Protocol

Here, we describe our heterogeneous cross-layer MAC protocol, VMAC HET+G, takes advantage of the space-division capability of the matrix lighting modules to reduce collisions and improve communication performance in V-VLC.

To achieve this, our protocol requires positional information of the neighboring nodes. This information is needed for selecting the transmitting sector that serves the area where the destination node is located. In vehicular scenarios there exist multiple techniques to obtain positional information of the immediate neighborhood. For example, via different sensors (on-board camera, LIDAR), Vehicular Visible Light Positioning, or using cooperative awareness messages (as defined in other Vehicle-to-Vehicle (V2V) protocols) and communication technologies, such as the beaconing concept from both DSRC/IEEE 802.11p and C-V2X.

In our initial proof of concept protocol, VMAC [18], we extracted precise positional information of the neighboring nodes from the simulation toolkit. Here, we take a more realistic approach and use GPS positions for the vehicles and RF transmissions to advertise it. The operation of our upgraded MAC protocol is outlined in Algorithm 1. VMAC HET+G differs by VMAC in that it adds Phases 1 and 2, and the respective inputs in Phase 3 (see Algorithm 1).

To summarize, the protocol runs as follows: each node periodically broadcast messages on the RF channel that advertise its GPS location. While the nodes populate and maintain their neighbor tables in the background, the main procedure of our layered protocol architecture executes: First, a node selects a viable destination node to communicate with from the set of nodes within its VLC communication range in the neighbor table.

Algorithm 1 VMAC HET+G

Phase 1 – RF broadcasting

Input: Transmitting node's id id_{node}
Input: Current position information pos_{node}
Input: RF message m_{RF} containing pos_{node} and id_{node}

```
loop
    broadcast(m_RF)
end loop
```

Phase 2 – Neighbor table maintenance

Input: RF message m_{RF} containing pos_{node} and id_{node}
Input: Neighbor table NT

```
upon event m_RF received do
    if id_node in NT then
        update entry in NT for id_node
    else if id_node not in NT then
        add new entry to NT for id_node
    end if
```

Phase 3 – VLC unicast with LED sector

Input: V-VLC unicast message m_d for destination node d
Input: Neighbor table NT storing position information of neighboring nodes, including d's position: pos_d
Input: Sector table $table_s$ storing the service area $area_s$ of each sector s of a transmitting antenna

```
for all sectors s in sector table table_s do
    if pos_d in area_s then
        send(m_d) via sector s
    end if
end for
```

Output: (m_d, s) pair for transmission

Next, a message destined to the selected node is generated by the application layer and is passed down to the MAC layer. At the MAC, we specify the appropriate sector to communicate with that destination, and we pass the message (along with the control information about the sector for communication) to the PHY. In the last step, the PHY immediately sends the packet to the channel.

5. Performance of VMAC

In Section 3, we established that intersections are the critical hotspots where more interference, and hence collisions occur. Therefore, we select the intersection with the highest number of collisions in the scenario to evaluate our protocols. We also select a time period in the busiest rush hour (i.e., 8–9 AM) in this intersection to run our simulations. Figure 7 shows the structure of the intersection.

Compared to the initial set of simulations (cf. Section 3), where all of the vehicles transmitted a single V-VLC message at different times of the day, here the vehicles continuously transmit a unicast data stream of 8192 Byte, over a

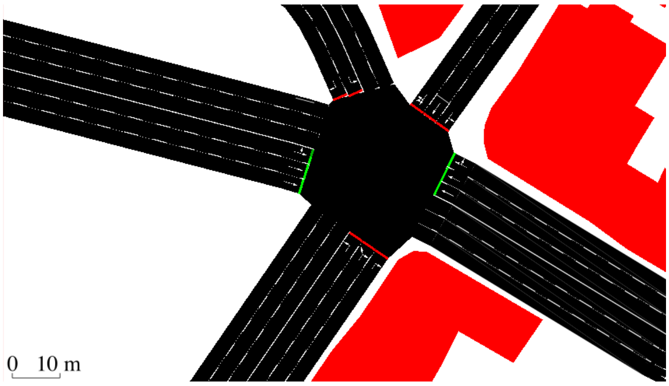


Figure 7: Image of the simulated intersection in the city of Luxembourg (also shows as pink circle in Figure 4). The intersection is formed by *Avenue Émile-Reuter* connecting with *Route d'Arlon*; and *Boulevard de la Foire* connecting with *Boulevard Grande-Duchesse Charlotte*. The number of vehicles in the simulated scenario ranges between 10 and 56 with an average of 29.9 and median of 29.

1 Mbit/s V-VLC channel, at a nominal frequency[2] of 1 Hz for the entire simulation duration of 10 minutes. Moreover, since our protocol relies on nodes' GPS position advertised over the RF channel, we also simulate IEEE 802.11p-based vehicle to vehicle communications. In the RF domain, vehicles periodically transmit 350 Byte messages over a 6 Mbit/s channel. The transmission rate in RF is varied between 0.5–20 Hz in different simulation runs.

Similarly, to capture the impact of the granularity of the antenna sectors, we vary the number of the sectors of a lighting module between one and four. The number of sectors is fixed for the duration of an experiment and concurrent transmissions via more than one sector are not possible. Note that, due to the larger angular span of the taillights, for the same number of sectors, the central angle of taillight sectors is slightly larger than headlight sectors. As such, for the same number of sectors, a taillight's service area can be slightly larger. Table 1 outlines important simulation parameters.

Table 1: Simulation parameters.

Parameter	**Value**
Simulation Models	Veins VLC 1.0, SUMO 1.8.0
Technology	IEEE 802.11p
Bit rate	6 Mbit/s
Frame size	300 Byte
Transmission rates	0.5, 1, 2, 5, 10, 20 Hz
Shadowing	disabled
Noise floor	−95 dBm
Carrier frequency	5.890 GHz
Transmission power	20 mW
Path loss (Friis model)	$\alpha = 2$
Technology	V-VLC
Bit rate	1 Mbit/s
Frame size	8192 Byte
Transmission rate	1 Hz
Shadowing	fully opaque vehicles
Noise floor	−110 dBm
Head-/Taillight height	55 cm / 70 cm [26]
Headlight angle span	90 ° [26]
Taillight angle span	120 ° [26]
Modulation	OOK
V-VLC Model	EmpiricalLightModel [25]
Antenna sectors	1,2,3,4 (see Section 4.1)

5.1. Protocol Features and Variations

For comparison and evaluation purposes, we design multiple versions of our protocol with different features and capabilities.

The base protocol is called VMAC, as presented in [18]. This is our proof-of-concept protocol which assumes perfect knowledge of nodes positions, hence it does not require RF transmissions or maintain a neighbor table. Furthermore, it is aware of ongoing transmissions in the channel through which it implements a collision avoidance mechanism. On the other hand, we have the original protocol presented in Section 4.2, which we name VMAC HET+G, hereafter. The HET notation in its name represents the heterogeneous communication capabilities (i.e., RF transmissions for exchanging position data, and storing them in neighbor table); the +G notation indicates the use of GPS positions, because VMAC HET+G does not assume perfect knowledge of the neighboring nodes' positions.

For each of the protocols we implement +G variant; and, for comparison we also use ALOHA. As such, we have the protocols with idealized positional information of the neighboring nodes (VMAC HET, VMAC [18], ALOHA) and their counterparts with GPS positions of the nodes (VMAC HET+G, VMAC+G, ALOHA+G). Further details of the aforementioned protocols can be found in Table 2, which summarizes their features for comparison.

VMAC HET+G is designed as a realistic protocol compared to the other VMAC protocols. Therefore, in VMAC HET+G there are two sources of neighbor position inaccuracies: inaccuracies due to GPS measurement errors and inaccuracies related to RF transmission delay and vehicle mobility. Furthermore, VMAC HET+G also does not have a collision avoidance mechanism. These factors together can affect the performance of the VMAC HET+G protocol, as we see later on.

5.2. Protocol Performance

In the following, we asses the performance of our protocols based on two relevant metrics: unicast collisions ratio and unicast delivery ratio. Unicast collisions ratio is calculated as the number unicast messages not received due to interfering frames divided by the total number of unicast

[2]This is the nominal transmission rate. The actual transmission rate depends on whether there is a destination node to communicate with.

Table 2: Simulated protocol versions and corresponding features. Note that the VMAC protocol is based on [18]. GPS error model for horizontal position accuracy is implemented based on the measurements from [27, Section 5.1].

Protocol	**V-VLC Unicast**	**Multiple Sectors**	**Collision Avoidance**	**GPS Error**	**RF Broadcast**
VMAC HET+G	✓	✓	✗	✓	✓
VMAC HET	✓	✓	✗	✗	✓
VMAC+G	✓	✓	✓	✓	✗
VMAC	✓	✓	✓	✗	✗
ALOHA+G	✓	✗	✗	✓	✗
ALOHA	✓	✗	✗	✗	✗

messages transmitted in the scenario. Similarly, unicast delivery ratio is calculated as the ratio of successfully received unicasts over the total number of unicast transmitted in the scenario. We first compare the ALOHA, VMAC and VMAC HET protocols between each other, and later we investigate their variants with more realistic neighborhood position info (i.e., including GPS position obtained via RF transmissions) to understand the implications of these features on protocols' performance.

Figure 8 shows the ratio of unicasts lost due to collision for different protocol types and sector counts. As expected, the number of collisions is the highest in the configuration with no sectors (i.e., single sector), where transmissions are carried out with the whole beam of the lighting module. In such cases, the transmitters form a larger collision domain causing interference in the channel. On the other hand, whenever multiple sectors are used for transmission, collisions are almost halved compared to the *no sector* configuration.

Following this trend, it is expected that the ratio of collisions decreases with increasing number of sector, however this does not hold true for the three sector configuration. This is due to the directionality of V-VLC and the road configuration in our intersection: a vehicle communicating with the central sector in the three sector configuration will cause interference to the vehicles at opposing roads. Although the effects caused by the sector configuration can be considered scenario dependent, they show that the road infrastructure and sector configuration can have an impact on communication.

Regarding the performance of the individual protocols, we note that VMAC and VMAC HET perform better than ALOHA. ALOHA has a relatively worse performance because it engages in more transmission attempts compared to the other protocols, as it is not affected by position inaccuracies stemming from the RF channel, like VMAC

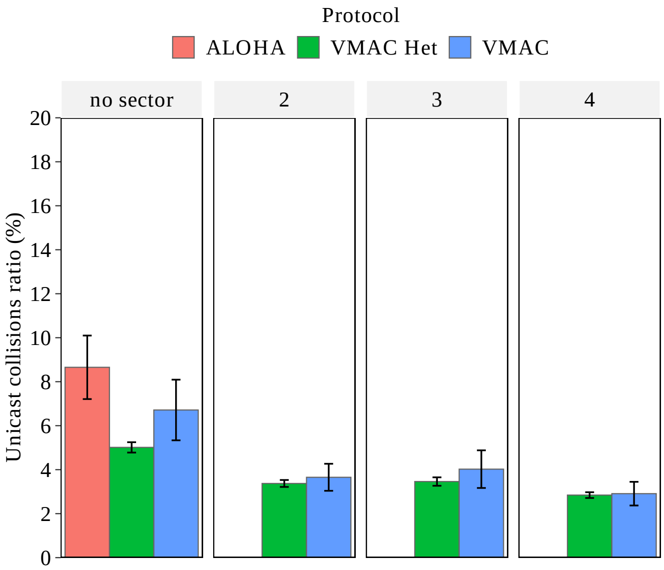


Figure 8: Ratio of colliding unicast messages. Different subplots show this metric for different number of sectors (noted above the corresponding plot). ALOHA does not support multiple sector configurations, hence only shown in the first plot.

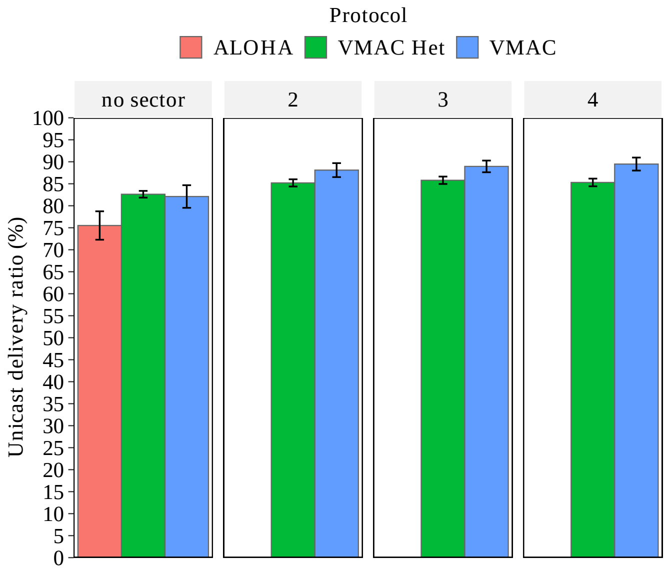


Figure 9: Delivery ratio for unicast messages for different protocols and varying number of sectors (noted above the corresponding plot). ALOHA does not support multiple sector configurations, hence not shown.

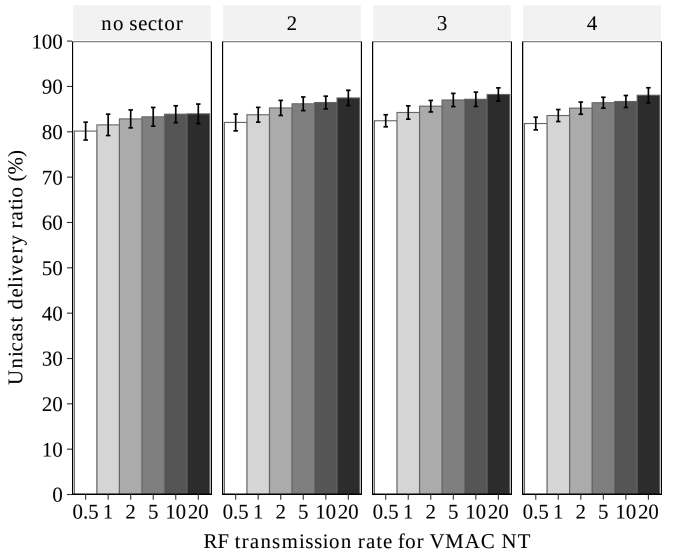


Figure 10: Unicast delivery ratio for V-VLC transmissions for the VMAC Het protocol for different RF transmission rate and number of sectors (noted above the corresponding plot).

Het does; and it does not deploy a collision avoidance mechanism, like VMAC.

Position inaccuracies from the RF transmissions have a prohibitive effect in the case of multiple sector configurations. With the increasing number of sectors, a protocol's requirement for higher accuracy positional data increases. In the contrary, a transmission is carried out with the wrong sector, or prohibited altogether (as a node may appear out of the service area). In the latter case, there are less transmissions in the channel, resulting in a lower collision ratio. That is why VMAC Het performs better than VMAC in terms of the collision metric.

Next, we consider the unicast delivery ratio metric shown in Figure 9. Overall, VMAC has the best delivery ratio performance, with at least 80 %, across all configurations; VMAC Het performs second best, while both protocols perform better than the ALOHA (single sector configuration). Here we observe an increasing trend with the increasing number of sectors. This effect is more pronounced for VMAC and not as much for VMAC Het, because VMAC is superior to the other protocols in terms of neighbors' position accuracy. This effect is discussed in more detail in Section 5.4.

5.3. Impact of RF Beaconing Rate

Note that, despite neighbors' position inaccuracies induced by RF transmission delays, VMAC Het does not perform significantly worse than VMAC (Figure 9). In the following we look deeper into the impact of RF beaconing rate on VMAC Het performance. Figure 10 shows the unicast delivery ratio for VMAC Het for different sector counts and RF transmission rates. We observe that with the increasing RF transmission rate, unicast delivery ratio for VMAC Het improves, approaching the performance

Table 3: Properties of the horizontal GPS error model.

Parameter	**Value (in meters)**
Mean (SD)	0.947 (0.547)
Median [Min, Max]	0.862 [0.001, 4.059]
90 % Quantile	1.672

of VMAC (for the highest transmission rate of 20 Hz), although at the cost of higher RF resource utilization. On the other hand, the improvement can be considered minimal, given the exponential increase in RF transmission rate. Similarly, the impact of RF transmission rate seems to be minimal with respect to the sector count. Increasing the sector count demands more accurate positional data for successful transmissions. A higher transmission rate is beneficial in this aspect, however it does not manifest in this particular scenario (explained below).

Considering the performance of VMAC Het, we can conclude that position inaccuracies due to RF transmission delays do not have a major impact on the protocol's performance. It is important to mention, however, that this effect can be scenario-specific, as in our scenario the vehicles are not too far away from each other (i.e., low transmission delay), and they spend a considerable portion of the time waiting in front of an intersection (i.e., low mobility). In a more dynamic dynamic scenario and over larger communication links the error induced by RF transmission delays can be larger.

5.4. Impact of GPS Position

In Section 4.2, we mentioned that we require GPS positions of the neighboring nodes for transmission decisions. Our horizontal GPS model is based on the empirical values from official sources, presented in [27, Figure 5.2]. Table 3 lists descriptive statistics about the GPS model. In the following, we asses the impact of GPS position on protocols' performance.

Figure 11 shows the collision ratio for the ALOHA+G, VMAC Het+G and VMAC+G protocols. The generic trend is the same as in Figure 8, therefore the same conclusions from Section 5.2 regarding this metric apply here, too. The ratio of collisions for the GPS-enabled protocol variants is slightly smaller compared to their non-GPS counterparts, but the difference is negligible. The reason for this is that the GPS error model is applied universally and uniformly: as such, the probability for a node that is not reachable to appear as if it is reachable, and vice-versa, is the same. Therefore, the number of total transmissions remains roughly the same. Hence, the ratio of colliding unicast messages does not vary significantly between GPS-enabled and non-GPS protocols (cf. Figure 8).

Figure 12 shows the delivery ratio for ALOHA+G, VMAC Het+G, and VMAC+G. As opposed to the collision metric, in the case of this metric the results differ by and large (compared to Figure 9), except for the *no sector*

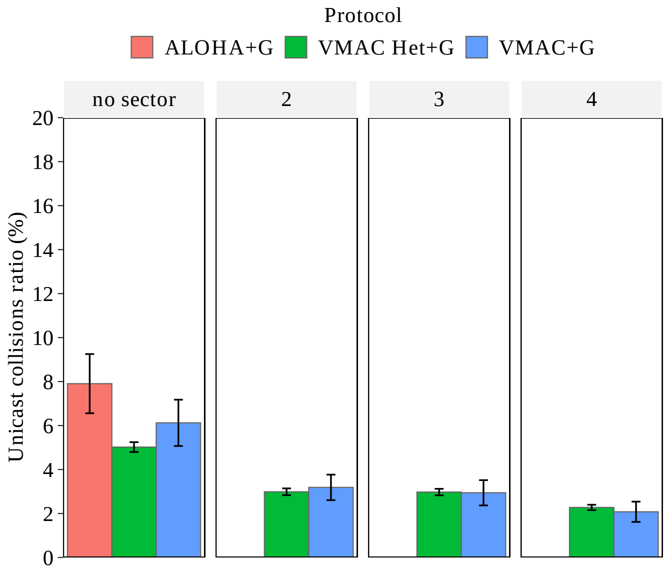


Figure 11: Ratio of colliding unicast messages for VMAC protocols with GPS feature. Different subplots show this metric for different number of sectors (noted above the corresponding plot). ALOHA does not support multiple sector configurations, hence only shown in the first plot.

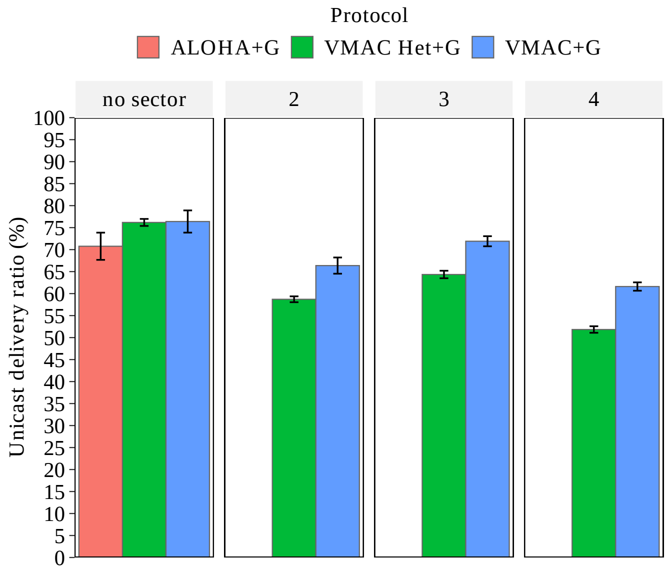


Figure 12: Unicast delivery ratio for V-VLC transmissions for VMAC protocols with GPS positions feature. Varying number of sectors is noted above the corresponding plot. ALOHA does not support multiple sector configurations, hence not shown.

configuration, where the difference is not as pronounced. In the no sector configuration, potential position error stemming from the GPS does not impact the choice of sector for transmission, but it determines whether a node will transmit or not: if a destination node appears to be outside the service area of a transmitter the transmission is not carried out.

For the multiple sector configurations, we observe an overall worse performance for the GPS-enabled protocols. There is a declining trend, where the unicast delivery ratio gets worse with increasing number of sectors. This is opposite to the trend in Figure 9. In general, as the number of sectors increases the central angle gets smaller. Thus, the service area covered by a sector decreases respectively; Therefore, more accurate position information of the neighboring nodes is needed for successful transmission decisions. The implication in Figure 12 is that when the nodes use GPS positions for transmission decisions, they end up transmitting with the wrong sector and they miss the intended destination. Evidently, the impact of the error associated with the GPS positions is critical enough to largely deteriorate protocols performance.

This effect is also manifested in the comparatively worse performance of VMAC Het+G relative to VMAC+G. By design, VMAC Het+G relies on positional information of the neighboring nodes gathered from RF transmissions (cf. Section 5.1). As a result, apart from the GPS inaccuracy, the RF transmission delay adds further error to the positional information, therefore degrading the performance of VMAC Het+G.

6. Conclusion

We presented a new concept for medium access in V-VLC based on a heterogeneous multi-layer protocol architecture. We exploit the space-division characteristic of LED matrix headlights, which provides 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 protocol relies on the exchange of position information between nodes via the RF channel, and the use of this information for V-VLC transmission decision. We designed multiple versions of our protocols to assess the impact of different protocol features, in particular the accuracy of position data.

The results presented in this paper clearly show the benefits of our approach when using multiple sectors for V-VLC communication. Overall, we observe that the use of sectors for transmissions reduces the collisions, regardless of the inaccuracies is position data, because sectors have smaller collision domains. However, we also found that position inaccuracies from the GPS measurements have more adverse impact on protocols performance than the inaccuracies from RF transmissions and node mobility, although the former depends on scenario dynamics and node mobility. Given the capabilities of modern vehicles this can be achieved using error correction techniques such as assisted GPS and a combination of more than one sources of positioning technology.

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