The Chosen One: Combating VLC Interference in Platooning using Matrix Headlights

Max Schettler, Agon Memedi, Falko Dressler
Heinz Nixdorf Institute and Dept. of Computer Science, Paderborn University, Germany
{schettler,memedi,dressler}@ccs-labs.org

***Abstract*—Platooning is one of the Intelligent Transportation System (ITS) applications that is envisioned to improve both road traffic safety as well as road capacity and environmental impact. The coordination of vehicles in a platoon depends on reliable real-time communication. In addition to Radio Frequency (RF)-based technologies such as Dedicated Short Range Communications (DSRC) and Cellular V2X (C-V2X), Line Of Sight (LOS) technologies such as Vehicular VLC (V-VLC) are considered to establish the necessary communication links. In previous work, we investigated the LOS behavior of V-VLC and found that there is a non-negligible amount of interference caused by cars on neighboring lanes or by following cars when driving on a curved road. In this paper, we investigate the impact of such interference on platooning applications. As a solution, we further suggest the use of spatial multiplexing using modern Adaptive Front-Lighting Systems (AFSs). The narrow beams of single LEDs of such matrix lights massively reduce the interference level and make the communication even more robust and reliable.**

I. Introduction

Road traffic accidents caused by motor vehicles remain one of the leading causes of death worldwide,[1] while motor vehicles participating in the road traffic are one of the main air pollutants.[2] To address such critical global issues, and many others arising from the road traffic, various organizations worldwide have supported the development of Intelligent Transportation System (ITS). *Platooning*, technically referred to as Cooperative Adaptive Cruise Control (CACC), has emerged as one of the most promising ITS applications [1], [2]. This application, suggests the formation of vehicle convoys which drive cooperatively and in coordination with each other. Benefits of platooning such as improved safety, fuel efficiency, road utilization, have already been demonstrated in the literature, even for low market penetration [3], [4]. For this technology to work, however, information exchange enabled by Inter-Vehicle Communication (IVC) technologies is mandatory.

Radio Frequency (RF)-based IVC technologies, like Dedicated Short Range Communications (DSRC) and Cellular V2X (C-V2X) have been mainly considered for ITS applications, including platooning [5]. As a safety-critical vehicular networking application, however, platooning has tight reliability and latency requirements: For the safe operation of a platoon, vehicles need to exchange messages frequently with high reception rates. Considering the omnidirectional propagation of RF waves, and the high node density that occurs commonly in road traffic scenarios, it is likely that communication quality will be affected due to network congestion and these requirements cannot be fulfilled. Having in mind that not only platooning, but also other vehicular networking applications might be contending for the same communication resources, it is even harder to guarantee the safe operation of a platoon.

One potential solution is the integration of more than one communication technology with different characteristics in a heterogeneous communication system, e.g., complementing RF with Line Of Sight (LOS) technologies such as mmWave or Visible Light Communication (VLC), to increase the probability of timely and successful delivery of messages [6], [7]. Not relying on a single communication channel is highly desirable for vehicular networking applications to avoid single points of failure, in particular for those concerned with driver and passenger safety, like platooning.

Modern vehicles are already equipped with hardware that can be repurposed as VLC transmitters, namely, LED-based headlights and taillights. This allows a reduction in the implementation costs for such a system. Additionally, VLC has other properties which can benefit platooning as an application. For instance, the LOS nature of VLC can improve security, as the interception of the LOS link can be noticed by the communicating parties; and, the smaller collision domain can help to reduce network collisions [8], [9].

Recent advances in automotive lighting technology have paved the way for new opportunities in terms of Vehicular VLC (V-VLC). For example, the deployment of Adaptive Front-Lighting Systems (AFSs) based on matrix headlights allows the selection of the most adequate LEDs within a headlight for communication with a given vehicle [10]. Motivated by this concept, in this paper, we investigate the extents of interference in platoons, and how it might be mitigated by employing matrix lighting. Our main contributions can be summarized as follows:

- We extend our simulation framework with a mechanism to emulate the behavior of matrix lighting;
- we run an extensive simulation campaign with different scenarios and observe how interference behaves; and
- we compare the performance of the communication within platoons with and without matrix lighting.

II. Related Work

Platooning is among the topics that has attracted the most interest in vehicular networking literature. The feasibility of platooning has already been demonstrated in practice [11],

[1] www.who.int/news-room/fact-sheets/detail/road-traffic-injuries
[2] www.who.int/airpollution/ambient/pollutants/en/

[12]. Particularly, timely communication is essential for the safe operation of a platoon.

Segata et al. [13] have shown that in order to operate safely, a platoon can tolerate communication delays in the range of 200–300 ms at most. To address this issue, Segata et al. [7] have considered the use of VLC for platooning. In their setup, platoon leaders exchange messages with platoon members via DSRC, whereas platoon members use VLC to communicate with their direct neighbors. Simulation results show that even in the highest density scenario with 640 vehicles, at least 95 % of the packets were delivered within 200 ms. One drawback of [7] is that is based on an unrealistic channel model.

In [14], we deployed a realistic V-VLC model [9] to model RF and VLC communication among the vehicles in platoons. We presented two protocols with various degrees of RF and VLC integration, and the simulation results showed that indeed using multiple communication technologies can benefit platooning, and improve reliability even in high traffic and communication density scenarios.

Previous work has also demonstrated the benefits of VLC in terms of security attacks in platoons. For example, Ucar et al. [15] show that various security attacks (i.e., packet injection, channel overhearing, jamming, and platoon maneuver faking) can be mitigated considerably if VLC is used in addition to IEEE 802.11p-based RF communication.

Besides simulations, some authors have also showed the feasibility of VLC for platooning applications with real prototypes. In a static outdoor scenario, Abualhoul et al. [16] demonstrate a VLC transmitter-receiver system, which uses an array of red LEDs as the transmitter. The prototype achieves 100 % Packet Delivery Ratio (PDR) up to 30 m distance, when 40 dB transimpedance gain is applied at the photodiode. In [17], for the first time, Shen et al. demonstrate tail-to-front V-VLC in real driving scenario, proving that platooning can indeed be implemented in the real world.

Despite the fact that V-VLC has a directional collision domain and limited transmission power (as per road regulations), Memedi et al. [9] have shown that interference can still happen in certain scenarios. A potential solution to this has been presented by Tebruegge et al. [10], where by means of simulations the authors show that interference can be effectively reduced by choosing the most adequate LED for communication from a matrix LED headlight. However, the authors did not consider node mobility or a particular application.

In our publication, we aim to build upon this paper by applying matrix lighting to an application, in particular platooning, to investigate how large the influence of interference is, and how reducing it improves the performance.

III. Matrix-lighting in VLC-based Platooning

Platooning is enabled by exchanging information about vehicle dynamics, e.g., their position, velocity, and acceleration. This allows the individual vehicles to compute accelerations that maintain a fixed headway to their preceding vehicle, i.e., their front vehicle. In order to safely support this technology, reliable, timely communication within the platoon is crucial.

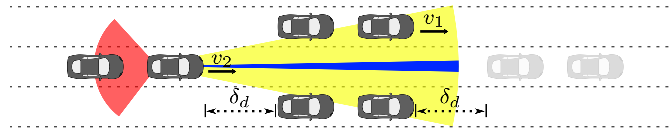


Figure 1. The traffic considered in simulation: one platoon passes between two others. The overtaking platoon starts δ_d behind neighboring platoons and passes them with a velocity difference of $\delta_v = v_2 - v_1$ until it is δ_d ahead of them. The yellow and red area roughly illustrate the head- and taillight's radiation pattern. The blue subset of the headlights pattern depicts a region that is illuminated by a single matrix LED, in this case the central one.

Commonly, DSRC and other non Line of Sight (NLOS)-technologies are used to provide connectivity between platoon members. The large transmission range of these technologies however results in lots of interference, as singular transmissions affect many vehicles. As a result, complex coordination mechanisms are used such as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) in the case of DSRC, or dedicated resource allocation for cellular communication. A promising alternative are LOS communication technologies such as VLC or mmWave. VLC-based platooning in particular has shown improved reliability irrespective of traffic densities [14].

The signal optical propagation characteristics of V-VLC and its long coherence time [8] govern, how VLC can be used for beaconing in platoons. The LOS property necessitates the use of relaying such that the beacons can be received by all platoon members. When relaying is used, unsuccessful receptions do not only affect a single vehicle, but also following vehicles which cannot receive the beacon as well. Accordingly, the individual transmissions need to be very reliable. The close proximity of platoon members results in relatively high received signal strengths. Nevertheless, packet loss can still occur, especially due to interference caused by vehicles on neighboring lanes. One measure against this is the use of Automatic Repeat Request (ARQ), however, due to the long coherence time, it cannot solve this issue alone. A neighboring platoon with similar inter-vehicle distances can lead to severely degraded communication performance, jeopardizing the platoon's safety.

Therefore, we propose leveraging the capabilities of modern matrix lighting modules to limit the interference experienced in platoons [10]. These use multiple LEDs, that each provide illumination to a small sector of the combined radiation pattern (see Figure 1). Such modules are used for illumination, allowing vehicles to leverage the high beam without blinding oncoming vehicles by selectively dimming LEDs. An example headlight is the HELLA HD84, which combines 84 LEDs. The ability to control the LEDs independently from each other also enables using the headlight as a spatially selective transmitter. Such a transmitter only modulates the signal transmitted by the LED that illuminates the intended recipient of a transmission. Consequently, while the illuminated area does not change, information is only being transmitted within a small subset of that region. Therefore, the interference introduced at other receivers within the illuminated area is vastly reduced. Headlight modules that provide this capability are currently being developed, and the general technique is

Table I
KEY PARAMETERS OF OUR SIMULATION SETUP.

Parameter	Values
Scenarios	Straight & Curved highway
Curved highway radius	230 m
Platoon size	8
δ_d	10 m
δ_v	10 km/h
Repetitions	5
Datarate	1 Mbit/s
Beacon rate	10 Hz
LED opening	8°
Matrix headlight attenuation	60 dB

also applicable to taillights. In summary, we aim to investigate how interference by neighboring platoons influences packet reception probabilities, and whether matrix lighting modules can reduce the amount of interference that is observed.

IV. PERFORMANCE EVALUATION

In order to analyze the influence of VLC interference in platooning, and in particular to observe the effects of matrix lighting modules, we ran an exhaustive simulation campaign. The simulations are based on the OMNeT++ 5.4 simulator and use the projects Sumo 1.2, Veins 5.0, Veins VLC 1.0, and Plexe 3.0a1 for mobility, bidirectional traffic coupling, VLC models, and platooning logic, respectively. Veins-VLC in particular provides the models for VLC communication, which are based on empirical measurements [9]. The models describe the radiation patterns observed in real-world lighting modules, giving signal levels for different relative orientations of vehicles. These allow to derive Bit Error Rates (BERs) for individual transmissions. We consider both a straight, and a curved freeway with three platoons of eight vehicles each, where the middle platoon passes the other two with a fixed velocity of 10 km/h (see Figure 1).

The platoons' vehicles use the Path CACC controller [12] and generate beacons to their followers at a fixed rate. The leader's beacons are relayed by the platoon members such that all vehicles of a platoon can receive them. Individual transmissions are acknowledged by the receiver, and retransmitted up to six times in case no acknowledgement is received. We simulate these scenarios for inter-vehicle distances of 3–20 m in increments of at most 1 m. The matrix lighting modules are simulated by applying an additional attenuation of 60 dB to received signals, when the recipient of a signal is too far (more than half the LED opening angle) misaligned from the intended recipient of the signal. The specific values are chosen based on the observations Tebruegge et al. [10], such that the resulting model always offers at most the performance measured in real world. The most relevant simulation parameters are summarized in Table I.

In our simulations, the beacon transmissions are subject to substantial packet loss (see Figure 3a). Starting at inter-vehicle distances of 5 m, the PDR starts decreasing. The losses are first due to collisions, i.e., they would have been received successfully without interference introduced by other, concurrent, signals. With increasing inter-vehicle distances, these losses increase, peaking at 34% (12 m). At this point, we start observing losses caused by low signal strength, in addition to those caused by interference. These losses rapidly rise until no packets can be successfully delivered beyond distances of 16 m. The increase in collisions is a result of the vehicles' orientations and the wide taillight radiation patterns: Signals of vehicles from neighboring lanes can be received with relatively large signal strengths, while the signal strength of actual intra-platoon transmissions decreases with increasing distance.

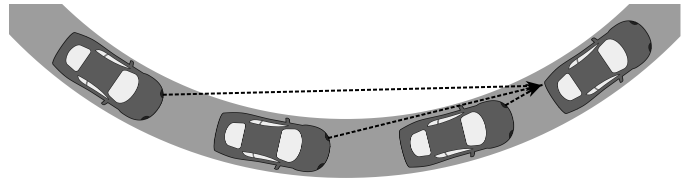
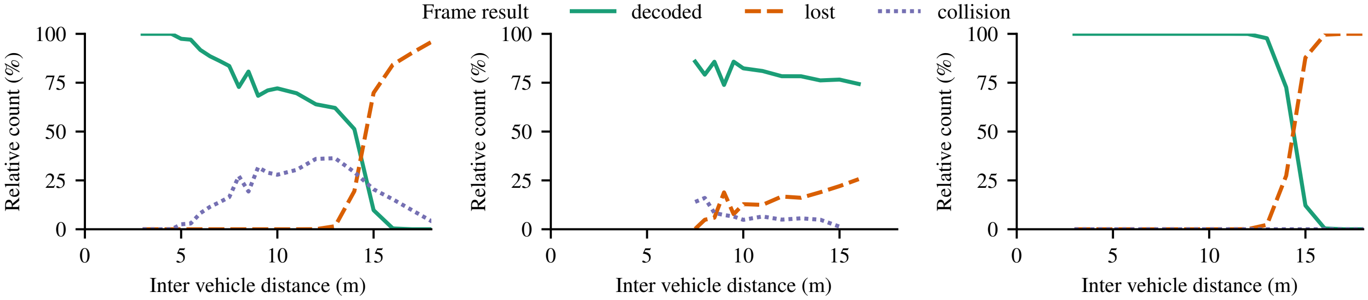


Figure 2. Direct transmission possibilities within a platoon on a curved highway. Note that road curvature and inter-vehicle distances influence between which vehicles a LOS exists.

Receptions of signals sent by the headlights are less prone to collisions. At the intended recipient vehicle, i.e., the sender of the beacon that triggered the acknowledgement, no collisions occur at all. Interference at these nodes still does occur, albeit at sufficiently low levels such that the intended transmission is not harmed. This is due to the narrow beam of headlights: The sources of interfering signals are much farther away than the main signal source (see Figure 2). Therefore, the interference they cause is too small to impact the packets reception. At small inter-vehicle distances, no interference occurs, at all, as the LOS to possible interferers is blocked by the other vehicles.

Even though the interference caused by these signals is not strong enough to affect transmissions between direct platoon members, the signals by themselves can be strong enough to be successfully received. This is outlined in Figure 3b, which shows the reception results for transmissions within the overtaking platoon which were received by vehicles other than the intended receiver, i.e., the front vehicle. About 80 % of the signals that were detected in these cases were successfully received. Given the results, it makes sense to reevaluate the assumptions that led to the communication topology used in the beaconing algorithm. Taking exact positions and orientations into account can allow more efficient beacon dissemination strategies, reaching vehicles near the end of the platoon in fewer hops, and thus, quicker.

With matrix lighting enabled, we note that no collisions are recorded for both beacons (see Figure 3c) and acknowledgements (i.e., transmissions by tail or headlight) for any of the parameters we investigate. The technology effectively avoids interference at unintended recipients to such a degree, that it does not affect packet reception negatively anymore. As a result of the reduced packet loss, the beacon dissemination for platooning increased in efficiency. With matrix lighting, less



(a) Without matrix lighting on a straight highway (b) Without matrix lighting on a curved highway (c) With matrix lighting on a straight highway

Figure 3. Ratio of beacons received, and lost, both due to low signal power and high interference power.

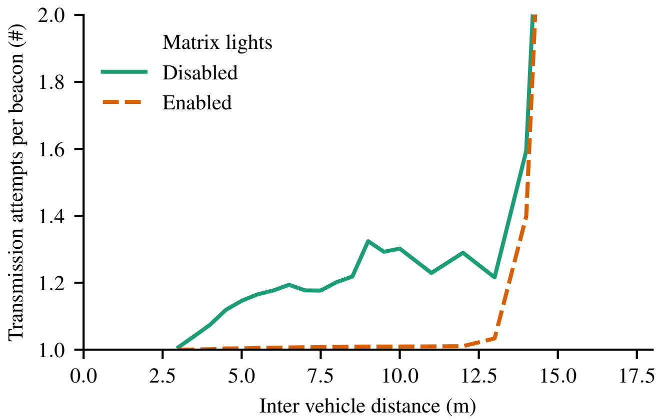


Figure 4. Required transmissions attempts per beacon on a curved road with and without matrix lighting on a curved highway.

transmission attempts are required per beacon, leading to less used airtime, delays, and computational overhead. This effect is depicted in Figure 4. We see, depending on the distance, an additional overhead of up to 27 % without matrix lighting enabled.

V. Conclusion

In this paper, we investigated the influence of interference on Vehicular VLC (V-VLC)-based communication in platooning applications. Our results clearly show that interference from transmissions on neighboring lanes or of following vehicles on a curved road is non-negligible. To overcome this limitation, we suggest to employ Adaptive Front-Lighting System (AFS), which allows to reduce the effect of interference on beacon dissemination by steering the transmission specifically to the intended recipient. Our results show that this reduces interference experienced by the vehicles drastically. In total this approach can reduce the required transmissions by up to 21 %. This demonstrates the possible advantages matrix lighting can provide for cooperative driving applications.

Acknowledgments

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