Deeply Integrating Visible Light and Radio Communication for Ultra-High Reliable Platooning

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***Abstract*—Platooning is one of the most promising Intelligent Transport Systems (ITS) applications, which is set to reduce the negative aspects of road traffic, by improving safety, fuel efficiency, and road efficiency. Reliable data communication is the key to such applications, besides better and smarter local sensors (e.g., radar or video). Current platooning solutions primarily build upon vehicular networking technologies such as Dedicated Short Range Communication (DSRC) and cellular V2X. However, high communication reliability is still a concern, particularly with high vehicle densities due to increasing interference levels. In order to alleviate this, the use of Visible Light Communication (VLC) instead of, or in addition to Radio Frequency (RF), has been proposed. We explore the capabilities of RF and VLC based communication protocols for platooning with a strong focus on reliability. Additionally, we propose and explore heterogeneous solutions using RF and VLC together complementing each other. By means of extensive simulations, we analyze the performance of all these solutions. Based on realistic simulation models, we show that significant improvements in terms of reliability can be achieved by integrating VLC. In this initial study, we also show that deeply integrated heterogeneous communication with RF and VLC can bring platooning one step closer to large-scale real-world deployment.**

I. Introduction

Platooning is a promising upcoming technology that is set to improve many aspects of road traffic. Using platooning, improvements in road utilization, safety, fuel efficiency, and driving convenience are possible [1]–[3]. Because these effects can be observed even at low market penetration rates, thus, platooning is an ideal application for early adoption of Intelligent Transport Systems (ITS). To enable the operation of platoons, however, cars need to exchange information to close the local control loop steering the acceleration of each individual car. Current proposals achieve this mostly by the use of Radio Frequency (RF)-based communication such as Dedicated Short Range Communication (DSRC) based on IEEE 802.11p or cellular V2X [4], [5].

In order for platooning to work safely, high update rates, and thus, high message rates, are required [6]. Additionally, the close inter-vehicle distances result in an increased vehicle density, especially if multiple platoons are supported in close proximity on the same freeway. Therefore, relying only on RF can cause significant network congestion, because a lot of transmissions are needed, and large amounts of vehicles are affected by them. This monopolization of the shared network is not desirable, as it leaves few resources for other applications. Moreover, the network congestion can become so large, that even stable, and thus safe, platooning cannot be guaranteed anymore [5]. One approach to solve this issue is to deeply integrate communication protocol design with the control loop used for the operation of the cars, such as in the context of the 5G Tactile Internet [7].

Another solution is to integrate classical RF with line-of-sight (LOS) technologies. Initial studies suggest, that complementing RF with Visible Light Communication (VLC), thereby exploiting an additional part of the electromagnetic spectrum, helps to achieve higher communication reliability [8]. Vehicular VLC (V-VLC) is enabled in cars by Light-Emitting Diodes (LEDs) used in modern head and taillights. The LEDs can be switched at high frequencies that are not perceptible by the human eye. By this means, the signal can be modulated such that it transmits information between vehicles, thus, leveraging the large amount of unlicensed bandwidth available in the visible light spectrum. Due to the light's propagation characteristics, reception is mostly dependent on the LOS between sender and receiver. It can only reach a relatively small number of nodes, that is vehicles in our case, which limits network congestion.

Despite these advantages, the use of VLC in cars also has some downsides. When aiming to reuse the LEDs already present in the head and taillights to save costs, the VLC component cannot alter some properties of the system, such as the average transmission power or the radiation pattern. Consequently, communication by means of the headlight, for example, can operate up to distances of about 120 m within a narrow beam in front of the car [9]. Moreover, adverse weather conditions like fog and heavy rain or bright daylight can reduce the achievable range severely [10].

Given the different properties of RF and VLC communication, heterogeneous communication for platooning has attracted attention in the research community. Early studies indicate an improvement of safety can be achieved, but further work with more realistic VLC models has to be done [11]. Since such models have become available recently [9], in this initial study, we investigate the performance of VLC in the context of Inter Vehicular Communication (IVC) in greater detail by means of simulation.

Our main contributions can be summarized as follows:

- We design and implement two communication approaches which employ heterogeneous communication using RF and VLC;
- we complement the developed approaches with mechanisms for reliable beacon delivery and multi-hop communication; and

- we evaluate the performance of the approaches in comparison with two non-heterogeneous protocols in an extensive simulation campaign.

II. Related Work

Platooning is a research topic which recently has attained significant interest. Working systems already have been described and proven to operate successfully, e.g., by the PATH project [12] in the US and the SARTRE project [13] in the EU. For a platooning system to work, besides local distance sensors, communication between vehicles is fundamental. For example, Segata et al. [5] have shown that a maximum intra-platoon communication delay of 200–300 ms has to be achieved to guarantee safe operation. Using large-scale simulations, the authors have also demonstrated that achieving this bound is challenging using only RF-based protocols. This was observed in particular in high traffic density scenarios, which suffer from large network congestion. In these scenarios, only 90 % of the required messages were delivered within 200 ms.

In order to alleviate such effects of network congestion, VLC was considered for use in platooning applications. Abualhoul et al. [14] simulated the expected channel quality between vehicles in a platoon. In their simulation, they assumed an Additive White Gaussian Noise (AWGN) channel with a Lambertian emitter and found that the Bit Error Ratio (BER) is below 10^{-6} for a 10 MHz for vehicle arrangements typical in a freeway platoon. In a followup study, the authors demonstrated an actual VLC transmitter-receiver system [15]. The system showed a high Packet Delivery Ratio (PDR) up to 30 m, as well as a low latency of below 36 ms. The main limitation in this study has been the relatively low data rate of 3.8 kbit/s, which results mainly from processing limitations imposed by the used low-cost hardware. Based on the performance of the VLC system, the authors simulated a platoon of three vehicles which relied on VLC to exchange information. Even though the simulated vehicles relied only on their front vehicle's information, according to the authors, they were able to match its speed within 35 ms.

A different study conducted by Béchadergue et al. [16] also developed prototype VLC transmitters and receivers. The prototypes are based on commercial of-the-shelf (COTS) head and taillights, and a photodiode-based receiver circuit and were tested for suitability in platooning. The authors concluded that for vehicle orientations and distances (up to 10 m) typical in platoons, communication is possible at 100 kbit/s with a delay of 5 ms for all of the investigated light modules, i.e., head, tail, and brake light in traffic mode. At the same time, the interference received from neighboring lanes remained below 7 % of the total signal power.

Given these results, and given the fact that RF-based platooning is also susceptible to jamming attacks [17], Ishihara et al. [8] have investigated VLC in combination with RF. The authors demonstrated in simulations that heterogeneous communication with RF and VLC decreases the susceptibility to an RF outage induced by an attacker drastically. A similar study conducted by Ucar et al. [18] additionally considered application level security, e.g., replay attacks or malicious injected packets. Both studies show the advantages of heterogeneous communication with VLC in simulations, however, using a relatively small amount of vehicles, i.e., 60 and 15 vehicles, respectively.

A first large-scale simulation of VLC-enabled platoons was conducted by Segata et al. [11]. They simulated up to 640 vehicles which formed platoons. While the platoon leaders used IEEE 802.11p to transmit information to all platoon members, direct neighbors exchanged information via VLC. With this adapted control topology, even in the most demanding scenario with 640 vehicles, a maximum latency of 200 ms was achieved for at least 95 % of the packets. However, the channel model which was used is not very realistic, as it models the channel's PDR as a simple Bernoulli process.

To this end, more realistic models of VLC channels have been published recently by Memedi et al. [9]. The authors used the measured received Signal to Noise Ratio (SNR) of a headlight empirically for different lateral and longitudinal distances. Based on these values, they fitted a model which can be used for accurately predicting the received SNR at arbitrary positions and orientations to the sender.

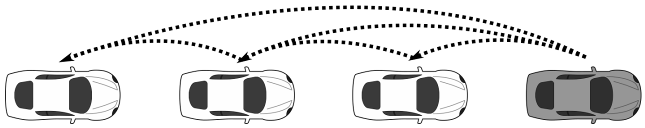
The literature reviewed above indicates potential benefits from employing VLC with platooning, however, large-scale simulations with realistic VLC models have not been conducted so far. We present results from such a study and also develop protocol variants that deeply integrate RF and VLC communication.

III. Protocols

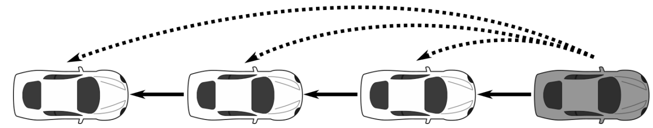
We propose beaconing protocols that rely on VLC to varying degrees. The protocols are designed to transport both leader and front beacons to all platoon members in a timely manner. Two of the protocols are heterogeneous, i.e., they use both RF and VLC, while the other two only use one of the available communication channels.

The different approaches are designed such that they differ in the extent of VLC integration, as well as their focus on safety and efficiency (cf. Figure 1):

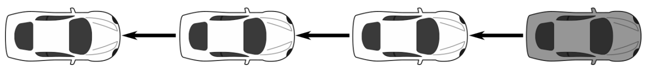
- *RF*: This approach solely uses RF communication for message dissemination. It is included as a baseline for comparison with the other approaches. As has been shown by existing research, this approach suffers from high congestion caused by DSRC's large interference domain, high traffic density, and message rates [5].
- *VLC*: This approach uses only VLC. The main challenge is therefore, that only direct neighbors within a platoon have direct LOS between each other. As a result, the beacons need to be forwarded via multiple hops, in order for the leader's information to arrive at its followers. Hence, this method is particularly vulnerable to packet loss, as the overall PDR is reduced with each hop. Additionally, the beacons' information ages while it propagates through the platoon.
- *Het-L* (Heterogeneous-Leader): A main challenge of the use of RF is its high predisposition for network congestion, particularly in platooning. To alleviate this issue, with the



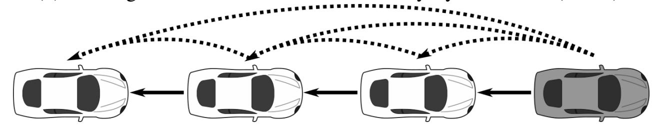
(a) RF only (*RF*).



(b) Heterogeneous communication used only by the leader (*Het-L*).



(c) VLC only (*VLC*).



(d) Heterogeneous communication used by all platoon members (*Het-X*).

Figure 1. The different communication approaches within a platoon. Dashed and solid lines indicate the transmission of beacons with RF and VLC, respectively. Acknowledgements (not shown in the figure) are transmitted in the opposite direction of the beacons.

Het-L protocol, not all of the beacons are transmitted by RF. Only the platoon leader transmits beacons via RF and VLC, while the followers use solely VLC. As a consequence, the RF-channel is used less, and thus is more reliable. This approach corresponds to the one used in [11].

- *Het-X* (Heterogeneous-All): Since the main goal of platooning is to increase safety, this approach aims to maximize it by reducing the combined channel's outage probability. To this end, the *Het-X* protocol introduces redundancy by using both available channels in parallel. That is, all beacons are transmitted both by RF and VLC. As a result, a beacon is lost only if both transmission methods fail.

Following state-of-the-art protocol designs for platooning, all of the four protocols employ a slotted beaconing protocol [5], with a rate of 10 Hz. Here, platoon followers self-assign a transmission slot for their beacons based on the reception of the leader beacon in order to avoid intra-platoon contention. Additionally, they reduce the RF transmit power of their beacons to minimize interference (see Table I).

IV. Simulation setup

We evaluate the performance of the proposed protocols using the Veins simulation framework [19] and its platooning extension, `Plexe` [20], and VLC extension, Veins VLC [9]. The simulation scenario is designed such that both safety aspects and network performance can be observed.

Since the early adoption of platooning is focused on freeways, we chose a freeway scenario for the simulations. On the freeway, one or several platoons are placed in a dense constellation on the freeway's lanes. Each platoon's leader maintains a time-constant headway to the previous platoon using Adaptive Cruise Control (ACC). The leader of each lanes' first platoon initially drives at a fixed speed and performs an emergency braking a few seconds after initialization. During such emergency braking, which we consider a worst case situation, vehicles decelerate with 8 m/s, until they come to a stop. The simulation then continues until either after all vehicles have stopped, or a crash between vehicles occurred.

While the leaders are controlled by a regular ACC controller, the followers employ the Cooperative Adaptive Cruise Control (CACC) controller described by Rajamani [21]. Simulation configuration and most relevant parameters are listed in Table I. Note that the VLC thermal noise has been deliberately increased in order to simulate a lossy channel for VLC for the desired inter-vehicle distance of 5 m.

Table I
Simulation parameters

Traffic	Vehicles	[8, 160, 320]
	Platoon size	8
	Lanes	4
	Engine actuation delay	0.5 s
ACC	Headway	1.2 s
	Desired speed	100 km/h
CACC	Desired distance	5 m
	C_1	0.5
	ω_n (controller bandwidth)	0.2 Hz
	ξ (dampening factor)	1
RF	Standard	IEEE 802.11p
	Path loss model	Free space ($\alpha = 2$)
	Fading model	Nakagami ($m = 3$)
	Bandwidth	10 MHz
	Bitrate	6 Mbit/s
	Transmit power (leader vehicle)	20 dBm
	Transmit power (follower vehicle)	1 dBm
	Thermal noise power	−95 dBm
	Access category	AC_BK
VLC	Modulation	OOK [9]
	Bitrate	6 Mbit/s
	Sensitivity	−92 dBm
	Thermal noise power	−95 dBm

In this scenario, we compare the proposed protocols, and additionally study the impact of the following parameters:

- Number of vehicles: The large interference domain of IEEE 802.11p results in decreasing performance in higher node scenarios. For this reason, we simulate different scenario sizes with 8, 160, and 320 vehicles, corresponding to 1, 20, or 40 platoons.
- Beacon acknowledgements: To address packet loss, we introduce optional acknowledgements for beacons. In simulations where this option is enabled, beacons are retransmitted up to seven times, which corresponds to the number of the retransmissions used in IEEE 802.11 [22]. These acknowledgements are implemented within the application layer in order to ease (de-)multiplexing of the two communication methods, RF and VLC. Acknoledge-

ments are transmitted the same way the corresponding beacon was transmitted. More specifically, if a beacon is transmitted via both channels its acknoledgement will be transmitted in the same way.

- Leader beacon forwarding: Since VLC communication is only possible when the LOS is unobstructed, most platoon members cannot receive the leader's beacons. To solve this, we introduce beacon forwarding. When this option is enabled, platoon members relay received leader beacons to their successor via VLC, thus, enabling all platoon members to receive the beacons. This option is always enabled in conjunction with the *VLC* protocol, since in this case there is no other way for platoon members to receive the leader beacon. With *RF* however, it is not used, as in this case the vehicles are considered to be not VLC enabled. For the two heterogeneous communication protocols, *Het-X* and *Het-L*, we run simulations for both enabled and disabled beacon forwarding.

Each simulation run is repeated ten times to gain confidence in the recorded results. For the data we report in the next section, the confidence intervals are very narrow and we observe little variation of the network's performance between different simulation runs.

V. Network performance

We first investigate the networking performance of our protocols; therefore, in the following we discuss about related metrics such as received beacon ratio, beacon delay, critical time ratio, and VLC packet collisions.

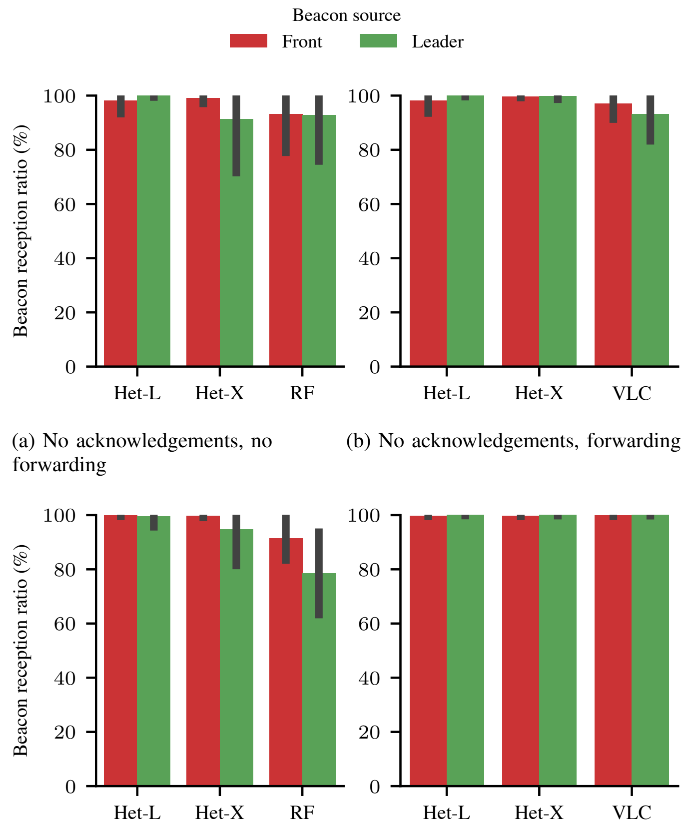
A. Received beacon ratio

Platooning is a safety critical application. As such, minimum beacon loss is crucial to ensure safe operation of the platoon, in particular if such beacons contain information about abrupt changes in vehicle parameters (e.g., immediate acceleration.) The beacon reception ratio is depicted in Figure 2.

A considerable numbers of beacons are lost for all approaches when beacon acknowledgements and forwarding mechanisms are not used.

For *Het-X*, 91.4 % leader beacon reception ratio is observed with disabled acknowledgements (Figure 2a) and 94.7 % with enabled acknowledgements (Figure 2c.) We argue that the leader beacons are not received since the channel is also used for transmitting the front beacons. While front beacons can also be received via VLC, this is not the case for the leader beacons if forwarding is disabled. Enabling forwarding increases the leader beacon reception ratio to 99.8 % for disabled acknowledgements (Figure 2b) and 100 % for enabled acknowledgements (Figure 2d.)

In the *Het-L* approach, this loss of beacons does not occur: the RF channel is used exclusively for leader beacons and acknowledgements thereof. Consequently, the busy time is low, and all leader beacons are received even without additionally relying on forwarding. This doesn't come without drawbacks though, as the front beacons' reception ratio is 98.3 % if no acknowledgements are used (Figure 2b). When



(a) No acknowledgements, no forwarding
(b) No acknowledgements, forwarding
(c) Acknowledgements, no forwarding
(d) Acknowledgements, forwarding

Figure 2. Beacon reception ratio with 160 vehicles. Data for disabled (first row) and enabled acknowledgements (second row) as well as disabled (first column) and enabled forwarding (second column) is shown. The mean of all simulation runs are shown, the error bar indicates the standard deviation. Note that data for *RF* and *VLC* is only available for dis- and enabled forwarding, respectively.

acknowledgements are enabled, however, this ratio is increased to 99.8 % (Figure 2d).

In summary, *Het-X* relies on the diversity gain provided by the use of different channels, which benefits all beacons only when forwarding is used. *Het-L* on the other hand benefits from the reduced channel load but requires time diversity by means of acknowledgements such that front beacons have a high reception ratio.

Regarding the single technology approaches, *VLC* suffers from packet loss for both front and leader beacons when acknowledgements are not used. When acknowledgements are enabled however, this loss is drastically reduced.

In the case of *RF*, the use of acknowledgements is actually detrimental: when enabled, it reduces leader and front beacon reception ratio due to the channel overload. Furthermore, this reduction is more pronounced for the leader beacons. This might be in part due to the use of application layer acknowledgements, but even without acknowledgements, *RF* shows poor performance in higher traffic densities.

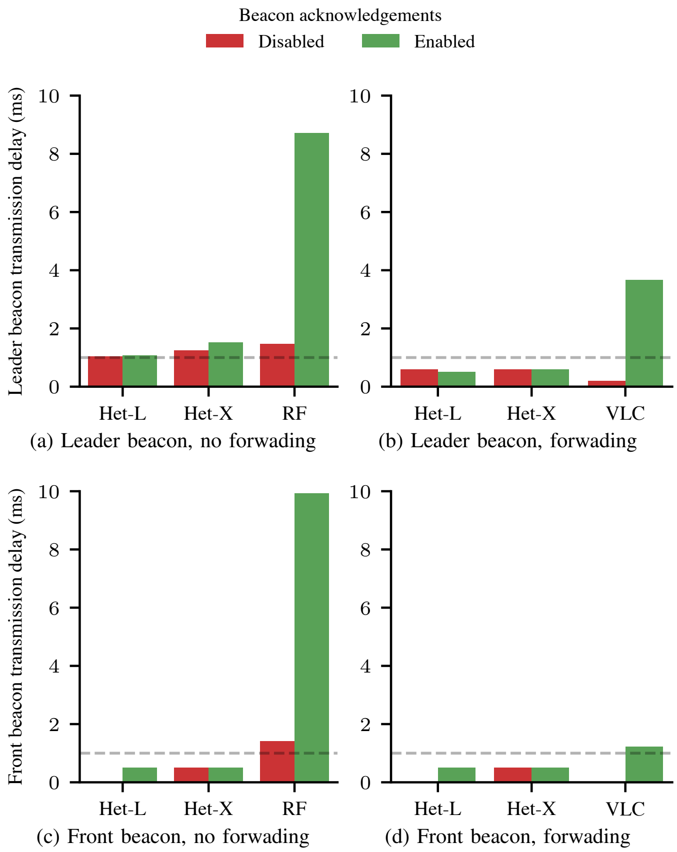


Figure 3. 99th percentiles of transmission delays in scenarios with 160 vehicles. Data for leader (first row) and front beacons (second row) with disabled (first column) and enabled forwarding (second column) is shown. The dashed line indicates a delay of 1 ms, i.e., 1% of the time a beacon is expected to be valid. Note that data for *RF* and *VLC* is only available for dis- and enabled forwarding, respectively.

B. Beacon delay

In order to support platooning the platooning controller has to be provided with accurate information. Accordingly, not only frequent updates are required, but also the delay between beacon generation and reception should be kept low. Furthermore, since platooning is safety relevant, it should work at all times. Therefore, we decided to examine the 99th percentiles of the transmission delays instead of their means as they are good indicators for the maximum delay that is usually observed.

In general, the transmission delays for all approaches we simulated are relatively low, as can be seen in Figure 3. The RF transmissions take at least about 0.5 ms due to channel access, even when there is little channel utilization. When the channel utilization is large, however, the transmission delays are also high; in the case of *RF* with acknowledgements even above 10 ms. With *Het-X* this effect can also be observed, albeit less pronounced (see Figure 3a), since many beacons are received via VLC, which avoids RF transmissions. Additionally, VLC has only a thin Medium Access Control (MAC) layer and does employ channel arbitration; consequently, a beacon transmission only takes about 29 µs.

One concern with forwarding of leader beacons is that the multi-hop communication takes too much time. For the VLC channel model we use, 99 % of the vehicles receive the leader beacons within 4.2 ms when the *VLC* approach with acknowledgements is used (Figure 3b).[1] In comparison to the update period, which is 100 ms when using 10 Hz beaconing, this is only a small additional factor contributing to the information age. In fact, the transmission using VLC is so fast, that even *Het-L* and *Het-X* benefit from it, because many leader beacons are received via VLC before the transmission using RF is finished.

The front beacons' transmission times are even lower than those of the leader beacons as no multi-hop transmission is involved.

For *Het-L* and *VLC*, without acknowledgements, the front beacons are either received very quickly or not at all. When acknowledgements are enabled, they usually take two to three retransmissions to be received, and thus require less than about 2–3 ms, due to the unicast timeout of 1-1.5 ms.

Het-X front beacons are not affected by this, since beacons that are not successfully received via VLC are likely received via RF, thus, avoiding retransmissions.

C. Critical time ratio

Due to the beacon delay, the information conveyed by beacons has already aged. When the sensor information ages, it becomes less suited to accurately control the acceleration of vehicles. This effect is captured by the critical time ratio, which measures the time ratio within which vehicles are in a critical state, i.e., where the vehicle relies on information that is older than a threshold. This idea depicted in Figure 4. The threshold t_c describes the tolerance to stale information: with a higher threshold, beacon information is considered relevant for a longer time. A high threshold therefore yields lower critical time ratios, as less information is regarded as outdated for shorter time intervals.

Figure 5 shows the critical time ratios for the simulation runs with 160 vehicles. It can be seen that the performance determining factors and parameters differ between the considered approaches.

With *Het-L*, the time spent in a critical state does not change significantly if forwarding is used. Since only platoon leaders contend for RF channel access, the RF communication is very reliable and few leader beacons are lost. Consequently, enabling leader beacons to be transported via VLC has only a minuscule influence (0.4 % in both cases, $t_c = 250\,\mathrm{ms}$). Communication on the VLC channel, however, has a non-perfect PDR in our simulations. Hence, the use of acknowledgements decreases the critical time ratio from 0.4 % to 0.1 % ($t_c = 250\,\mathrm{ms}$, see Figure 5a). When acknowledgements are used, additionally enabling forwarding can help reduce the residual critical time ratio to 0 % (see Figure 5b). This is likely due to the fact that even VLC-only leader beacon transport also becomes very

[1]This value is even lower (0.2 ms) when not using acknowledgements; this effect is mainly due to packet loss.

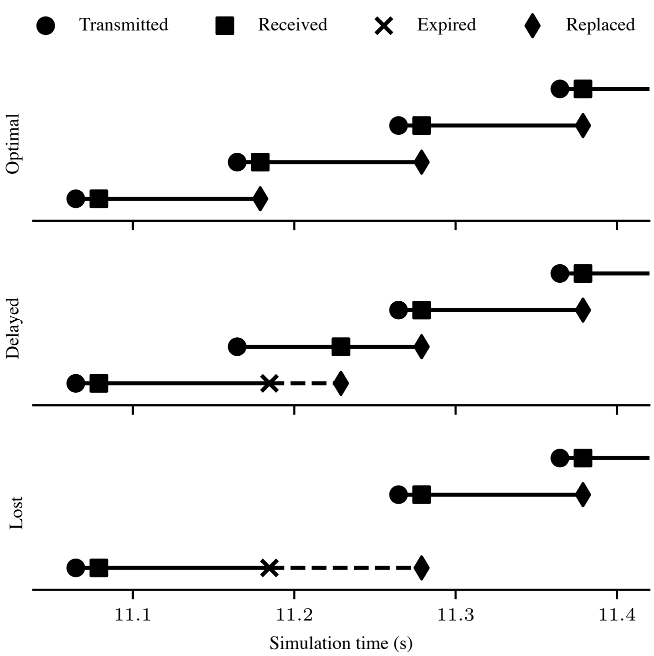


Figure 4. Examples of beacon reception from the platooning application's perspective of a specific vehicle: In the *optimal* case, beacons are received shortly after they are emitted by a different vehicle and replace the present information before it is considered outdated. When a beacon is *delayed*, due to retransmissions, or channel access, the vehicle relies on outdated information (dashed line), until the second beacon is eventually received. During this time, the vehicle is assumed to be in a *critical state*. *Lost* depicts the loss of the second beacon, which also results in it being in a critical state until the third beacon is received.

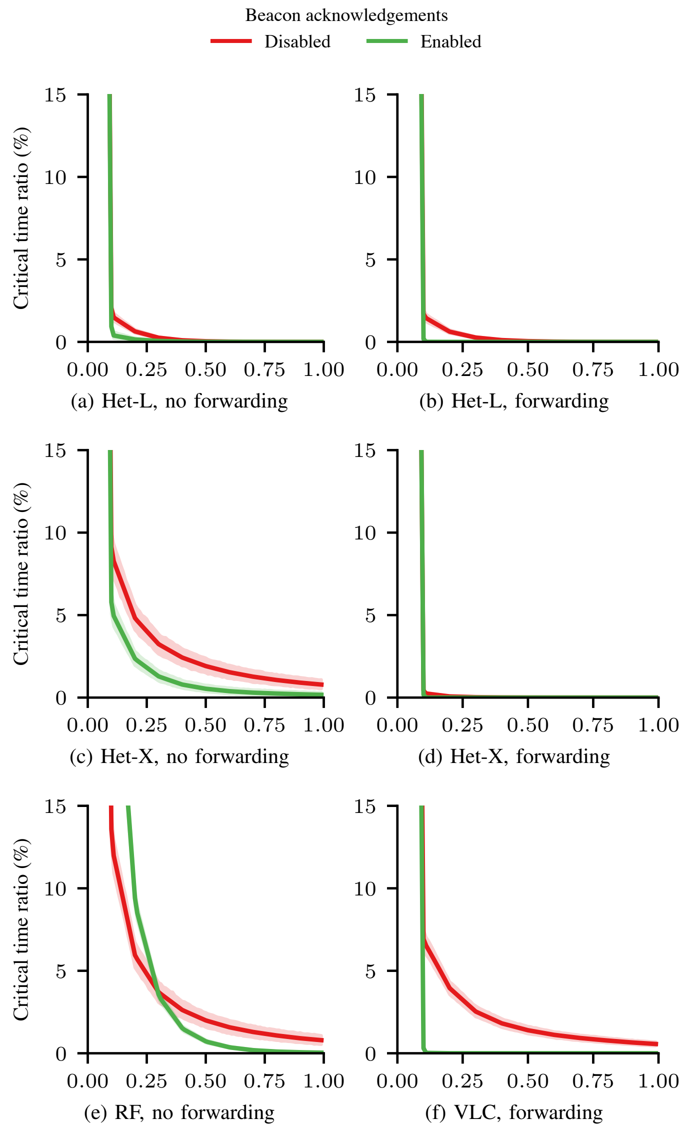


Figure 5. Critical time ratios for 160 vehicles. The left column shows data for the approaches with enabled forwarding, the right column for disabled forwarding. The shaded areas around the lines indicate the 95 % confidence interval.

reliable in this case, as is evident from the *VLC* approach's performance.

The critical time ratio is very high for *Het-X* if not using forwarding (see Figure 5c). As discussed earlier, this is mostly due to lost leader beacons, which are only transmitted via RF. Therefore, the critical time ratio does decrease only by a factor of two when enabling acknowledgements (4 % compared to 1.8 %, $t_c = 250\,\mathrm{ms}$), as the acknowledgements further impact the channel load. Enabling forwarding, however, allows for leader beacons to be received on a second channel, i.e., via VLC. This leads to substantial improvements of the critical time ratio (4 % compared to 0.05 %, $t_c = 250\,\mathrm{ms}$, see Figure 5d). When both acknowledgements and beacon forwarding are used, the critical time ratio is further reduced to 0 %, indicating that at no point in the simulation a vehicle relied on information older than 250 ms.

Since *VLC* does not use RF, forwarding is always enabled with this approach. Without acknowledgements it suffers packet loss similar to the way *Het-L* does, and has a relatively high critical time ratio (3.2 %, $t_c = 250\,\mathrm{ms}$). It decreases however vastly when acknowledgements are enabled and approaches zero (2.3×10^{-4} %, $t_c = 250\,\mathrm{ms}$, see Figure 5f).

D. VLC collisions

The close formation we simulated can result in packet collisions on the VLC channel. These are detected when packets are not decodable due to the additional interference power. Most vehicles, across all parameters, experience no such collisions. Some vehicles (at most 19 %), however, experience them, in particular when beacon forwarding is enabled. Enabling acknowledgements makes VLC packet collisions more likely, as the acknowledgements are transmitted with the headlights which have a larger transmission range (cf. Figure 6). When there are relative positions between vehicles that allow for VLC collisions to occur, these, most of the time, happen repeatedly. A possible reason for this is the simulation scenario and the beacon generation. In our scenario, all vehicles initially share the same velocity, and start braking at a similar time. As a result, the relative positions between vehicles are not changing a lot. Also, the beacon generation does not change over time, so it is likely that, when transmissions coincide in time, this

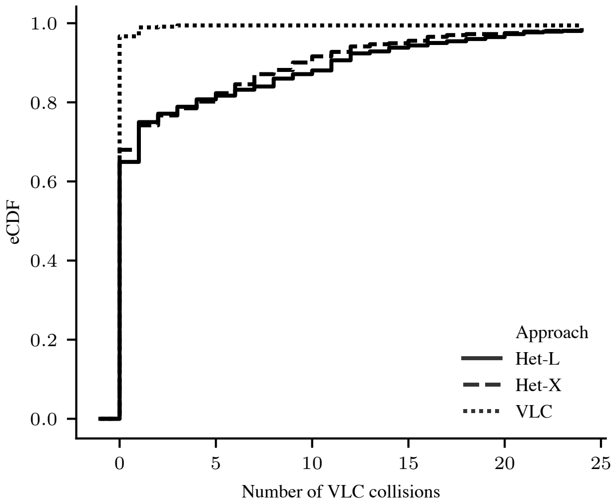


Figure 6. eCDF of the observed amount of VLC packet collisions for the taillights with the 160 vehicle scenario, enabled acknowledgements and beacon forwarding.

will repeat later as well. Another contributing factor for *Het-L* and *Het-X* is, that vehicles receive the leader beacons over RF virtually simultaneously. Therefore, when forwarding is enabled, these beacons are forwarded at the same time, and as a result also their acknowledgements, which increases the chance of VLC collisions occurring at vehicles on neighboring lanes.

VI. Platooning performance

Overall, the performance observed in the metrics discussed above also can be observed in the application's performance. For platooning, this can be quantified by how well vehicles are able to maintain the distances to each other. For this purpose, Figure 7 shows the minimum distances between any two platoon members for each simulation run. We chose this metric as it is an indicator of the worst reaction on the emergency braking observed in the respective simulation run. A value of zero indicates a crash between two vehicles.

For eight vehicles, almost all cars are able to maintain the required distance in all simulation runs. This is due to the low channel utilization: all RF packets can be received perfectly. The only exception are *Het-L* and *VLC*, where the minimum intra-platoon distances are slightly reduced, as some beacons which are transmitted via VLC are lost. In the ten runs simulated, this has not been a problem; with more repetitions however, one can expect that crashes will occur eventually.

When simulating 160 vehicles, the vehicles experience significantly more channel utilization. Without forwarding, only *Het-L* performs perfectly, i.e., without any crashes and with a high minimum intra-platoon distance of at least 3.5 m (see Figure 7c) . Both *Het-X* and *RF* suffer from channel congestion, resulting in crashes when not using acknowledgements. Even with enabled acknowledgements, *Het-X* still cannot guarantee safe operation, while in the *RF* approach the minimum distances are far lower than their optimum. Interestingly, *Het-X* performs

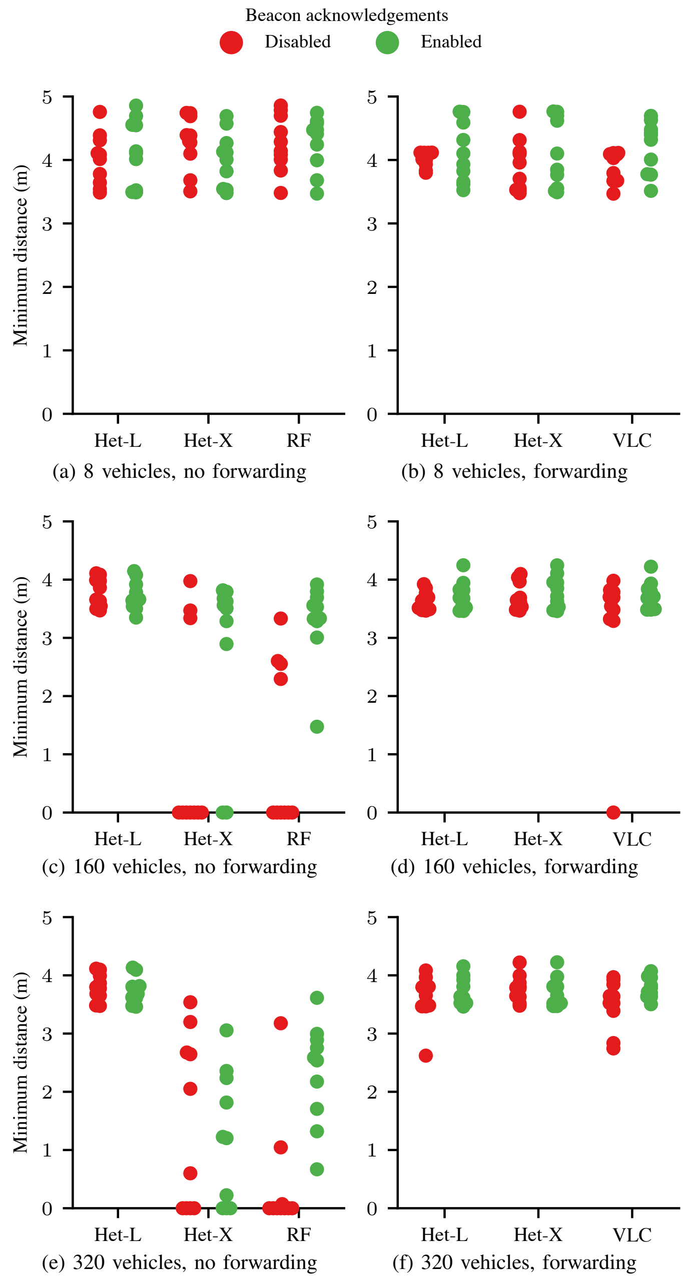


Figure 7. The minimal distances between any two vehicles of the same platoon within each simulation run. The left column shows data for the approaches with disabled forwarding, the right column for enabled forwarding. Note that data for *RF* and *VLC* is only available for disabled and enabled forwarding, respectively.

worse, even though its critical time ratio indicates the opposite on the first glance. However, while the critical time ratio for small thresholds is better for *Het-X*, *RF* approaches zero for large thresholds. This suggests, that most vehicles in the *Het-X* simulations receive updates in a timely fashion, while there are a few vehicles which receive information rarely, and therefore are more likely to cause a crash. In *RF* runs however, the vehicles rely on older information, which causes shorter intra-platoon distances on average, but no crashes, as the vehicles practically always receive the information within at most a second. With forwarding enabled, all three VLC-enabled approaches prevent crashes, except for a single *VLC* run that does not use acknowledgements (see Figure 7d).

With even more platoons, i.e., 320 vehicles, the effects observed in the simulations with fewer vehicles are even more pronounced. If forwarding is disabled, *Het-X* and *RF* performs worse than before in runs that did not crash, while *Het-L* still prevents any crashes (see Figure 7e). With forwarding however, no crashes occur, and the minimum inter-vehicle distances are kept above 3 m in all runs with acknowledgements (see Figure 7f). In general, the heterogeneous approaches (i.e., *Het-L* and *Het-X*) provide higher reliability due to the added communication redundancy, however, with proper parameterization *VLC* proves to be equally reliable in our scenario. This indicates that an adaptive solution might achieve comparable performance with even lower usage of RF resources (as in *VLC*).

VII. Conclusion

In this paper, we investigated the benefits of combining Visible Light Communication (VLC) and Radio Frequency (RF) communication for platooning. We presented two heterogeneous beaconing protocols for platooning with various degree of VLC and RF integration (*Het-L* and *Het-X*) and compared them against single technology protocols (RF-only and VLC-only.) Moreover, we extended our VLC-based protocols with forwarding and acknowledgement mechanisms to improve beaconing reliability.

Using extensive simulations, we assessed the performance of the individual protocols under challenging platooning and networking conditions, i.e., emergency braking and high node density, respectively. Results from our initial study show that by exploiting the respective advantages of RF and VLC in a heterogeneous networking approach, we achieve an optimal setup of improved platoon safety and reduced channel load. In particular, with proper parameterization, we can ensure safe operation of platoons with inter-vehicle distances of 5 m at 100 km/h, even in the scenario with the highest vehicle density.

In future work, we plan to extend our heterogeneous protocols with adaptive capabilities: choosing the best communication technology based on network load. We also plan to consider different platoon controllers and use improved Vehicular VLC (V-VLC) radiation models.

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