Towards Heterogeneous Communication Strategies for Urban Platooning at Intersections

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Abstract—**Platooning promises to solve worldwide traffic problems by using wireless communication for tight control of convoys of vehicles to reduce their inter-vehicle gaps. To date, however, most research on platooning has focused on freeway scenarios. In this paper, we provide a realistic exploration of platooning in urban environments: We consider traffic lights and buildings, realistic vehicle dynamics, platooning controllers, and network communication. We highlight the challenges that urban platooning faces because of the particularities of the Radio Frequency (RF) channel, specifically near the centers of intersections. We demonstrate that using Visible Light Communication (VLC) as an alternative can alleviate some problems, but causes others. Using extensive simulations, we show how a situation-aware combination of VLC and RF communication can be used as a solution: It reduces the overall amount of lost information by approx. 85 % compared to traditional approaches.**

I. INTRODUCTION

Traffic worldwide is on the rise and an increasing number of vehicles on streets has always coincided with traffic problems like congestion, increased accident risk, and also with increased emissions (e.g., greenhouse gas and noise) [1]. Already, road congestion is becoming one of the most significant challenges for modern cities. Moreover, the overall amount of people living in urban areas is projected to more than double by 2045 and thus congestion is likely to get much worse [2].

Platooning promises to address the aforementioned problems. It is an Intelligent Transportation System (ITS) application that forms convoys of vehicles and lets them drive in close coordination, keeping a distance of only a few meters between consecutive vehicles [3]. This small inter-vehicle gap, in turn, has a positive impact on both overall road utilization and fuel consumption. To keep such a small inter-vehicle gap, none but the first vehicle in a platoon can be driven by a human; the remainder is driven by a Cooperative Adaptive Cruise Control (CACC) computer system. A CACC exploits data from other platoon members to work and to be able to potentially react better to (or to entirely avoid) dangerous situations. The required data from other vehicles in the platoon is exchanged wirelessly via Vehicle-to-Everything (V2X) communication, traditionally using Radio Frequency (RF) technologies like IEEE 802.11p or mobile broadband Device-to-Device (D2D) communication.

Yet, while the literature [3], [4] has repeatedly shown the benefit of platooning in terms of road utilization, safety, and fuel savings on freeways, current research gives only little consideration to *rural* or *urban* environments.

Urban environments are different from freeways in many respects: Besides the existence of different road users like pedestrians and cyclists, urban environments are characterized by intersections (that may be controlled by traffic lights), buildings, speed limits, right of way rules, one-way streets, etc. Buildings and other obstacles, in particular, impact platooning as they hinder wireless transmissions between vehicles.

Since urban environments offer quite different challenges for wireless communication, conclusions from freeway platooning cannot be directly transferred to rural and urban environments. In this paper, we show that challenging channel conditions increase the probability of message loss while crossing the area where communication is needed most for realizing the full potential of platooning applications: at the intersection. We then examine four different heterogeneous approaches that are using Visible Light Communication (VLC) as an alternative and/or as a complementary channel to enhance the safety of the platooning system. Using extensive simulations, we show that the introduction of the VLC channel as an alternative reduces the overall channel load, but does not solve the safety problem. However, by using a protocol that considers the characteristic of the road network and combines both the RF and the VLC channel in a situation-aware manner, we are able to reduce the amount of lost information by approx. 85 % (thus improving safety) and the overall channel load by approx. 49 %.

In brief, the key contributions of this paper are:

- We provide a realistic exploration of platooning in urban environments with special consideration of traffic lights and buildings; including realistic vehicle dynamics, platooning controllers, and network communication.
- We highlight the challenges that such an approach faces because of the particularities of the RF channel and demonstrate that using VLC can alleviate some problems, but causes others.
- We show how a situation-aware combination of VLC and RF communication can be used as a solution.

II. RELATED WORK

Platooning is one of the most challenging applications in the context of cooperative mobile systems and a lot of research is still ongoing in the areas of communication [5], controllers [3], and maneuvers [6]. One of the most well-known projects tackling a broad range of challenges in platooning in Europe was the SARTRE project [7]. Its purpose was the development of a platooning concept to be used for public motorways in

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parallel with non-platoon traffic. Likewise, a broad range of platoon formation and maneuver strategies have been proposed in recent years [6], [8].

To ensure a stable platoon, the control system is based on reliable communication to exchange messages in the platoon. The consequence is a periodical transmission of messages to all vehicles within the platoon. Such messages contain information that is exploited by the CACC to improve the reactivity of the platoon, thus enabling small inter-vehicle gaps.

There are different approaches of how message exchange can be addressed from an application layer perspective. Segata et al. [9] proposed an approach that is using Transmit Power Control (TPC) and a Time Division Multiple Access (TDMA) like approach within a single platoon. The resulting protocol, *Slotted Beaconing*, assigns time slots to platoon members based on their position within the platoon, thus reducing random channel contention. Another approach, *Jerk Beaconing* [5], further reduces the load on the wireless channel by using an adaptive beaconing frequency. Jerk Beaconing is based on the idea of transmitting messages only when necessary, e.g., when the acceleration of a vehicle changes. In simulations, the protocol showed improved performance in terms of both safety and network resources. Both protocols mentioned above, however, are considering only freeway scenarios.

Besides protocols for more adaptive beaconing techniques on the application layer, a lot of research considers heterogeneous communication using VLC. Schettler et al. [10] proposed different beaconing protocols that use heterogeneous RF and VLC channels. All protocols were assessed utilizing simulations in challenging scenarios like emergency braking or at high vehicle densities. The results showed that safety and a reduced RF channel load can be achieved while still maintaining the desired distance of 5 m. The experiments, however, are only covering platooning on freeways meaning a straight street without any curves or other characteristics that might affect VLC based communication.

Whereas platooning has repeatedly been discussed in the literature as a way to improve road utilization, road throughput, and fuel savings on freeways, platooning in urban scenarios is only considered by few publications:

Lioris et al. [11] investigate the effect of platoons in urban scenarios using a single intersection. They show that the throughput of an intersection can be nearly doubled by simply applying the concept of platooning without changing the traffic light scheduling. We note, however, that these results are based on highly idealized assumptions, also abstracting away from several key properties like acceleration characteristics of the vehicle and wireless networking effects. Lin-heng et al. [12] present a way of optimizing platoons crossing traffic light controlled intersections in terms of both waiting time at traffic lights and fuel consumption. They show that the total travel time and fuel consumption decreases by 19 % and 18 %. The simulations, however, are also based on idealistic assumptions, abstracting away from the acceleration or deceleration process – which has repeatedly been shown to have a high impact on both fuel consumption and traffic flow [13].

In previous work [14] we investigated dynamic platoon formation at an urban intersection that is controlled by a traffic light. We showed that the proposed fuel efficient strategy leads to an improvement to save both 14 % fuel and travel time. However, although we are using realistic models for wireless communication, we do not investigate further consequences on the communication caused by urban characteristics.

The aforementioned publications illustrate that most of related work on communication is not considering rural and urban scenarios, but only focuses on the protocol to exchange beacons or on the channel individually. When urban platooning is considered, results commonly ignore characteristics of wireless networking and vehicle dynamics.

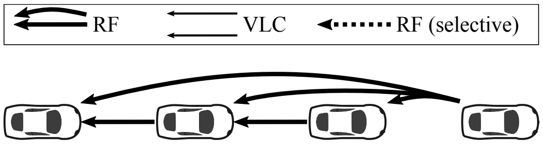
In this paper, we close this gap; we investigate the wireless networking characteristics of RF and VLC approaches for platooning (including platoon formation) in an urban area using realistic simulation models for vehicle characteristics, wireless networking, and obstacle shadowing.

III. PLATOON FORMATION IN URBAN AREAS

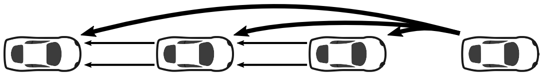
We adopt the platoon formation strategy we employed in our previous work [14]: exploiting red traffic light phases to form platoons. The vehicle at the very front of each platoon (the *Leader*) is driven by a human and a single vehicle is acting as a platoon of size 1. All other vehicles in a platoon (the *Followers*) are driven by a CACC system. To be able to form platoons, each platoon Leader is advertising its platoon by sending Advertising Beacons (A-Beacons) as wireless broadcasts. Such beacons contain information about the position of the platoon, its length, or the route it will be taking. To maintain the platoon and to keep the desired distance for the CACC, all platoon members are transmitting CACC information in Platooning Beacons (P-Beacons). Both types of beacons are used for the platoon formation process and thus stored in a neighbor table.

If a car approaches a traffic light, the formation process is started. We allow vehicles to start a join process only for the end of the platoon. The join maneuver is following a protocol that is started by the joining vehicle and conducted in cooperation with the platoon Leader. A vehicle is allowed to join a platoon if both are sharing a common route and there is no vehicle between the end of the platoon and the joining vehicle that might disturb the join process.

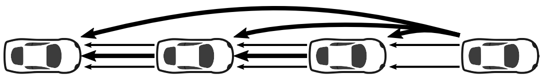
In addition to the join maneuver, we also consider a split maneuver, executed when a platoon is not able to cross the intersection as a whole during a green phase. Since all Followers in a platoon are controlled by the platoon Leader it must determine, for all Followers in a platoon, if this Follower can cross the intersection within the green phase. To give an example, let us consider a platoon with 15 vehicles and a remaining green phase duration of 8 seconds. Assuming a vehicle length of 4 m and an inter-vehicle gap of 5 m, this means that no more than 12 vehicles can pass the intersection during this green phase. Without any further action, the remaining 3 cars would cross the intersection during a red phase and thus violate traffic rules.



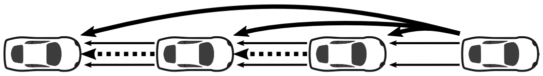
(a) Traditional RF



(b) Traditional VLC



(c) RF and VLC



(d) Situation Aware

Figure 1. Heterogeneous communication strategies investigated in this paper. (a) Leader and Followers are using RF communication. (b) The Leader vehicle uses RF, all Followers are using VLC communication. (c) Leader and Followers are using RF and VLC in parallel. (d) Leader and Followers are using RF and VLC in parallel if they are within the ready area at the intersection. If the platoon is not within the ready area, all vehicles are following the *Traditional VLC* approach.

To make this possible, we assume each traffic light is periodically transmitting information about the current and next phase schedule in what we call Traffic Light Beacons (T-Beacons). The Leader considers the T-Beacon to calculate the number of vehicles that can cross the intersection within the green phase. If the platoon is too long to cross the intersection, the Leader initiates a platoon split maneuver. Our approach to split platoons mainly considers the platoon length (based on data stored in the neighbor table) and the acceleration process of a platoon. Considering the acceleration process is important since a platoon gets created during a red phase (while the speed and acceleration are 0). Based on the current sensor values (speed and acceleration), the Leader calculates the separation point of the platoon. The first vehicle after the separation point stops in front of the traffic light and starts to announce its platoon again. The formation process starts and a new platoon gets created to start driving in the next green phase.

IV. HETEROGENEOUS PLATOONING

Platooning faces many challenges, many of which are related to the system being based on RF based communication and distributed channel access [15]. The first class of problems are those related to security threats like jamming of the channel or malicious attacks like false data injection, which makes communication and cooperation impossible [16]. The second problem is congestion of the wireless channel which leads to higher message loss and thus to unreliable communication. For platooning, a reliable channel is needed, even in crowded and unpredictable scenarios where other applications are using the wireless spectrum in parallel.

Similar to much of the latest research in platooning [5], [6], [10], [16], we are focusing on the CACC PATH [17] controller for platooning, since this enables platoon members to drive with a constant spacing of only a few meters. This leads to the highest benefit in terms of road utilization and road throughput. The PATH controller exploits data transmitted from both the immediately preceding vehicle and from the Leader (Figure 1a).

As VLC communication is a Line of Sight (LOS) technology and thus easily blocked by other vehicles, communication to the Leader always requires RF communication. In this paper we examine four strategies for using VLC in parallel with RF communication to make the exchange of P-Beacons within the platoon more reliable.

- *Traditional RF* (Figure 1a): This approach uses RF based communication for all vehicles in a platoon. It is most commonly used in the literature [5], [6], [9]. We employ it to serve as a baseline scenario to see the impact of more advanced approaches combining the VLC and RF channel.
- *Traditional VLC* (Figure 1b): This approach is using VLC as an alternative medium to transmit P-Beacons. Vehicles' tail lights are used to establish a communication link between two consecutive vehicles in a platoon (using tail lights is necessary since the PATH controller requires information from the preceding vehicle and not from the following one). As the Leader P-Beacons must reach every vehicle in the platoon, they are still sent via RF.
- *RF and VLC* (Figure 1c): This approach uses both RF and VLC based communication for all members in a platoon. This leads to redundant transmissions of the same information, so information of a beacon is lost if and only if both channels suffer from message loss – however, at the expense of increased channel load.
- *Situation Aware* (Figure 1d): This approach exploits geographic information about the road network. It aims to ensure a reliable communication link especially at the point where communication is needed the most: close to the center of the intersection. For this, the approach uses both RF and VLC based communication for all members in a platoon which are within a ready area, close to the intersection.

All other applications (A-Beacons, T-Beacons, the join, and the split maneuver protocol) are always using RF based communication. The scheduling of beacons is following a static approach using pure CSMA/CA without any further adjustments.

V. EVALUATION

We investigate the performance of all four heterogeneous communication strategies using computer simulation.

We consider the single intersection scenario we proposed in [14], which is a symmetric intersection with four legs, governed by a traffic light. Each of the legs has a length of 500 m, where the first half of the road is a single lane road whereas the second half consists of three lanes. The intersection allows vehicles to turn right, to go straight, or to turn left;

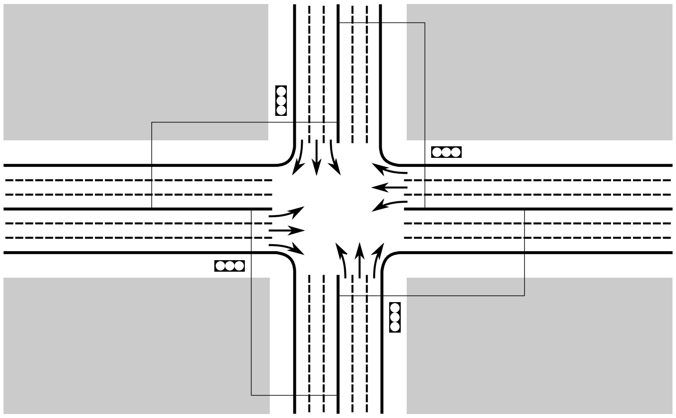


Figure 2. Ready area of the intersection. All vehicles within this area are following the *Situation Aware* approach.

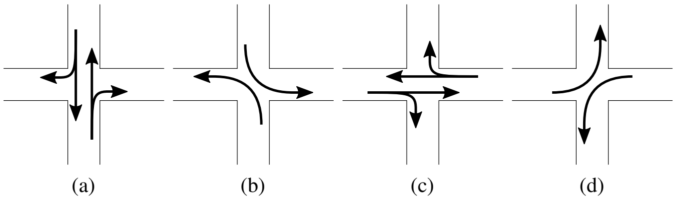


Figure 3. Four phases of the traffic light controlling the intersection.

vehicles take these turns with weights of 1:4:1, respectively. Vehicles are entering and leaving the road network at its edges. Thus, each vehicle travels a total distance of approx. 1000 m.

The ready area for the *Situation Aware* approach is defined to cover just the first vehicle queueing in front of the traffic light as well as the first 3 vehicles leading away from the intersection; in more detail, it is defined as the last 2.40 m of any lane leading up to the intersection up to the next 30 m of any lane leading out of the intersection (Figure 2).

Besides the intersection, the network contains fully opaque buildings placed at a distance of 5 m to the street. Without loss of generality, we assume that P-Beacons are transmitted periodically, at a frequency of 10 Hz. A-Beacons and T-Beacons are also transmitted periodically, but at a frequency of 1 Hz. For simplicity, we further consider cars to be uniquely identifiable, though this assumption can easily be relaxed using established privacy concepts. Received beacons are maintained in neighbor tables of each vehicle. Their entries are updated each time a vehicle receives a new beacon from a corresponding neighbor. Platoon entries for which three consecutive beacons were missed are considered invalid and thus removed from the table. The same holds for traffic light beacons for which a beacon was missed.

Following recommendations by Koonce et al. [18], we use a static green time of 8 s and a static yellow time of 3 s for the traffic light. The traffic light cycle consists of four phases with a total cycle length of 44 s. For ease of interpretation, all four phases of the traffic light are configured to be non-competing, as illustrated in Figure 3.

Table I
SIMULATION SCENARIO.

Simulation time	1000 s
Replications	100
Intersection legs	4
Intersection leg length	500 m
Number of lanes at intersection	3
Spawn position of vehicles	random (north,east,south,west)
Spawn rate of vehicles	0.48 veh/s
Turn direction	random (1:4:1 left:straight:right)
Traffic light scheduling	Non-adaptive
Green / Yellow phase duration	8 s / 3 s
Cycle time	$44\,\mathrm{s} = 4 \times (8\,\mathrm{s} + 3\,\mathrm{s})$

Table II
PLATOONING SIMULATION PARAMETERS.

Simulation models	Plexe 3.0a1 with SUMO 1.2.0
SUMO update interval	0.01 s
Car Following (CF) model	Krauss and CACC
Vehicle length	4 m
Desired speed v_d	13.9 m/s (approx. 50 km/h)
Max speed $v_{\max}$	13.9 m/s (approx. 50 km/h)
Min speed $v_{\min}$	0 km/h
Max acceleration	2.5 m/s^2
Max deceleration	9.0 m/s^2
Krauss driver imperfection σ	0.5
Krauss desired headway	0.5 s with 5 m minimum
CACC implementation	California PATH controller [17]
CACC desired gap d_d	5 m
CACC bandwidth ω_n	0.2 Hz
CACC damping ratio ξ	2
CACC weighting factor C_1	0.5
Maneuver timeout	1 s

We implement all four heterogeneous communication strategies in the simulation tool Plexe [20]. Plexe extends the popular open source[1] vehicular network simulator Veins [21] with simulation models for platooning and uses the SUMO [22] simulator for modeling road traffic. The lateral controller is emulated by the default SUMO lane changing algorithm. For the longitudinal control policy of human-driven cars, we rely on the Krauss [23] model. For the longitudinal controller of computer-driven cars, we rely on the PATH CACC, following the values proposed by Segata et al. [5]. Since the PATH controller is following a constant gap policy, we can set the distance to 5 m in our experiments. As the platoon Leader is driven by a human we set $\xi = 2$ for stronger damping and thus improved string stability of the platoon [24]. We note, however, that an analysis of the properties of CACC controllers is out of the scope of this paper.

For the simulation of VLC based communication we use Veins VLC [25] to model the transmission of an OOK modulated signal from both tail lights of a vehicle to a photodiode mounted at the front bumper of each following vehicle. Veins VLC calculates the Bit Error Rate (BER) of each transmission depending on the Received Signal Strength (RSS) which, in turn, is based on radiation patterns for tail lights that are fitted to real world measurements. Traditional radio-based communication uses the IEEE 802.11p model of Veins.

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[1] http://veins.car2x.org

Table III
WIRELESS NETWORK SIMULATION PARAMETERS.

Simulation models	Veins 5.0
P-Beacon interval	0.1 s
A-Beacon interval	1.0 s
T-Beacon interval	1.0 s
P-Beacon length	2758 bit
A-Beacon length	1158 bit
Access category for beacons	AC_VI
Technology	IEEE 802.11p
Carrier Frequency	5.890 GHz
Transmission power	20 mW
Bit rate	6 Mbit/s
Noise floor	−95 dBm
Path loss (Friis model)	$\alpha = 2$
Shadowing	fully opaque buildings

Table IV
VISIBLE LIGHT COMMUNICATION (VLC) SIMULATION PARAMETERS.

Simulation models	Veins VLC 1.0
Bit rate	1 Mbit/s
Noise floor	−110 dBm
Minimum power level	−114 dBm
Modulation scheme	OOK
Analogue model	“EmpiricalLightModel” [19]
Transmission angle	±45°

We remove transient phases at the beginning and the end of the simulation from statistic collection and perform 100 independent runs for statistical significance.

The most relevant parameters of our simulation setup are summarized in Tables I to IV.

A. Metrics

We choose four metrics to analyze our approach.

First, we consider *RF P-Beacons sent*, that is, the number of P-Beacons sent via the RF channel. This allows us to gauge the amount of network load that cannot be offloaded to the VLC channel and thus impacts other applications or must be paid for.

Second, we consider *frame collisions* on the RF channel. We deem a frame reception attempt a collision if the sender is no more than 50 m away and the simulation model (using identical pseudorandom numbers) would have decided on successful frame reception when ignoring interference. This allows us to gauge the impact of channel load on network performance.

Third, we consider *missing information*. This is measured as the contents of P-Beacons sent by the Leader or the immediately preceding vehicle, but not received by a Follower using either technology. In more detail, each Follower in the network increments this number as long as the time gap to the last CACC information update is larger than the beacon interval (plus a small margin for processing and propagation delay). Segata et al. [9] illustrate how missing information directly leads to degraded safety in a platoon, so this is a direct indication of system performance.

Fourth, we consider the *RSS of VLC frames*. Memedi et al. [25] showed that the distance and angle of the communicating vehicles have a significant impact on communication. In contrast to this work, which is using headlights, our experiments are relying on communication using tail lights. We especially have a look at critical scenarios like a platoon taking a turn at an intersection. While taking a turn, the VLC-based communication can result in a lower RSS and thus in frames that cannot be decoded. This leads to missing information from the preceding vehicle and impacts the stability of the platoon.

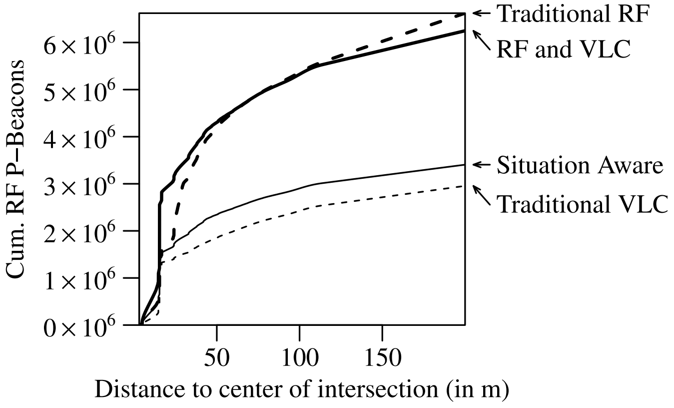

Figure 4. Cumulative values of the *RF P-Beacons sent* metric (over distance to the center of the intersection).

B. Channel effects

Figure 4 shows the cumulative sum of the *RF P-Beacons sent* metric depending on a vehicle's distance to the center of the intersection. In more detail, for all distances x from the center of the intersection and values $f(x)$ of the metric at this distance (as well as considering all replications i of the simulation), we plot the value of $F(x) = \sum_i \sum_{\xi \leq x} f_i(\xi)$.

We can observe a high number of transmissions at the stop line in front of the intersection. This is due to the queuing of vehicles in front of the traffic light. Since a single green phase has a duration of 8 s, a vehicle might be queueing in front of a red traffic light for more than 30 s while P-Beacons are transmitted at a frequency of 10 Hz.

After leaving the ready area, both the *RF and VLC* and the *Traditional RF* approach continue to use RF-based communication for all vehicles within the platoon. Thus the number of transmitted P-Beacons are roughly the same for both approaches. The reason for a slight difference in sent number of P-Beacons and for a shift of network load to further away from the intersection for the *Traditional RF* approach lies in lost information causing differences in platoon behavior, as we will show later.

The *Traditional VLC* and (when outside the ready area) *Situation Aware* approaches are using RF communication only for the Leader to Follower transmissions and all Followers are using VLC only. Therefore, the amount of transmitted P-Beacons on the RF channel is much lower. Since Followers in the *Situation Aware* approach are also using RF communication within the ready area, the amount of RF beacons is higher compared to the *Traditional VLC* approach.

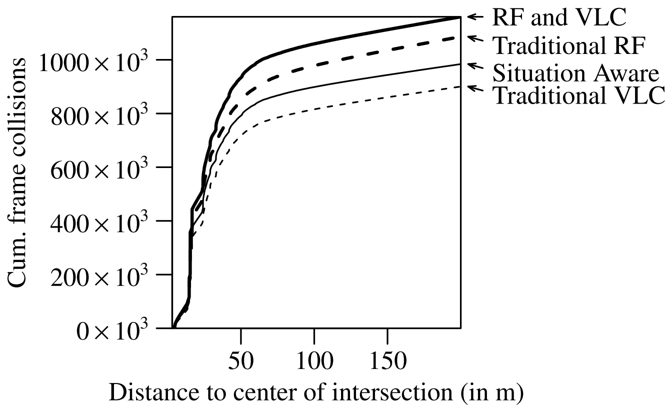

Figure 5. Cumulative values of the *frame collisions* metric (over distance to the center of the intersection).

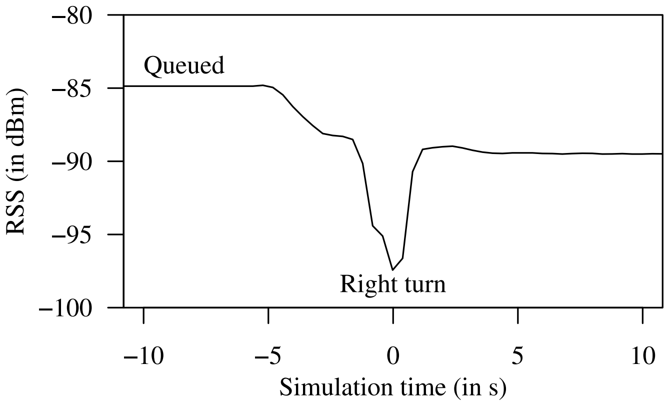

Figure 6. Average values of the *RSS of VLC frames* metric while a platoon is taking a right turn.

The high amount of transmissions on the RF channel leads to a non-negligible load on the wireless channel, which the CSMA/CA channel access procedure has to manage. We, therefore, investigate cases where CSMA/CA has failed, i.e., one node's frame being non-decodable because of another node transmitting at the same time.

Figure 5 shows the cumulative sum of the *frame collisions* metric (again, versus distance to the center of the intersection). We can see that only few collisions happen on the intersection's legs, except for the general area around the intersection.

Considering the *Traditional RF* scenario, we conclude that CSMA/CA is working well on roads that are fully surrounded by buildings (and thus are not affected by interference from other cars besides that road). However, this is not the case when a vehicle is near center of the intersection and attempting to receive messages from a vehicle further away; here two collision domains overlap (one for each road flanked by buildings). This results in a classic hidden terminal problem, as two simultaneously transmitting nodes from each of the collision domains are not aware of each other's transmission.

This behavior is exhibited similarly by the other approaches that are using VLC in parallel to the RF channel. Still, the *Traditional VLC* approach is resulting in fewer collisions than the *Traditional RF* approach. Since all Followers in a platoon are not transmitting any information on the RF channel, we observe a decrease in the frame collision of approx. 20 % compared to the *Traditional RF* approach.

When considering the *Situation Aware* approach, the frame collision metric increases in the area close to the intersection as in the *Traditional RF* approach. The reason is that, in this area, the number of transmissions on the RF channel is identical to the number of transmissions in the *Traditional RF* approach. However, considering the full scenario it is still approx. 9 % lower compared to the *Traditional RF* approach.

The *RF and VLC* approach shows the same overall behavior as the *Traditional RF* approach. However, like for the *RF P-Beacons sent* metric, the additional VLC channel partly compensates collisions on the RF channel. As a result, fewer vehicles are getting separated from a platoon, which leads to more transmissions of P-Beacons on the RF channel and thus to a higher amount of frame collisions compared to the *Traditional RF* approach.

Since we so far only considered the impact on the RF channel, we now turn to the impact of VLC communication using tail lights. We investigate the consequences of this approach especially in critical scenarios: turning maneuvers at the intersection. For this, we are considering the *RSS of VLC frames* metric.

To evaluate the effects of the VLC based communication we consider a sample of four cars from our simulations that are following the same route and form a platoon when approaching the red traffic light. After the platoon formation was successful, all vehicles are following the *Traditional VLC* approach to exchange P-Beacons. When the traffic light changes to green, the platoon starts to drive and performs a right turn.

Figure 6 illustrates that, as vehicles are turning right, an average drop of the RSS by more than 10 dB occurs because of tail light characteristics. We also note that, in approx. 10 % of all replications, at least one Follower in a platoon loses connectivity to the rest of the platoon and consequently is not able to close the gap to the vehicle in front (data not shown). Since the RSS gets very low while taking a turn, vehicles are affected by message loss in approx. 75 % of cases. After the turn maneuver has been performed by all vehicles, they continue to drive in LOS and the RSS increases again. However, we notice a lower RSS after all vehicles finish the turn. This is because the inter-vehicle distance is now slightly increased. The reason for this is the fact that the platoons in our experiments are led by a human driver. Thus, a leader is not able to perfectly predict the desired acceleration u_0, which is expected as an input for the CACC PATH [24]. The consequence is a platoon that has a slight lack of string stability and thus the vehicles get a slightly higher distance to the Leader compared to the desired distance of 5 m. This gap cannot be closed anymore since the

Leader is driving at the speed limit, which Followers were configured to obey. String stability is an important property of a platoon since it ensures the system does not cause vehicle collisions (under normal conditions) [5]. However, this negative impact on string stability can be ignored in this scenario, since the effect is minimal and does not cause vehicle collisions.

C. Impact on the application layer

We now turn to the consequence of the high RF load, especially the increased frame collisions. Since the vehicle's speed in front of a red traffic light is zero, it is rather easy to close the gap to the vehicle in front. However, the implemented join maneuver still requires the handshake procedure described above. If one of the required transmissions gets lost, the maneuver cannot continue and is aborted and then restarted after a timeout of 1 s. This is because, following the conclusions of work by Klingler et al. [26], unicast transmissions are not repeated by the MAC layer in our setup. Our experiments are showing an increased number of aborted maneuvers in front of the intersection for all protocols (data not shown). To further investigate this insight, we perform additional experiments. For this, we change the distance of the buildings to the street from 5 m to 20 m in 5 m steps. Our results show that the number of aborted maneuvers is decreasing with increasing distance between buildings and streets. The lowest number of aborted maneuvers is achieved when no buildings are around.

Yet, the consequence of an aborted maneuver has no impact on the platoon formation, since the maneuver gets restarted and the red phases are sufficient to try a join more than once during a cycle. The effect can be further weakened by introducing retransmissions for the platoon formation since the handshake is done by unicast transmissions.

Considering the control topology of the CACC, however, it is clear that lost information has a significant impact on the stability of the platoon as a whole. The PATH controller requires input data from the leading and the preceding vehicle in a platoon to keep the platoon stable. This control topology is one of the major differences to time headway based CACC implementations like that of Ploeg et al. [27] and allows string stability with inter-vehicle distances of only a few meters. Thus, message loss can have negative effects on the stability of a platoon and on safety [28].

Figure 7 shows the cumulative sum of such *missing information* (again, versus distance to the center of the intersection). Especially for the *Traditional RF* approach we can observe an increasing amount of missing information in front of the intersection (while waiting for a green light), but also on the intersection itself. These lost beacons carry the acceleration and speed of the platoon, which is used as an input for the PATH CACC. So, due to the unreliable channel, the platoon's string stability property is easily violated.

The *Traditional VLC* approach exhibits a lower amount of lost information compared to the *Traditional RF* approach. This can be explained by a more robust channel and by the substitution of RF-based transmissions by VLC based communication, which leads to a lower load (reduced by about 40 %) on the RF channel. Still, the amount of lost information is too high to ensure a stable communication link for a safety critical application. These lost beacons are particularly caused by the aforementioned RSS drop during turning maneuvers (cf. Figure 6).

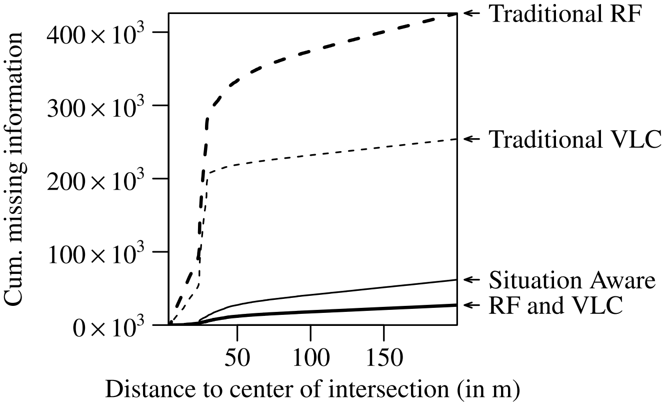

Figure 7. Cumulative values of the *missing information* metric (over distance to the center of the intersection).

The solution lies in our proposed *Situation Aware* approach, which considers the geographic information about the network. This approach mitigates this problem by using the RF and VLC channel in parallel. The data in Figure 7 shows that this approach reduces the amount of lost information by about 85 % compared to the *Traditional RF* approach.

We note that, since the *RF and VLC* approach is using VLC and RF communication regardless of the road network topology, the amount of lost information is even lower compared to the *Situation Aware*, as it is also lowered on the intersection legs. Yet, for the critical area around the intersection, our *Situation Aware* approach results in the same, low amount of lost information as the *RF and VLC* approach.

D. Discussion

We conclude that – without further adaptations – pure RF-based communication for platooning is not sufficient to meet the communication requirements for safe driving in a platoon in urban areas. Introducing a second VLC channel relaxes the situation and decreases the load of the RF channel by approx. 55 %. However, both the *Traditional RF* and the *Traditional VLC* approach suffer from different problems. The RF D2D channel suffers from high channel load and hidden terminal problems near the center of the intersection, whereas the VLC channel suffers from lost LOS during turning maneuvers. Thus, a combination of both channels is necessary to enable platooning in urban areas. The straightforward *RF and VLC* approach (constant usage of both RF and VLC based communication) results in the best improvement in terms of *missing information*. However, we note that this higher reception rate comes with a comparatively strong increase of RF channel load.

We thus advocate for the presented *Situation Aware* approach. Although the channel load caused by the *Situation Aware* approach is approx. 45 % lower compared to the *RF and VLC* approach, the overall amount of missing information in critical areas (close to the center of the intersection) is roughly the same for both approaches. In more detail, the *Situation Aware* approach reduces the number of frame collisions and transmitted RF beacons by approx. 9 % and approx. 49 % respectively.

VI. CONCLUSION

We have analyzed the impact of urban characteristics on platooning, especially the consequences for the wireless channel. Summing up all results, the platoon formation strategy [14] is viable, yet urban platooning supported only by Device-to-Device (D2D) Radio Frequency (RF) communication can be considered problematic in terms of safety due to the unique propagation conditions offered by intersections. Our results show that platoon *formation* is not strongly affected due to frame collisions; however, our results also serve to illustrate that, without further measures, *driving* in such a platoon in the shown scenario may be violating safety requirements for platooning applications. This is because frame collisions negatively impact precisely the point where communication is needed the most: near the center of the intersection.

The problem can be mitigated by introducing Visible Light Communication (VLC) as a second channel. While VLC has not proven advantageous as the sole channel for platooning in urban scenarios, a protocol that allows a situation-aware switching between both channels has. Using extensive simulations, we showed that such situation-aware switching can reduce the overall amount of lost information by approx. 85 % without causing an undue increase of channel load.

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