HEINZ NIXDORF INSTITUT
UNIVERSITÄT PADERBORN

Max Schettler

Investigating the Feasibility of Visible Light Communication for Platooning Applications

Masterarbeit im Fach Informatik

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Distributed Embedded Systems (CCS Labs)
Heinz Nixdorf Institute, Paderborn University, Germany

Fürstenallee 11 · 33102 Paderborn · Germany

http://www.ccs-labs.org/

Investigating the Feasibility of Visible Light Communication for Platooning Applications

Masterarbeit im Fach Informatik

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Max Schettler

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(CCS Labs)

Heinz Nixdorf Institut
Universität Paderborn

Betreuer: **Agon Memedi**
Gutachter: **Falko Dressler**
Tibor Jager

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(Max Schettler)
Paderborn, 17. September 2018

Abstract

Platooning is a promising Intelligent Transport System (ITS) application which is set to reduce the negative aspects of road traffic, by improving safety, fuel efficiency, and road efficiency. In order to operate safely, however, platooning requires reliable communication at high rates. Achieving this with current Radio Frequency (RF) technology is challenging with high vehicle densities, because the high network load reduces its reliability. In order to alleviate this, the use of Visible Light Communication (VLC) instead of, or in addition to RF, has been proposed.

To investigate VLC's feasibility I design different communication approaches which use RF and VLC and analyze their performance in an extensive simulation campaign. These simulations show that significant improvements in terms of safety and RF channel utilization can be achieved by beaconing with VLC. Based on realistic simulations, my results indicate that heterogeneous communication with RF and VLC is beneficial, and can bring platooning one step closer to real-world deployment.

Kurzfassung

Platooning ist eine vielversprechende Anwendung von Fahrzeugnetzen, die die negativen Effekte des Verkehrs zu reduzieren verspricht, indem Sicherheit, sowie Energieeffizienz erhöht, und Straßen besser ausgelastet werden. Damit Platooning zuverlässig funktioniert, muss jedoch verlässliche Kommunikation selbst bei hohen Nachrichtenaufkommen gewährleistet sein. Dies ist mit aktueller Funktechnologie insbesondere bei hohen Verkehrsdichten schwierig, da in solchen Fällen die Zuverlässigkeit des Netzwerks durch Überlastung stark reduziert wird. Eine mögliche Lösung ist, zusätzlich zum Funk, oder anstatt dessen, Kommunikation im sichtbaren Spektrum einzusetzen.

Um diese Möglichkeit zu evaluieren, entwerfe ich verschieden Kommunikationsansätze, die Funk und sichtbares Licht nutzen, und analysiere ihr Verhalten durch Simulationen. Die Ergebnisse dieser Simulationen zeigen, dass durch Verwendung von sichtbarem Licht deutliche Verbesserung sowohl der Sicherheit, als auch der Funkkanallast möglich sind. Die Ergebnisse der realistischen Simulationen weisen darauf hin, dass heterogene Kommunikation mit Funk und sichtbarem Licht für Platooning von Vorteil ist, und dass damit ein weiterer Schritt zur Verwendung in der Praxis.

Contents

Chapter 1

Introduction

Affordable transportation has transformed society in the last centuries. However, with the still rising amount of traffic, in particular road-based traffic, different challenges arise. The environmental impact created by the vehicles is large, accidents result in loss of life, and the infrastructure is often overloaded and thus time and resources are wasted.

Intelligent Transport Systems (ITSs) can help tackle these issues, e.g., such that people spend less time on the road and arrive safely at their destinations [1]. Such systems use computational resources within vehicles and communication between them to provide applications. A variety of such potential applications has been envisioned and designed, which range from infotainment to improvements of safety. Depending on their type, these applications generally impose different requirements on the network [2]. Infotainment applications for example, require a high network throughput, while latency is not as important. Safety applications on the other hand, require high reliability and low latencies. One such safety application is Cooperative Adaptive Cruise Control (CACC), also known as *platooning*: the automated control of "road trains". By use of platooning, individual vehicles follow each other at short distances to their predecessors by adapting their acceleration based on other vehicles' information [3].

Deployment of such a system results in a number of advantages: smoother driving and lower air drag reduce the ecological impact, close inter-vehicle distances increase road efficiency, and the automation improves end-user safety and convenience [4–6]. These effects can be observed even at low market penetration rates [5, 6]. This makes platooning an ideal application for early adoption of ITS vehicles. To enable the operation of platoons however, the cars need to exchange information. Current proposals achieve this mostly by the use of Radio Frequency (RF)-based communication (e.g., Dedicated Short Range Communication (DSRC) based on 802.11p) [7].

In order for platooning to work safely, high update rates, and thus, high message rates, are required [8]. Additionally, the close inter-vehicle distances result in an increased vehicle density. 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 [9].

Initial studies suggest, a potential solution might be to complement RF using Visible Light Communication (VLC), thereby exploiting an additional part of the electromagnetic spectrum [10]. VLC is enabled in cars by Light-Emitting Diodes (LEDs) in the head- and taillights. The LEDs can be switched at high frequencies that are not perceptible by humans. 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 spectrum. Due to the light's propagation characteristics, reception is mostly dependent on the line-of-sight (LOS) between sender and receiver. Therefore, it can only reach a relatively small number of nodes, i.e., vehicles, which limits the amount of network congestion.

Despite these advantages, VLC use 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 [11]. Moreover, adverse weather conditions like fog and heavy rain or bright daylight can reduce the achievable range severely [12].

Given the different properties of RF and VLC communication, heterogeneous communication for platooning has attracted attention in the research community. Previous studies indicate an improvement of safety can be achieved, but further work with more realistic VLC models has to be done [13]. Since such models have become available recently, it is now possible to investigate the performance of VLC in the context of IVC in greater detail by means of simulation [11].

For this thesis initially I identify different approaches to incorporate heterogeneous communication with RF and VLC, based on their specific strengths and weaknesses. I investigate these hybrid RF-VLC-Platooning approaches using a simulation campaign with different platoon densities.

In order to examine the approaches' operation, I collect data for various metrics from the simulations. The metrics are chosen in such a way that both the behavior of platooning, i.e., the application, as well as that of the network are reflected by them. Therefore, they allow me to compare the performance of the approaches within different traffic situations.

The contributions of this thesis are the following: I designed and implemented two communication approaches which employ heterogeneous communication using RF and VLC. Furthermore, I added two communication approaches for comparison, which exclusively use RF and VLC respectively. Since VLC allows only for direct LOS connections, and since there is little congestion, I also added different variants of the approaches above, called *beacon acknowledgements* and *beacon forwarding*, which enable multi-hop transmissions and add time diversity to increase the reliability of the communication. Using these approaches and their variants, I ran an extensive simulation campaign and analyzed its results to determine how heterogeneous communication with VLC impacts reliability, safety and resource usage by platooning. For this purpose I created a simulator platform based on a merge of Plexe and Veins VLC, that enables simulations with both platooning and accurate VLC models.

The remainder of the thesis is structured as follows: In Chapter 2, I describe the related work associated with my work. Afterwards I introduce the basic concepts and technology required to understand the subsequent chapters in Chapter 3. Chapter 4 describes the software I use, the approaches and their variants mentioned above, as well as their implementation. In Chapter 5 I then present the simulation setup, the metrics I collect data for, and discuss the results from the simulations, before summarizing the results and proposing ideas for further investigation in Chapter 6.

Chapter 2

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 [14]. For a platooning system to work, communication between vehicles is fundamental. Segata et al. [9] 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. This was observed in particular in high traffic density scenarios, which suffer from large network congestion. In these scenarios, 90% of the required messages were delivered within 200 ms.

In order to alleviate the effects of network congestion, VLC was considered for use in platooning applications. Abualhoul et al. [15] 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 bandwidth and the distances and orientations between vehicles which are to be expected in a highway platoon. In a followup study, the authors demonstrated an actual VLC transmitter-receiver system [16]. 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 datarate 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, Chassagne, and Guan [17] 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 typical distances, i.e., up to 10 m, and orientations between vehicles 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 taillight 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 susceptible to jamming attacks [18], Ishihara, Rabsatt, and Gerla [10] have investigated VLC as a potential solution. 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, Ergen, and Ozkasap [19] 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 large scale simulation of VLC-enabled platoons was conducted by Segata et al. [13]. They simulated up to 640 vehicles which formed platoons. While the platoon leaders used the RF protocol IEEE 802.11p to transmit information to all platoon members, direct neighbors exchanged information by 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 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, Tsai, and Dressler [11]. 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.

Chapter 3

Fundamentals

In this chapter, I introduce the concepts and technologies which form the base of my thesis. First, I describe IVC, its applications, challenges, and enabling technologies. In Section 3.2 I introduce platooning, as the central application I focus on. Afterwards, I describe the general idea of simulation as a tool to investigate hypotheses, in particular the simulation of vehicular networks, as well as the software used for this thesis.

3.1 Inter Vehicular Communication (IVC)

IVC refers to various technologies which enable vehicular networking. Using wireless communication, individual vehicles are able to exchange information. This communication enables a multitude of applications, which can be categorized into different areas, such as infotainment or safety applications [1]. Infotainment applications can provide access to, e.g., traffic information which can be leveraged to increase traffic efficiency, or multimedia data from within vehicles. Safety applications, on the other hand, aim to improve safety and security of traffic participants.

One main goal of these safety applications, such as Electronic Emergency Brake Light (EEBL) or platooning, is to significantly reduce accidents. EEBL is a technology which notifies surrounding vehicles of hard braking, even without a direct line of sight [20]. Platooning (see Section 3.2) is the formation of so called *road-trains*, within which vehicles drive automatically in close proximity.

To enable vehicle-based communication, different technologies can be used. Existing cellular systems like Long Term Evolution (LTE) are able to connect vehicles both to each other and to services on the Internet. While they can provide comparably high bandwidth, they rely heavily on expensive infrastructure. Moreover, this reliance can be problematic, particularly during disaster scenarios where infrastructure might be inoperative, but also for less populated or developing regions where network coverage is low. Therefore, for safety applications, infrastructureless, ad hoc solutions are preferable. Such ad hoc solutions are called Dedicated Short Range Communication (DSRC), where a wireless system is used for interconnecting vehicles at short ranges of up to several hundred meters. An alternative is the emerging LTE Direct standard, which enables infrastructureless communication with LTE [21]. In this thesis, however, I focus on DSRC, since it is more widely used for platooning in existing research.

With DSRC, vehicles can form a Vehicular Ad Hoc Network (VANET), which is a dynamic network between vehicles that operates without infrastructure. Communicating in such a network is challenging. This is mainly due to the network's dynamic topology, as the individual stations, i.e., the vehicles, are mobile.

Multiple protocol stacks have been developed using DSRC. The most common ones are the U.S. American WAVE protocol stack [22], the European ITS-G5 [23] and the Japanese T109 [24]. These protocol stacks provide additional networking functionality on top of their data-link layer. They define the message formats which are used to exchange information. Additionally, they provide services. For example, they mandate implementations to periodically send data about the vehicle such as its position, velocity, and acceleration. This process is known as *beaconing*.

By aggregating this information from other vehicles, knowledge about the neighborhood is gained. This is useful, as it can extend the information vehicles can gather with their own sensors. This information can be used to prevent network congestion by adapting parameters like the beaconing rate or transmit power based on traffic density. Also, an overlay IP network for routing to distant vehicles can be created.

In order to enable DSRC, a physical layer connecting the vehicles are required. For DSRC, RF communication in the 5.9 GHz frequency band is used. Due to RF-based DSRC's downsides, however, in particular its vulnerability to network congestion, the feasibility of using different parts of the electromagnetic spectrum for IVC has been investigated recently. Particularly, communication within the visible spectrum, VLC, is a promising technology, which has already found applications in indoor communication. But also radar-based communication might be used in future DSRC systems.

When using more than one of these technologies, one can combine their advantages to overcome each individual one's specific shortcomings and improve reliability of the overall system. The outage probability of such a combined system is vastly reduced, as it only fails if all communication options fail simultaneously. They can also be used exclusively for different transmissions which causes less network congestion on the individual channels. This combination of individual communication methods is called *heterogeneous communication*.

3.1.1 RF-based Dedicated Short Range Communication (DSRC)

RF-based DSRC uses frequencies of several hundred MHz to a few GHz for short range communication. There exist different implementations for RF-based DSRC, most of which rely on the IEEE 802.11p standard [25]. This is a standard from the widely used 802.11 protocol family designed for use in vehicular environments. Regular 802.11 protocols are not suitable for these scenarios as they are designed mainly for indoor use with static access points. Therefore, they require association to an access point and are susceptible to multi-path propagation, an issue that is particularly problematic in vehicular scenarios. To accommodate for this, 802.11p adapts parameters of both the physical and the MAC layer, e.g., by using an extended symbol time to reduce inter-symbol interference.

802.11p is used in all of the common Dedicated Short Range Communication protocol stacks, i.e., ITS-G5, WAVE, and T109. However, in some of them it has been adapted. In T109 for example, it operates on the 700 MHz frequency band, and in WAVE the MAC layer is modified such that it switches between different channels. Due to its use in the most common DSRC, 802.11p has been extensively researched and is often used in proposed cooperative driving applications.

3.1.2 Visible Light Communication (VLC)

Even though most wireless communication systems use frequencies below 100 GHz, higher frequencies can be used, too. These frequencies offer large amounts of usable bandwidth, but have different propagation characteristics. Signals at these frequencies are highly directional and don't penetrate opaque materials well, or at all. Therefore, line-of-sight (LOS) is necessary for signals to be received. As a result, the propagation area is relatively small compared to the omni-directional propagation of RF. This reduces the impact of network congestion on communication performances, as the number of possible communication partners is much smaller.

In the higher frequency range, in particular the visible light spectrum (430 THz to 770 THz) is promising. As humans rely heavily on visible light, technology for generating and detecting it is readily available. For the same reason, however, introducing new lights solely for communication can affect humans negatively. Hence, for a VLC system it seems natural to try and reuse existing light sources. Since changes in lighting at rates above several hundred Hz are imperceptible to humans, it is possible to transmit information this way without impacting the lighting perceived by humans.

In the vehicular context, VLC can be used by augmenting the head- and tail-lights of vehicles. Without changing the road illumination, the emitted light can be modulated to transmit information. Therefore, VLC can offer an additional method for implementing DSRC and provide improved reliability with less congestion of the RF spectrum.

A drawback of VLC is its susceptibility to weather conditions. Most obviously, sunlight will interfere with transmissions during daytime, but also other weather effects like fog or heavy rain can influence transmissions heavily [26].

3.2 Platooning

Platooning, also referred to as Cooperative Adaptive Cruise Control (CACC), is a concept where a set of vehicles which drive in conjunction is controlled by an Advanced Driver Assistance System (ADAS). Within this so called *platoon*, the vehicles drive in close proximity to each other. This is achieved by computing each vehicle's desired acceleration (or deceleration), its *control input*, based on the other vehicles' control inputs. This distinguishes platooning from regular Adaptive Cruise Control (ACC), where the control input is computed based solely on local information, e.g., radar measurements. Further, wireless communication enables reception of information from cars which are not in LOS. Both factors decrease the delay between changes of one vehicle's control input and other vehicles' reaction on it. In consequence, it is possible to decrease the safety distances without sacrificing overall system safety.

The advantages of platooning are diverse. Due to these close inter-vehicle distances, vehicles take less space on the road. Additionally, the aerodynamic drag is reduced [5]. Since the vehicles are controlled automatically, they drive more smoothly [6]. In combination, both an improved road utilization and fuel efficiency can be achieved [4]. Also, platooning makes driving more convenient as the driver does not need to focus on driving at all times.

Because platoons can be formed even with a few vehicles, platooning can benefit early adopters of vehicles fitted with IVC technology. This makes it a great initial application for such vehicles.

In order to implement a platooning system, two main issues have to be solved: guaranteeing reliable, low latency communication, and computing control inputs, such that the platoon is stable, i.e., the desired inter-vehicle-distances can be kept, and therefore safe. Low latency is critical for platooning, as it corresponds to the minimum time the controller operates without proper knowledge of the other vehicles' current state. With this in mind, the communication delay is aimed to be 100 ms, which corresponds to an update rate of 10 Hz. Such a high update rate, however, leads to channel congestion, particularly in scenarios with high traffic density. This is especially problematic as it results in increased packet loss which may impact system safety.

Different beaconing algorithms have been proposed which aim to guarantee low latency while combating network congestion in challenging situations. However, all of these rely on RF-based DSRC. Heterogeneous communication can be used to improve beaconing even further. In particular, VLC is a good candidate to complement RF. As its transmission distance is smaller than that of RF, and the signal propagation is highly directional, VLC is less affected by RF's main issue, channel congestion.

The control inputs of a platoon's vehicles are computed by their corresponding *controllers*. There are different controllers, which differ in the algorithm used to calculate their control inputs. This also includes the input they rely on. The least amount of information which a practical controller can use is the information received by the immediately preceding vehicle, i.e., the *front* vehicle. This is advantageous, as it enables 'ad hoc' platooning, where vehicles are not explicitly grouped into platoons. With such controllers, the vehicle's minimum headway time, i.e., the minimum inter vehicle distance, expressed in seconds driven at current speed, can be reduced to less than a second.

In addition to the front vehicle's information, one can also include the platoon's *leader*'s information. The leader is the very first vehicle in a platoon. Therefore, its movement dictates the remaining vehicles' movement. As a result, the inter-vehicle distance can be reduced to constant values, e.g., 5 m, irrespective of the speed.

More sophisticated approaches dynamically include information of all platoon members [27]. The resulting controller is more robust to heterogeneous communication delays and packet loss.

3.3 Simulation

When developing complex systems, one wants to be able to predict the impact of changes. It is often unfeasible to do so by changing the real system. The system might not yet exist or adapting it might be too expensive or too dangerous. Additionally, sufficiently detailed analytical models for complex systems are prohibitively difficult to develop.

This also applies to platooning: In order to observe network effects in future deployments, large numbers of vehicles need to be used. Currently, however, only small-scale prototypes exist. Due to the many effects which are relevant to platooning, like vehicle movement, signal propagation, and the environment, purely analytical models are also not feasible.

Simulations are the middleground between real-world tests and analytical models. Within the simulation, simplified models for the system's constituents are used. These try to predict real-world behavior with a reasonable accuracy.

Simulations which are run on computers have several additional advantages. The experiments are repeatable as all random effects are determined by the seed for the pseudorandom number generator (PRNG). This allows for short development cycles. Running experiments is mostly limited by computational resources. Therefore, running many simulations in parallel is possible, which improves confidence in the results as the effect of random deviations is reduced. Such results are not easily achievable in real-word experiments. However, a drawback is, that since the models describe a simplified reality, the results are prone to inaccuracies. This is problematic as the extent of such defects cannot be easily estimated.

For feasibility studies such as the one presented in this thesis, however, the advantages of simulations outweigh their downsides, and previous studies have shown that the results are apply reasonably well in the real world. Therefore, I am using simulation to investigate how VLC can be used in platooning. In the following I give a brief description of the software components I use as a basis for my simulations.

OMNeT++ [1] is a Discrete Event Simulator (DES) which is primarily used for simulating computer networks [28]. While it is proprietary, its use is free for academic purposes. In a DES the simulation state is changed by events which occur at discrete times. Between events, the state is assumed not to change. This allows the simulator to run as fast as it can process the scheduled events. OMNeT++ provides multiple components to aid running experiments. The most important one is the simulation core which allows to write modules that can be interconnected and schedule messages. These modules and networks can be described using a Domain Specific Language (DSL). The resulting simulations can be parameterized using a sophisticated configuration format that simplifies conducting parameter studies.

Sumo [2] is a traffic simulator which is maintained under an open source license by the German Aerospace Center (DLR) [29]. It predicts the movement of vehicles on a road network. The simulation advances in timesteps of a configurable time, typically 100 ms. The vehicle's behavior is computed with different models. Using these models one can simulate human drivers, but also automated driving.

Veins [3] is a framework built upon OMNeT++ for simulating vehicular communication [30]. Veins is built by different research groups, particularly CCS Labs.[4] It was forked from MiXiM,[5] a framework for implementing wireless networks

[1] http://omnetpp.org/
[2] http://sumo.dlr.de/
[3] http://veins.car2x.org/
[4] http://ccs-labs.org/
[5] http://mixim.sourceforge.net/

in OMNeT++. Veins' main strength is the coupling of a network simulator with a traffic simulator. Therefore, it instantiates network nodes for vehicles and delegates their traffic simulation to Sumo. On top of this, it provides implementations of IVC protocols, most notably 802.11p and Wireless Access in Vehicular Environments (WAVE).

Plexe [6] The Plexe project maintains forks of both Sumo and Veins and adds platooning functionality to them [31]. On the Veins side this means mostly extending the application layer. On this layer, modules are added which generate beacons and pass information received from other vehicle's beacons to Sumo. Additionally, it aids in creating and managing platoons. In Sumo, different controllers have been implemented which simulate vehicle's behavior for different ACC and platooning methods.

Veins VLC [7] extends Veins support for simulations involving VLC [11]. It provides a channel model for computing the signal propagation. This channel is accessible by physical-/mac-layer modules to integrate in simulations.

[6] `http://plexe.car2x.org/`
[7] `http://www.ccs-labs.org/software/veins-vlc/`

Chapter 4

Methodology

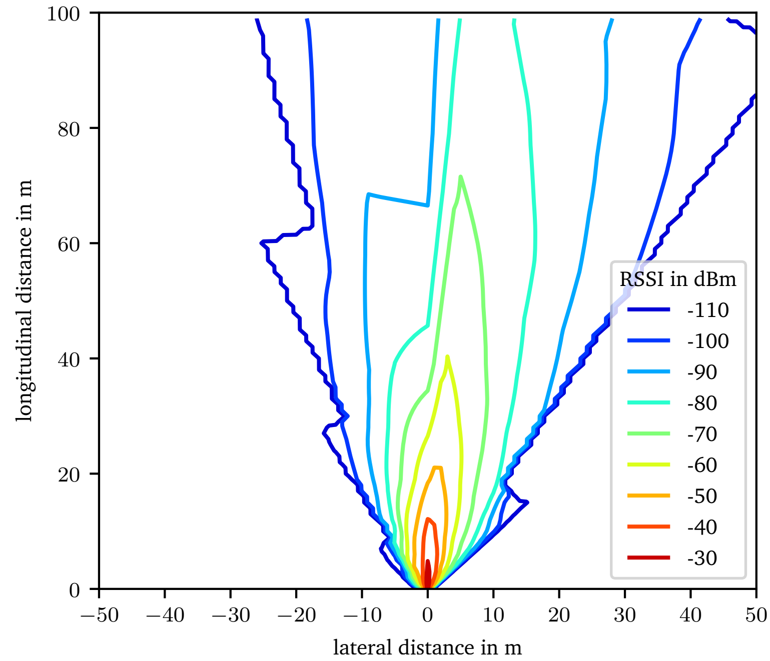
In this chapter I describe the methods used to investigate the feasibility of VLC for platooning. First, I describe Veins VLC, which provides the VLC model I use in my simulations. Then, I describe the four approaches I implemented, as well as beacon acknowledgments and -forwarding mechanisms that can be used in conjunction. Afterwards, I describe the structure of my implementation within Plexe in detail.

4.1 Veins VLC

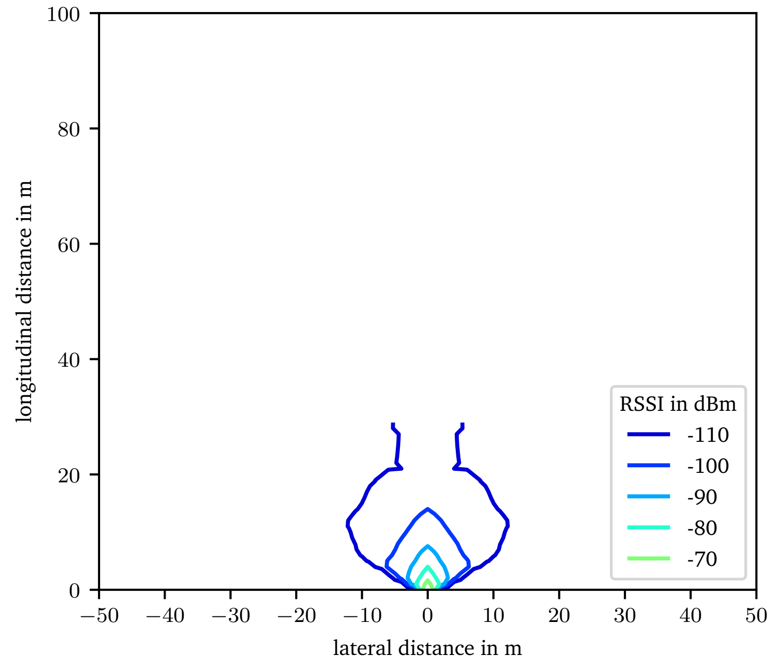
The VLC model which is provided by Veins-VLC extends the existing framework with simulation support communication in the visible light spectrum. It provides a module which models the physical layer of a VLC network stack. So far, only a very simplistic Medium Access Control (MAC), ALOHA, is used for VLC, as the interference domain is small enough that such an approach is feasible [32]. Therefore, messages are immediately transmitted and might collide when a node has LOS to two active senders.

The signal propagation is computed based on the senders' and receivers' relative positions and orientations, as well as the lights' propagation patterns. Memedi, Tsai, and Dressler [11] measured such patterns with real head- and taillights and a photo diode. The VLC modules in my simulation are based on empirical radiation patterns from Figure 4.1.

When a signal is transmitted, it starts being received at any VLC node within maximum interference domain, that is statically set to 380 m. The received transmission power is computed by attenuating the signal transmission power according to different analogue models. In Veins VLC this is a obstacle shadowing model which accounts for vehicles, as well as the empirical light model discussed earlier. If a signal's received power is below a configurable threshold corresponding to the receiver's reception sensitivity, it is ignored. The remaining packets are checked



(a)



(b)

Figure 4.1 – The radiation patterns for a head- (4.1a) and taillight (4.1b) according to data gathered by Memedi, Tsai, and Dressler [11]. Depcited as a contour plot of the RSSI in dBm received at different locations in front of the lights. Note the open contour for the taillight. This occurs due to missing data for longitudinal distances greater than 29 m.

whether the decoding was successful, which is calculated based on the received SNR, the packet size, and the modulation and coding scheme. When packets are successfully decoded, they are passed to higher networking layers, if not, only data about the packet being dropped due to low received signal strength or high interference are recorded.

4.2 Protocols

There are many possible ways to combine RF and VLC to achieve heterogeneous communication. These affect the way beacons are distributed. Since the focus of this thesis is the message dissemination, rather than beacon generation, all proposed protocols are based on a static 10 Hz beaconing algorithm, which is commonly used in research and has been proven to suffice experimentally [8].

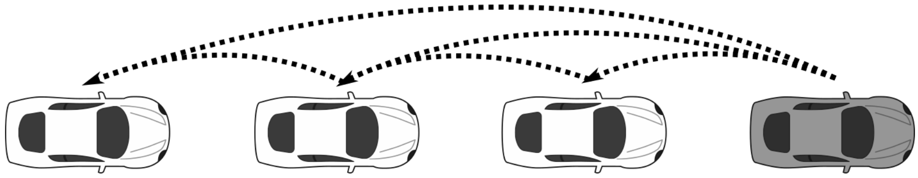
Within a platoon, different dissemination strategies aim to regularly update each platoon member's knowledge about its front and leader vehicle's movement. If these updates are provided in a timely manner, the delay between one vehicle's change in acceleration and the response of following vehicles can be kept short. This is critical for the platoon's safe operation, i.e., the avoidance of crashes (see Section 3.2). In order to identify weaknesses and strengths of different communication methods, I compare three VLC-based approaches with each other and a baseline approach which solely uses RF.

The different approaches are designed such that they differ in the extent of VLC integration, as well as their focus on safety and efficiency (see Figure 4.2):

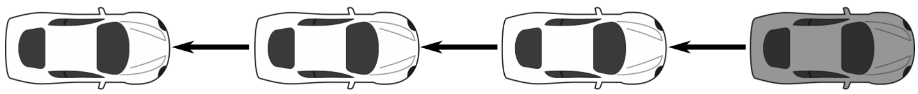
RF This approach solely uses RF communication for message dissemination. It is included as a baseline for comparison with the other approaches as well as existing research. As has been shown by existing research, this approach likely suffers from high contention caused by RF-based DSRC's large interference domain, high traffic density, and message rates [9].

VLC This approach uses only VLC. The main challenge is therefore that only direct neighbors within a platoon have direct a 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 will age while it propagates through the platoon.

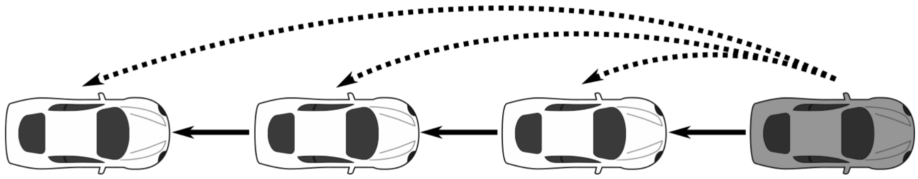
***Het-L* (Heterogeneous-L)** A main challenge of the use of RF is its high predisposition for network congestion, particularly in platooning. To alleviate this issue, within the *HetL*, not all of the beacons are transmitted by RF. Only the platoon



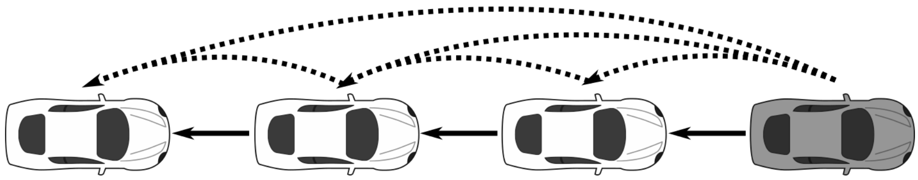
(a) RF only (*RF*).



(b) VLC only (*VLC*).



(c) Heterogeneous communication used only by the leader (*HetL*).



(d) Heterogeneous communication used by all platoon members (*HetX*).

Figure 4.2 – The different communication approaches within a platoon. Dashed and solid lines indicate communication with RF and VLC, respectively.

leader transmits beacons via RF and VLC, while the followers use solely VLC. In consequence, the RF-channel is used less, and thus is more reliable. This approach corresponds to the one used in [13].

***Het-X* (Heterogeneous-X)** 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* 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.

Note that, while the leader beacon is sent with both RF and VLC, only the first follower is able to directly receive it via VLC, as LOS to all other followers is blocked.

The approaches described above can additionally be used in variants which change how they transmit beacons:

Beacon acknowledgements The RF and VLC channel cannot always guarantee packet delivery. For the RF channel, this is mostly due to interference from other signals, for VLC due to low signal power. Therefore, in order to increase the PDR, the approaches can be configured to send the beacons with unicast. In this case, receivers reply to received beacons with an acknowledgment in the same medium the beacon was received in. If the sender does not receive this acknowledgment, it will retransmit the packet. The packet is dropped after a certain amount of attempts is exceeded.

In the case of RF beacons sent by the platoon leader, the packets account as both leader-beacons for all followers, and front beacon for the first follower. For this reason, such beacons sent such that they are received by all followers, but only acknowledged by the first follower.

Beacon forwarding When platoon leaders transmit their beacons using VLC, they can only be received by the first follower, since the LOS is blocked for all other followers. In order to enable platooning, multi-hop communication, i.e., *beacon forwarding*, must therefore be used. When it is enabled, followers will forward received leader beacons to their succeeding vehicle, using their taillight. As a result, the leader beacon will propagate through the platoon.

While the *VLC* approach cannot work without beacon forwarding, as most of the vehicles will never receive a leader-beacon, it can also be beneficial to other approaches. *Het-L* and *Het-X*, can use it to improve the redundancy for the leader-beacon, and therefore increase the overall reliability. For *RF* however, it cannot be used, as no VLC is enabled in this approach. Also, attempting to forward the leader-beacons via RF will increase the network load without added benefit, and is therefore not implemented.

4.3 Implementation Details

When using OMNeT++-based simulations, the logic is implemented as modules which exchange messages. Veins models vehicles as a specific module which is instantiated for every vehicle within the simulation. It contains submodules, which correspond to functionality within the vehicle and their connections denote the flow of messages. Typically, vehicles use a Network Interface Card (NIC) for communication, as well as some applications which generate and receive messages using this NIC. Additionally, helper modules which are not connected to other modules, but rather represent logical units of the vehicle, are often used. Such modules can be used, for example, to describe the vehicle's position in the simulation, such that the module acts as a "proxy" to the corresponding vehicle of the Sumo component.

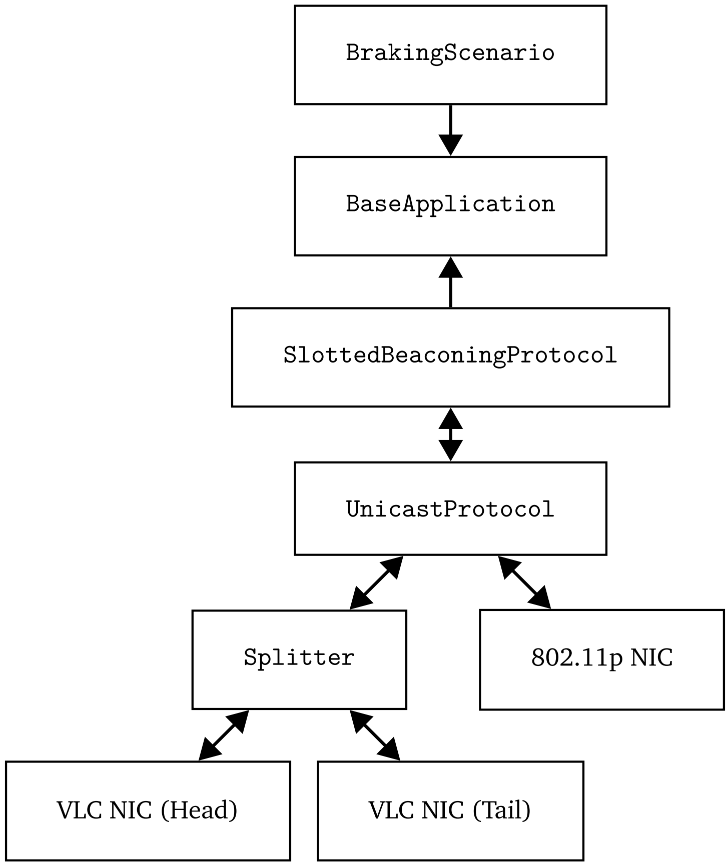


Figure 4.3 – The modules within a car. Edges correspond to information flow.

For the simulations used to evaluate the protocols described in Section 4.2, I modified the vehicle modules provided by Plexe. These modules are used to model a vehicle and its behavior, as is depicted in Figure 4.3. Most notably, I adapted them for heterogeneous communication. For this purpose, instead of a single NIC, multiple are used: One for RF communication and two for VLC. The two VLC-NICs model the head- and taillight of the vehicle and accordingly each is located at the middle of the front- and rear bumper respectively. Furthermore, they use a queue to avoid dropping packets which are scheduled in rapid succession. The VLC-NICs are connected to a `Splitter` which selects the appropriate NIC for outgoing packets and passes received packets up. Since neither the VLC, nor the 802.11p implementation of Veins VLC and Veins 4.6 support unicast, I use Plexe's application-layer unicast implementation which can be used with arbitrary lower layers. In addition, the `UnicastProtocol` chooses the correct network interfaces for a given packet, based on meta information passed along by the upper layer. This enables the `UnicastProtocol` to avoid unnecessary retransmissions on one channel, when the packet has been already acknowledged already on the other channel. On the other hand, it also imposes some limitations: since unicast is implemented on top of the MAC layer, it cannot adapt properties, e.g., the contention window to the amount of retransmissions. Moreover, the transmission timeout starts when the packet is queued instead of after it has been transmitted.

In my simulations, I've chosen to use the `SlottedBeaconingProtocol` for the upper layer, as it makes efficient use of the channel. With Plexe, `Protocol` subclasses are responsible for passing received packets up to registered applications, as well as generating platooning beacons. The `SlottetBeaconingProtocol` in particular is such a subclass, which implements SLBP, a beaconing protocol proposed by Segata et al. [9]. When using SLBP, each platoon member is assigned a timeslot. The leader generates beacons at a fixed rate, e.g. 10 Hz, which defines the zeroth timeslot. Based on the received leader-beacon, the followers compute their timeslot which coincides with their position in the platoon. Therefore, this approach avoids intra-platoon contention. In order to further reduce channel congestion, the followers transmit RF beacons with reduced power since the beacon's intended recipient is their successor and therefore in close proximity.

On top of the stack of modules described above, the `BaseApplication` and `BrakingScenario` are used to model the vehicle's and the simulation's high level behavior respectively. The `BaseApplication` passes information received from beacons to the CACC controller. The `BrakingScenario` triggers changes in vehicle's behavior, such as initiating emergency breaking of the first vehicle in each lane after a configurable simulation duration.

The CACC controller used by the vehicles is the one described by Rajamani [33]. Its control law is defined as:

$$\begin{aligned} u_i = &(1-C_1)u_{i-1} + C_1 u_0 + \left(2\xi - C_1\left(\xi + \sqrt{\xi^2-1}\right)\right)\omega_n \dot{\epsilon}_i \\ &- \left(\xi + \sqrt{\xi^2-1}\right)\omega_n C_1 \left(\dot{x}_i - \dot{x}_0\right) - \omega_n^2 \epsilon_i. \end{aligned}$$

To compute the control input (u_i), the controller takes different values into account:

- Front and leader vehicles' control input u_{i-1} and u_0.
- The relative velocity to the front and leader vehicle, $\dot{\epsilon}_i = \dot{x}_i - \dot{x}_{i-1}$ and $\dot{x}_i - \dot{x}_0$.
- As the spacing error to the front vehicle, $\epsilon_i = x_i - x_{i-1} + L$, where L is the desired distance.

C_1, ξ, ω_n are configuration parameters of the controller that can be used to tune its dependency on the front or leader vehicle.

Chapter 5

Evaluation

This chapter provides analysis of the different communication protocols I designed. First, I describe the setup that is used in the simulation campaign, as well as a description of what data I collected from it. Afterwards, I describe the results I obtained and discuss the effects that can be observed.

5.1 Simulation setup

In order to evaluate the performance of the different approaches (see Section 4.2), I observe their behavior in simulations. The simulation scenario is designed such that both safety aspects, and the network's performance can be observed.

Since the early adoption of platooning is focused on highways, I chose a highway scenario for the simulations. On the highway, one or several platoons are placed in a dense constellation on the highway's lanes. Each platoon's leader maintains a time-constant headway to the previous platoon using ACC. In order to evaluate the safety in demanding traffic situations, the leader of each lanes' first platoon initially drives at a fixed speed and performs an emergency braking a few seconds after the simulation started. The simulation then continues until either after all vehicles have stopped, or a crash between vehicles occurred. Upon a crash, the simulation cannot be continued, as the system has already failed.

The individual vehicles use the logic and communication modules described in Section 4.3. While the leaders are controlled by a regular ACC controller, the followers use the PATH project's CACC controller. For more details about the simulation's configuration and most relevant parameters, see Table 5.1.

This general simulation scenario is varied to determine how the approaches' behavior depends on different options.

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
	Transmission power	20 dBm
	Thermal noise power	−95 dBm
	Access category	AC_BK
VLC	Modulation	OOK [11]
	Bitrate	6 Mbit/s
	Sensitivity	−114 dBm
	Thermal noise power	−95 dBm

Table 5.1 – Simulation parameters

Protocol Since I want to observe the approaches I designed (see Section 4.2), I run the simulations with all parameter combinations for each of the approaches, i.e., *Het-L*, *Het-X*, *RF*, and *VLC*.

Number of vehicles Due to the large interference domain of 802.11p, an increased number of vehicles is likely to make communication more challenging when relying on RF. In order to observe this change for the different approaches, I use different counts of vehicles, namely 8, 160, and 320. As the platoon size is always eight, in the simulations with the fewest vehicles, there is only one platoon on a single lane. In the two larger cases, 20 or 40 platoons are evenly distributed on four lanes, respectively. They are placed in a steady state, i.e., the inter- and intra-platoon distances match the desired distances of the respective ACC and CACC controllers. To avoid effects due to symmetric placement, the vehicles on each lane are offset by a uniformly random distance between 0 and 20 m.

Acknowledgements This option determines the use of *beacon acknowledgements*, as described in Section 4.2. When it is enabled, there are up to seven transmission attempts for each packet, as this is the default amount of retransmissions for packets below a size of 375 B in 802.11 [34].

Beacon forwarding This option determines the use of *beacon forwarding*, as described in Section 4.2. While the option is required for *VLC*, and therefore always enabled with this approach, it cannot operate in *RF*, as it relies on VLC, and is disabled in this case.

Repetitions Because the simulations are rather short and might depend on the initial, randomized placement of the vehicles, I use repeated simulations to retrieve statistically significant results. For each parameter set, there are ten repetitions. These repetitions only differ in the seed of their PRNGs. Therefore, behavior that is affected by randomness, such as packet reception will change in the different simulation runs.

For each combination of these parameters, I execute a simulation run. From each of these runs, I collect data according to different metrics to analyze the approaches' effect on the vehicle's and network's behavior:

RF busy time The RF busy time, or *channel utilization*, is the fraction of time that nodes consider the RF channel to be busy. It is considered busy, due to ongoing transmissions the node overhears, which cause the Clear Channel Assessment (CCA) to fail, or transmissions by the node itself. Therefore, the busy time is a good indicator for the network's performance: high values will lead to delayed transmissions as an idle channel has to be awaited. Furthermore, a high busy time also increases the likelihood of collisions occurring due to simultaneous channel access of different nodes.

Beacon reception ratio This metric accounts for the loss of beacons. It corresponds to the packet delivery ratio of beacons, which is not well defined, as many transmissions use broadcast. Since all vehicles expect to receive ten beacons per second, from both their leader and their front vehicle, this metric can be derived from the amount of actually received beacons.

Beacon end-to-end delay This metric measures the beacon delay as observed by the application: the time between generation of the beacon and the reception at a vehicle that depends on it. It is critical for the operation of the CACC controller, as it corresponds to the beacon's information age at arrival. Since changes in the vehicle kinematics during this time are unknown to the controller, it cannot account for them. Therefore, the beacon end-to-end delay limits its performance.

The minimal beacon end-to-end delay is defined by the data rate, the signal's time-of-flight, and the duration of computation. Additionally however, it can be increased by different effects:

- Non-instantaneous channel access due to queued packets, ongoing transmissions (RF and VLC) or contention (RF only).
- When acknowledging packets, lost packets cause retransmissions after a timeout.
- Transmitting leader beacons via VLC requires transmission over multiple hops for a beacon to reach all platoon members (see Section 4.2). Since all of the individual transmissions are subject to the effects above, this will further increase the beacon age, as it progresses through the platoon.

Minimum intra-platoon distance Safe operation is the highest priority when designing a platooning system. Therefore, in order to evaluate such a system, one needs to find a way to quantify safety. Since I use an emergency braking scenario, such a quantification can be based on the distance between vehicles. Due to the harsh braking maneuver, these distances are expected to decrease, even though the CACC controller tries to keep them at a desired, constant value.

However, not all intra-platoon inter-vehicle distances are equally relevant: When beacons are not received successfully, this affects only the receiving vehicle and all its successors. Vehicles in the front, or on different lanes are unaffected. Therefore, from a single simulation run I measure only the minimum of the intra-platoon inter-vehicle distances, as it corresponds to the most unsafe situation within the simulation run. Since the inter-vehicle distances change continuously, I sample them with a frequency of 10 Hz.

Critical time ratio The vehicles in a platoon control their acceleration based on information they receive from their leader and the front vehicle. Upon reception of these beacons, their information is used to compute the control input, until a more recent beacon is received. While it is being used by the controller, the information from both front, and leader, ages and, thus, becomes less accurate. With this loss in accuracy, the controller becomes less capable of properly keeping the distance to the front vehicle. The critical time ratio is a metric which aims to capture this effect: it measures the fraction of time a vehicle is in a critical state, i.e., when its controller relies on outdated information, within its lifetime.

The point in time at which information becomes too old and the vehicle using it becomes critical cannot be fixed to a single value. Therefore, the *threshold*, that defines at which point information becomes outdated, is variable, and sampled in increments of 10 ms. A small threshold value, e.g., zero, will result in a high critical time ratio as any received information is considered outdated immediately. Higher values allow more tolerance to old information, and therefore reduce the amount of time the vehicle is considered to be in a critical state. As such, this metric only considers the actually received information, and its age. Therefore it captures various effects that occur on the network, like transmission delays, packet losses, and the differences in reception time between front and leader beacons.

5.2 Results

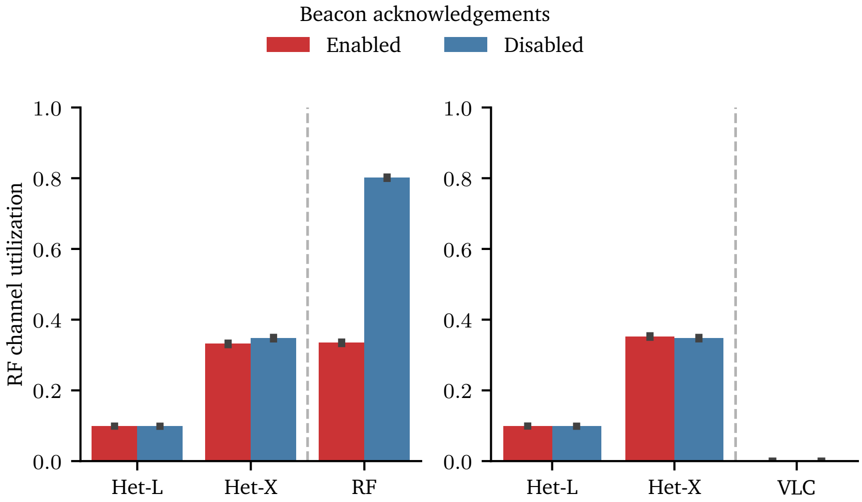
In the following I present the results obtained from the simulations described above. I start by describing the network's performance and go on to show the high level performance of platooning for the different approaches.

5.2.1 RF busy time

Since the main motivation for VLC-supported platooning is the extensive channel congestion caused by RF, I measured the channel utilization from the simulations for the individual approaches. Figure 5.1 shows the measured results for the simulation runs with 160 vehicles. It can be seen that the channel utilization of the RF enabled approaches is lowest for *Het-L*, as in this case only one vehicle per platoon sends beacons on the RF channel. *Het-X*, on the other hand, uses RF on all platoon members, resulting in a higher channel busy time.

For both of these approaches however, the busy time does not increase significantly when enabling acknowledgements. This is mainly due to the fact that in both cases the beacons which are sent using RF are also sent by VLC. Since VLC packets are sent immediately, without waiting for channel access (see Section 5.2.3), they are received first. Thus, when the beacon is successfully received, the acknowledgement is also sent on the VLC channel and doesn't contribute to RF channel utilization. Only when beacons are not received via VLC, but via RF, an RF acknowledgement is sent.

The *RF* approach utilizes a similar amount of channel capacity as *Het-X*, when no acknowledgements are used. If they are enabled, however, the channel becomes overloaded: there are more attempted transmissions than the channel can handle. As a result, beacons often cannot be successfully transmitted, which results in even more retransmissions which also contribute to the channel load.



(a) No forwarding **(b)** Forwarding

Figure 5.1 – RF channel utilization for simulations with 160 vehicles without (a) and with (b) forwarding. The mean between simulation runs are shown, the error bar indicates 95% confidence intervals. Note that data for *RF* and *VLC* is only available for dis- and enabled forwarding, respectively, as is indicated by the dashed lines.

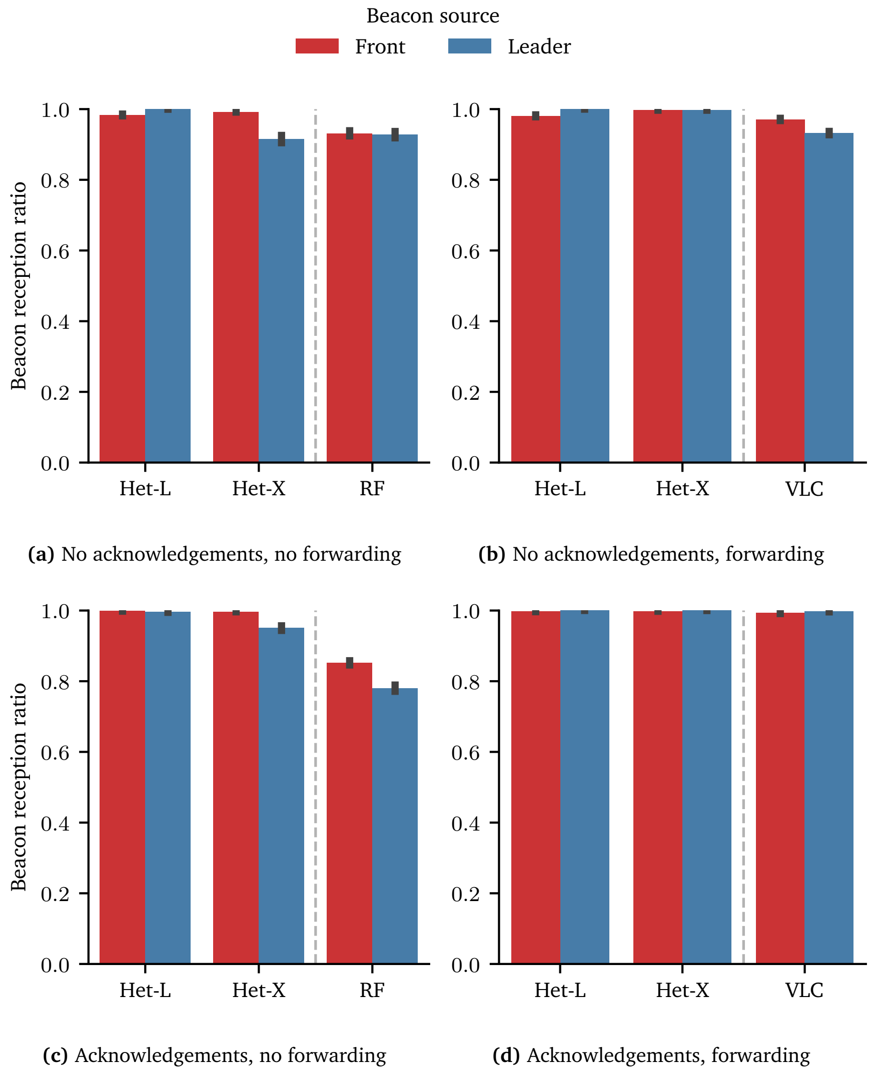
Enabling forwarding with both *Het-L* and *Het-X* does not affect the channel utilization, as the leader beacon is always forwarded with VLC. *VLC* never uses the RF channel and therefore also causes no utilization of it.

5.2.2 Received beacon ratio

The busy time only indicates the approaches' resource usage. For platooning however, it is of particular interest, how many of the expected beacons were received. This is depicted in Figure 5.2.

With neither beacon acknowledgements, nor forwarding enabled, significant numbers of beacons are lost. In particular, the *Het-X* leader beacons often cannot be received, since the channel is also used for transmitting front beacons. While these beacons can also be received via VLC, this is not the case for the leader beacons, if forwarding is disabled. This effect is also not compensated for by the reduced transmit power for front beacons (see Section 4.2), which should increase the leader beacons' reception probability.

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, busy time is low and practically all leader beacons are received, even without additionally relying on forwarding. This doesn't come without drawbacks, though, as the front



(a) No acknowledgements, no forwarding

(b) No acknowledgements, forwarding

(c) Acknowledgements, no forwarding

(d) Acknowledgements, forwarding

Figure 5.2 – 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 between simulation runs are shown, the error bar indicates 95% confidence intervals. Note that data for *RF* and *VLC* is only available for dis- and enabled forwarding, respectively, as is indicated by the dashed lines.

beacons reception ratio is only 98.3% with *Het-L* if no acknowledgements are used, . When acknowledgements are enabled, however, this ratio is increased to 99.8%, such that *Het-L* receives most of the sent beacons.

In summary, *Het-X* relies on the diversity gain provided by the use of different channels, which can only be fully exploited when forwarding is used. *Het-L* on the other hand operates ideally with time diversity by means of acknowledgements.

VLC suffers from packet loss with both front and leader beacons. When beacon acknowledgements are enabled, this loss is drastically reduced for both beacon types. Moreover, the reception probabilities are similarly high, irrespective of the scenario size (see Figure 5.3).

In the case of *RF*, the use of acknowledgements is actually detrimental, and, when enabled, it actually reduces its packet reception ratio of the leader and front beacon, due to the channel overload. Furthermore, this reduction is more pronounced for the leader beacons.[8]

5.2.3 Beacon delay

In order to support platooning, the goal is to provide accurate information to the controller. Consequently, not only frequent updates are required, also the delay between beacon generation and reception should be kept low, which is investigated in this section. Furthermore, since platooning is safety relevant, it should work at all times. Therefore, I have decided to examine the 99th percentiles of the transmission delays instead of their means. The 99th percentile of transmission delays indicates the delay which is above 99% of the recorded data. Accordingly, it is a good indicator for the maximum delay that is usually observed.

In general, the transmission delays for all approaches I simulated are relatively low, as can be seen in Figure 5.4. The RF transmissions take at least about 0.5 ms, due to channel access, even in case of 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. VLC on the other hand immediately starts transmitting packets, when the queue is empty, and only takes about 29 µs to complete a beacon transmission.

One concern with forwarding of leader beacons is that the multi-hop communication takes too much time. With the VLC model I employed however, it can be seen, that 99% of the vehicles receive the leader beacons within 4.2 ms in the *VLC* approach, when acknowledgements are used.[9] In comparison to the update period, which is 100 ms when using 10 Hz beaconing, this is only a small additional factor

[8] This might indicate that a different parameterization of the SLBP power levels can benefit beaconing, such that more leader beacons can be received.

[9] While the value is even lower without using acknowledgements (0.2 ms), a large part of this effect is due to packet loss, and therefore not as significant.

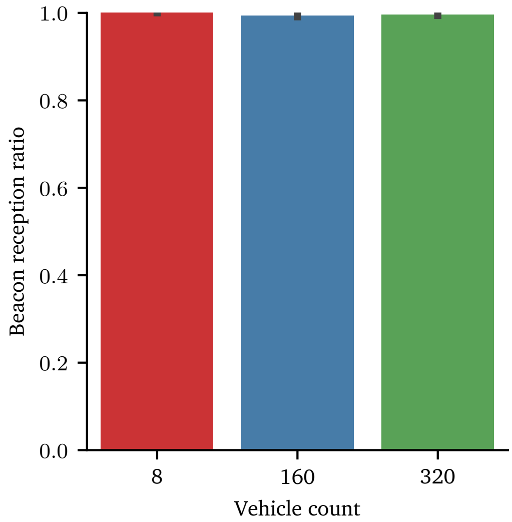


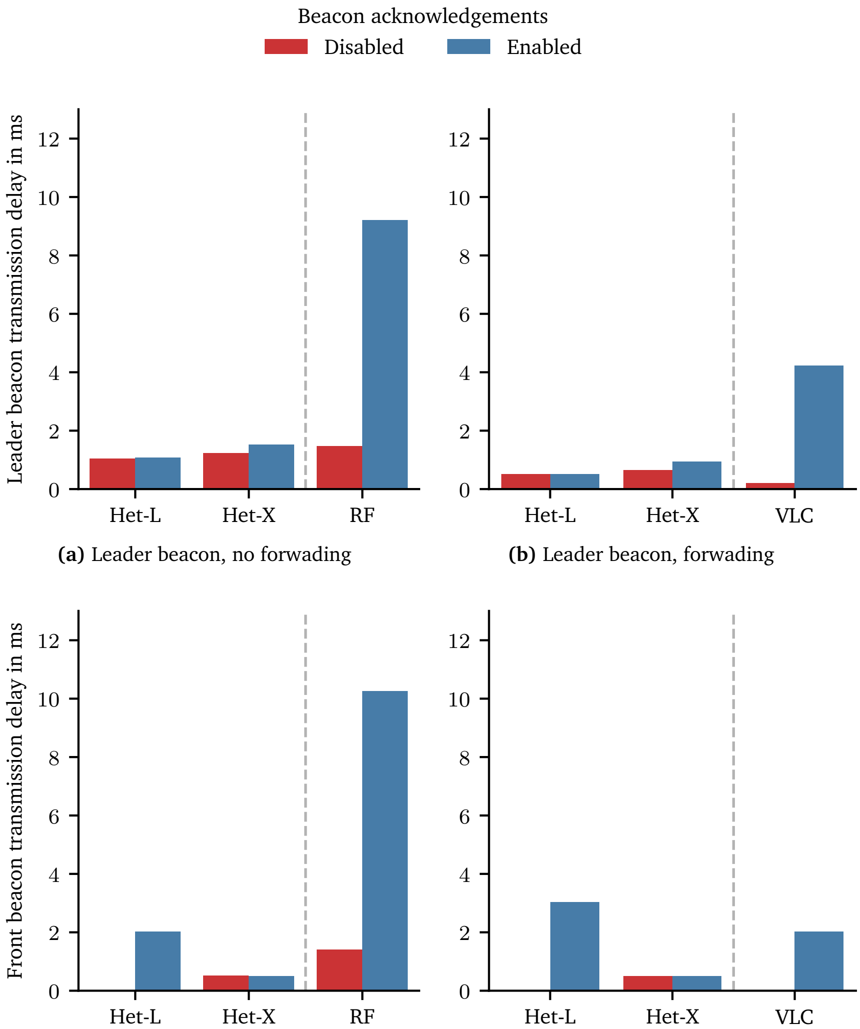
Figure 5.3 – Beacon reception ratio of front beacons with *VLC* and enabled acknowledgements for different scenario sizes.

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 beacon's 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, they are received either very quickly, or not at all. When acknowledgements are enabled, they usually take two to three retransmissions to be received, and thus require less then about 2-3ms respectively, due to the unicast timeout of 1 ms. *Het-X* beacons are subject to a similar effect: in most cases, they are usually successfully received via VLC, or, in case the reception fails, via RF. This results in a higher transmission delay for *Het-X* when acknowledgements are not used, but a lower one when they are enabled, as in this case the fraction of receptions via VLC is increased.

5.2.4 Critical time ratio

The combination of the effects described above is reflected in the critical time ratios. As described in Section 5.1, the critical time ratio describes the fraction of time vehicles are in a critical state, depending on a threshold which defines the maximum age, at which beacon information is considered useful. Figure 5.5 shows the critical time ratios for the simulation runs with 160 vehicles. It shows, that the determining factors differ between the considered approaches.



(a) Leader beacon, no forwading

(b) Leader beacon, forwading

(c) Front beacon, no forwading

(d) Front beacon, forwading

Figure 5.4 – 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. Note that data for *RF* and *VLC* is only available for dis- and enabled forwarding, respectively, as is indicated by the dashed lines.

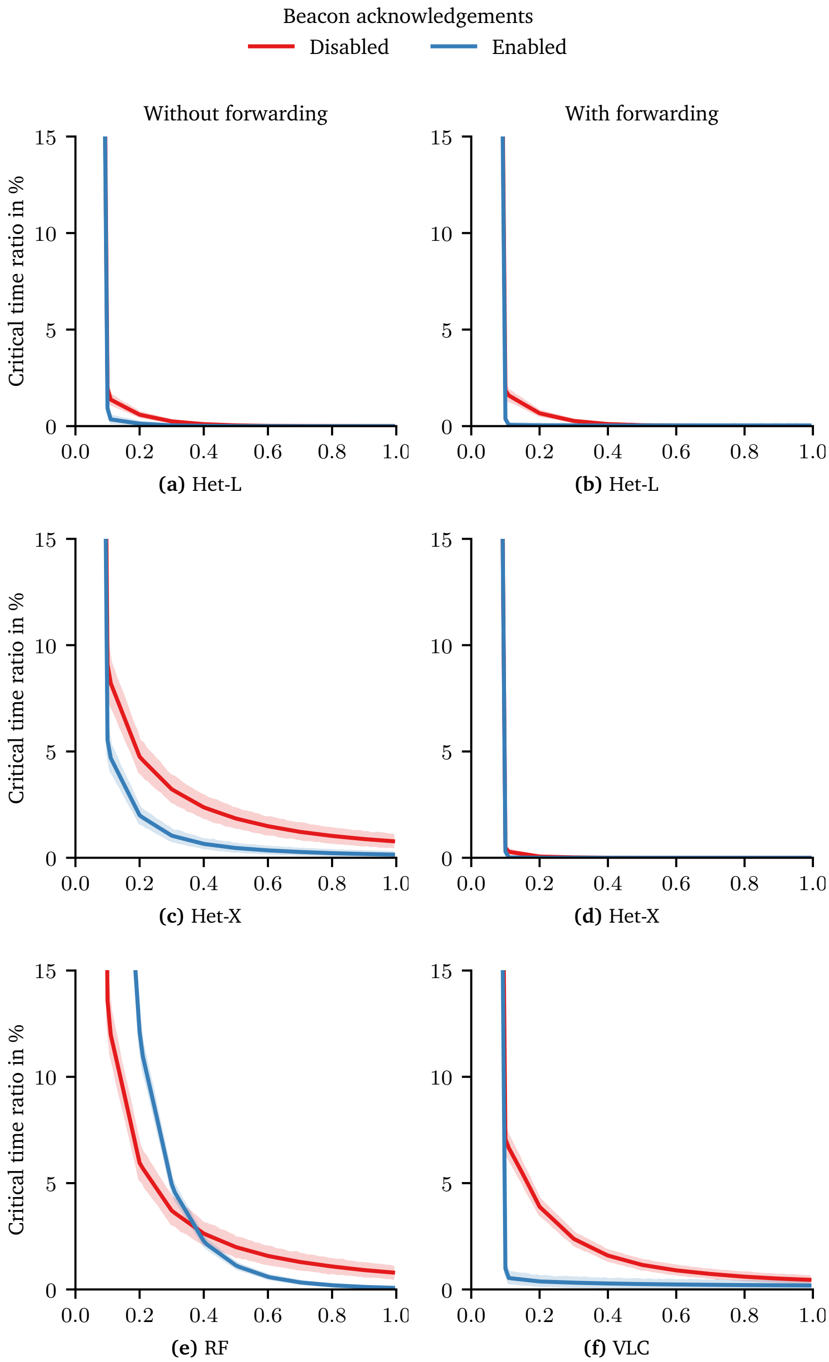


Figure 5.5 – Critical time ratios for 160 vehicles. The left column shows data for the approaches with enabled forwarding, the right column for disabled forwarding. The shaded areas around the lines indicate the 95% confidence interval.

- With *Het-L*, the time spent in a critical state does not change significantly if forwarding is used. The use of acknowledgements however decreases its critical time ratio at a threshold of 250 ms from 0.5% to 0.04%, with enabled forwarding.
- The critical time ratio is very high for *Het-X* if not using forwarding. As discussed earlier, this this is mostly due to lost leader beacons, the ratio is much smaller when these beacons can be received more often, e.g., by enabling forwarding. In this case, the remaining critical time ratio at 250 ms threshold is 0.001% when using acknowledgements and 0.04% without them.
- *VLC*, like *Het-X* without acknowledgements, has a quite high critical time ratio (3.1% at 250 ms threshold). While it decreases to 0.35% at 250 ms threshold with acknowledgements, it does not approach zero, and even at a threshold of 990 ms it remains at .19%.

5.2.5 Minimum intra-platoon distance

Overall, the performance of the platoons is reflected by how well they are able to maintain the desired distance in platoons. For this purpose, Figure 5.6 shows the minimum distances between two platoon members for each simulation run. It shows, depending on their parameterization, how well the approaches were able to keep vehicles from crashing in the emergency braking scenario.

For eight vehicles, almost all simulation runs perform very well. 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 though, it is to expect that eventually crashes do occur if beacon acknowledgements are disabled.

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. 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 for far lower than their optimum. Interestingly, *Het-X* performs worse, even though its critical time ratio indicates the opposite on the first glance. However, while the critical time ratio for 250 ms is better for *Het-X* relative to *RF* (1.5% to 8.3%), for 990 ms it is worse (0.15% to 0.08%). 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 usually cause a crash. In *RF* runs however, the

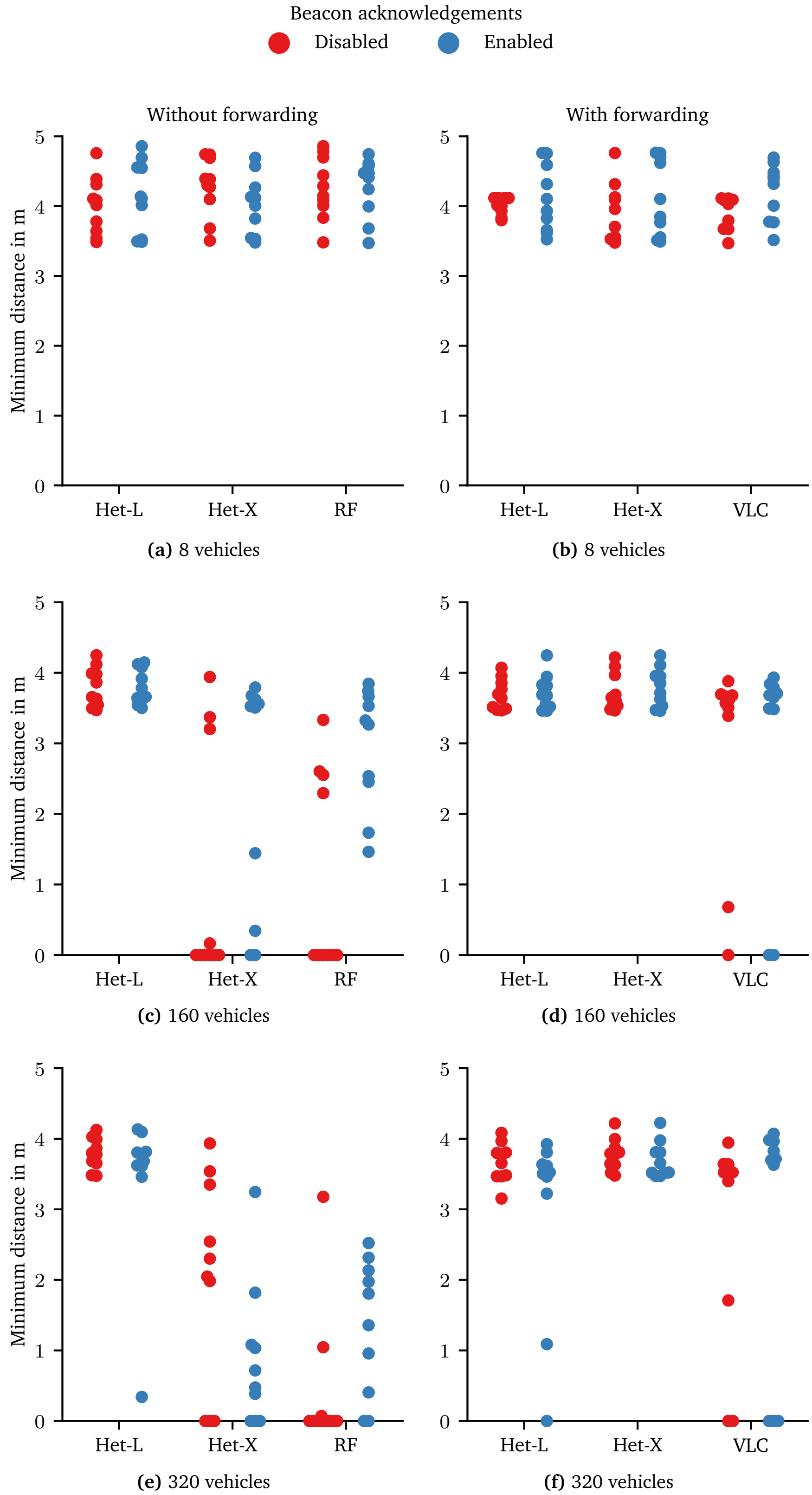


Figure 5.6 – The minimal distances between any two vehicles of the same platoon within each simulation run. The left column shows data for the approaches with enabled forwarding, the right column for disabled forwarding. Note that data for *RF* and *VLC* is only available for dis- and enabled forwarding, respectively, as is indicated by the dashed lines.

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, crashes only occur in the *VLC* approach. Interestingly, this happens both with and without beacon acknowledgements, even though the critical time ratios are worse in case of disabled acknowledgements. Apart from this, all three approaches perform very well, keeping a minimum distance of at least 3.4 m.

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* can avoid crashes in even fewer simulation runs, while *Het-L* performs quite well. With forwarding however, in most simulation runs the minimum intra-platoon distance is kept above 3 m, which is very good considering the harsh braking maneuver. For *VLC*, with and without acknowledgements, three and two simulation runs out of the ten crash, respectively. Another run without acknowledgements achieves a minimum intra-platoon distance of only 1.7 m. A similar behavior can also be observed for *Het-L* with acknowledgements, where one run crashes, while another avoids this, but only with a remaining distance of 1.1 m.

In summary, in the largest simulation runs, only *Het-X* with forwarding and *Het-L* without forwarding were able to prevent all crashes. *Het-L* with forwarding, and *VLC* simulations on the other hand, showed a bimodal behavior: Most of them ended safely, at comfortable distances between vehicles, while few runs crashed.

5.2.6 Crashes in VLC based runs

A particular effect which manifests itself in different metrics and shows bimodal behavior. It can be observed, for example, in the beacon reception ratio. While the mean values for *Het-L* with acknowledgements, *Het-X* with forwarding, and *VLC* with both acknowledgements and forwarding are very high (see Figure 5.2), some nodes experience a lot of packet loss. This is depicted in Figure 5.7, which shows the minimum of the front beacon reception ratios for the 320 vehicle simulation runs with forwarding and acknowledgements. While for *Het-X*, even the minimum front beacon reception ratios are at least 97.6%, both *Het-L* and *VLC* have minima well below 90%.

The effect also occurs with 160 vehicles, albeit with a smaller magnitude. It is therefore also reflected in the critical time ratio plots (see Figure 5.5), where the critical time ratios for *Het-L* and *VLC* with forwarding are reduced by 15% and 50%, respectively between thresholds of 250 ms and 990 ms, while other approaches typically see a reduction of several orders of magnitude for those thresholds.

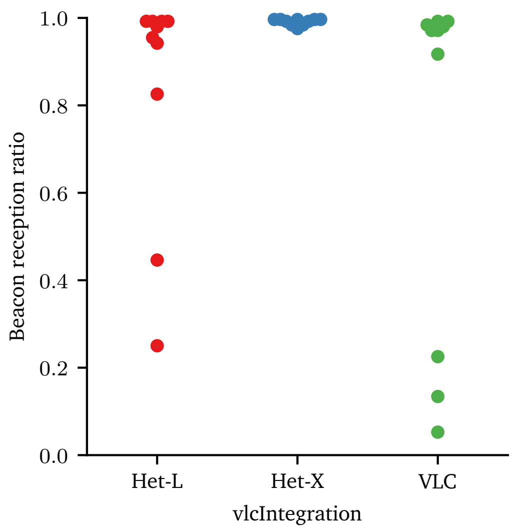


Figure 5.7 – Minimum front beacon reception ratios with 320 vehicles, forwarding and acknowledgements.

Accordingly, in the runs with individual cars that lose most of the beacons, crashes occur, while in the other runs the performance of both *Het-L* and *VLC* is generally good. The common property of these approaches is that they use solely VLC for transmitting the front beacons, which are subject to the drastic packet loss. The reason might therefore be a rare effect occurring with VLC transmissions, that persistently causes transmissions to fail. An alternative explanation might be an implementation issue, which requires further investigation.

Chapter 6

Conclusion

In this thesis I investigated possible benefits of the use of Visible Light Communication (VLC) for platooning. For this purpose, I designed four approaches, *Het-L*, *Het-X*, *RF*, and *VLC*, that utilize Radio Frequency (RF) and VLC to varying degrees. Additionally, I added beacon *forwarding* and *acknowledgement* mechanisms to improve the reliability of beaconing. In order to identify individual strengths and weaknesses of the approaches, I ran an extensive simulation campaign using an emergency braking scenario with different vehicle densities.

The results confirm that RF suffers heavily from high channel congestion in high vehicle densities. VLC on the other hand, is not affected by it. Augmenting RF with VLC to improve redudnancy, i.e., using the *Het-X* approach, increases the communication reliability. Crashes can therefore be avoided in the scenario with the highest vehicle density. With the *Het-L* approach, which relies heavily on VLC, a 3.5-fold reduction of channel busy time is achieved. In this case, the reliability improves compared to the RF-only approach, however in 10% of the highest vehicle density simulation runs, a crash still occured. Even with the *VLC* approach, which uses no RF communication at all, platooning operates safely in most simulation runs, however, in both of the larger simulations (160 and 320 vehicles), some runs did not complete without vehicles crashing. Additionally, the results show that the forwarding delay of leader beacons in platoons of size eight proved not to be an issue. In fact, transmission delays of VLC have a similar magnitude as RF transmissions.

These results demonstrate that using sufficiently reliable VLC for platooning applications is indeed feasible and beneficial, as improvements in both safety, and resource utilization can be achieved.

6.1 Future Work

Even though the insights gained in this thesis are promising, some effects are not yet fully understood. This applies in particular, to the apparently erratic behavior of a few vehicles in the simulation, which perform badly. It requires further investigation, to clarify whether this is a proper effect or occurs due to an implementation issue.

Furthermore, in addition to the parameters investigated in this thesis, like the platoon size, different controllers, or adverse weather effects, can be considered in future work. Also, heterogeneous scenarios, with varying platoon sizes, non-platooning vehicles, and dynamic platoons could be investigated to make the results more generalizable.

The simplistic approaches I use in this thesis show already promising performance. Based on these results, more sophisticated approaches can be designed, such as, e.g., reactive beaconing with VLC that falls back to RF when required.

Since the inclusion of VLC proves to be useful with platooning, additional communication methods, e.g., Long Term Evolution (LTE), might improve the performance even further. Perhaps, it is even possible to develop a framework that allows for optimal inclusion of arbitrary communication methods.

List of Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AWGN	Additive White Gaussian Noise
BER	Bit Error Ratio
CACC	Cooperative Adaptive Cruise Control
CCA	Clear Channel Assessment
COTS	commercial of-the-shelf
DES	Discrete Event Simulator
DLR	German Aerospace Center
DSL	Domain Specific Language
DSRC	Dedicated Short Range Communication
EEBL	Electronic Emergency Brake Light
ITS	Intelligent Transport System
IVC	Inter Vehicular Communication
LED	Light-Emitting Diode
LOS	line-of-sight
LTE	Long Term Evolution
MAC	Medium Access Control
NIC	Network Interface Card
PDR	Packet Delivery Ratio
PRNG	pseudorandom number generator
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SNR	Signal to Noise Ratio
VANET	Vehicular Ad Hoc Network
VLC	Visible Light Communication
WAVE	Wireless Access in Vehicular Environments

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