Technische Universität Berlin

Julia Mandana Horvath

Analysing the Proposed Communication Protocol for Multi-Brand Truck Platooning in Europe

Bachelor Thesis in Business Informatics

29 November 2021

Please cite as:
Julia Mandana Horvath, “Analysing the Proposed Communication Protocol for Multi-Brand Truck Platooning in Europe,” Bachelor Thesis (Bachelorarbeit), Institute of Telecommunication Systems, Technische Universität Berlin, Germany, November 2021.

TKN Telecommunication Networks Group

Fachgebiet Telekommunikationsnetze
Technische Universität Berlin, Germany

Einsteinufer 25 · 10587 Berlin · Germany

https://www.tkn.tu-berlin.de/

Analysing the Proposed Communication Protocol for Multi-Brand Truck Platooning in Europe

Bachelor Thesis in Business Informatics

vorgelegt von

Julia Mandana Horvath

angefertigt in der Fachgruppe

Fachgebiet Telekommunikationsnetze

Institut für Telekommunikationsnetze
Technische Universität Berlin

Betreuer:	**Julian Heinovski**
	Dominik S. Buse
	Max Schettler
Gutachter:	**Falko Dressler**
	Thomas Sikora
Abgabe der Arbeit:	**29. November 2021**

Erklärung

Ich versichere, dass ich die Arbeit ohne fremde Hilfe und ohne Benutzung anderer als der angegebenen Quellen angefertigt habe und dass die Arbeit in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen hat und von dieser als Teil einer Prüfungsleistung angenommen wurde.
Alle Ausführungen, die wörtlich oder sinngemäß übernommen wurden, sind als solche gekennzeichnet.

(Julia Mandana Horvath)
Berlin, den 29 November 2021

Abstract

In platooning multiple vehicles are organized in convoys driving autonomously with a minimized safety gap. In order to support the global deployment of platooning, an integrated multi-brand approach is required. The European HORIZON 2020 project ENSEMBLE tries to address this issue by unifying and standardizing platooning within Europe. To this end, ENSEMBLE published a new communication protocol and within proposed a concrete implementation of communication for truck platooning in Europe. We conduct an extensive simulation study of the proposed communication protocol, showing that the protocol, even with packet loss, works reliable in all tested scenarios and guarantees a certain level of road safety. Considering the protocol performance from the application layer perspective, we evaluate how effective the protocol fulfills the requirements of the controller. By doing that, we additionally provide a key performance indicator to measure how well the protocol ensures constant information flow. That can be used to determine whether a different controller would be reliable with the proposed communication protocol.

Kurzfassung

Beim Platooning werden mehrere Fahrzeuge in Konvois organisiert, die autonom und mit möglichst geringem Sicherheitsabstand fahren. Um den globalen Einsatz von Platooning zu unterstützen, ist ein integrierter Mehrmarkenansatz erforderlich. Das europäische HORIZON 2020 Projekt ENSEMBLE versucht, dieses Problem durch Vereinheitlichung und Standardisierung von Platooning in Europa zu lösen. Zu diesem Zweck hat ENSEMBLE ein neues Kommunikationsprotokoll veröffentlicht und eine konkrete Implementierung der Kommunikation für LKW-Platooning in Europa vorgeschlagen. Wir führen eine umfassende Simulationsstudie des vorgeschlagenen Kommunikationsprotokolls durch, die zeigt, dass das Protokoll selbst bei Nachrichtenverlusten in allen getesteten Szenarien zuverlässig funktioniert und ein gewisses Maß an Verkehrssicherheit gewährleistet. Wir betrachten die Leistung des Protokolls aus der Perspektive der Anwendungsschicht und bewerten, wie effektiv das Protokoll die Anforderungen des Controllers erfüllt. Auf diese Weise stellen wir zusätzlich einen Leistungsindikator bereit, um zu messen, wie gut das Protokoll einen konstanten Informationsfluss gewährleistet. Damit lässt sich feststellen, ob eine andere Steuerung mit dem vorgeschlagenen Kommunikationsprotokoll zuverlässig wäre.

Contents

Chapter 1

Introduction

Vehicle transportation takes a major share in the transportation sector. In the EU road transport for example continues to have the largest portion of inland freight transport and accounted in 2018 for over 75 % of the total volume. In the area of passenger transport a similar picture emerges, where in 2017 the passenger cars had a share of over 80 % of inland passenger transport. [1] Next to the public transport, the privately owned car is still the most used transportation system. Furthermore, the overall traveled distance, as well as the number of privately owned cars, increased. [2] Having such a high density on the road results in more road traffic and thus in more traffic congestion, accidents, and pollution [3]. This also effects the efficiency of transportation systems. To solve these problems, researchers and car manufacturers are continuously trying to improve and innovate driving, using, e.g., Intelligent Transportation System (ITS). One promising development in this field is *platooning*.

With platooning, multiple vehicles are organized in groups driving behind each other with a minimized safety gap. These convoys are called platoons. The vehicles of a platoon are driving autonomously using Cooperative Adaptive Cruise Control (CACC) to maintain the small safety gap. CACC utilizes data from build-in sensors and information from other vehicles via Inter-Vehicle Communication (IVC). By reducing the inter-vehicle gap, but keeping the same cruise velocity, platooning can increase the road utilization, improve the traffic flow and, due to less air drag, reduce the fuel consumption and therefore emissions. Furthermore, having the vehicles drive autonomously increases safety and can lead to an improved, less stressful driving experience [4]–[6].

The introduction of platooning in the transportation sector is less complex for trucks than for passenger cars. Since trucks travel more kilometers per year than other road vehicles, the fuel and time savings would be significantly higher [7], [8]. In Europe fuel cost make approximately one-third of all operational costs for long haulage heavy duty vehicles (HDVs), which is a strong economical incentive for truck operators, who can expect a faster return on investment. In 2011, driving experiments were conducted, showing fuel savings of approximately 4 - 5 % for the leader of the platoon and 10 - 14 % for the following vehicles. [9] In addition, automated driving could potentially decrease workforce expenses in the long run, which are particularly high in the trucking sector. [10] In order to support the global deployment of platooning, an integrated multi-brand approach is required. For such an approach, a standardized protocol is needed to regulate, e.g., the use of the wireless channel and provide interoperable protocols between Original Equipment Manufacturers (OEMs). This would avoid vendor lock-in and support forming platoons of different vehicle types and brands, which is necessary to reach the full potential of platooning. The European HORIZON 2020 project ENSEMBLE tries to address this issue by unifying and standardizing platooning within Europe. To this end, they published a new communication protocol and within proposed a concrete implementation of communication for truck platooning in Europe, which is currently under review at the European Commission (EC).

The need to analyze the proposed protocol derives from the fact that it is based on theoretical considerations and since the protocol is the first of its kind, one can not simply assume that all given specifications integrate without any complications. Hence, it needs to be investigated if the proposed protocol behaves in practice as desired. To do this we are going to conduct a simulation study, which enables us to evaluate many scenarios in a flexible manner. We use this to evaluate two main aspects of the proposed communication protocol, i.e., the communication and the impact of the communication on the CACC performance and therefore on the mobility. Therefore, the analysis will focus on regular operation, leaving other aspects defined by the protocol, e.g., security and maneuvers, out of scope.

In this thesis we started by analyzing and implementing the proposed communication protocol as defined by the ENSEMBLE project, using PLEXE as the simulation framework. Furthermore, several test cases were implemented to test and validate the proposed communication protocol. Lastly, we implemented scenarios to evaluate the network layer and application layer performance and the impact of the communication on the CACC and, therefore, on the mobility.

We contribute an in-depth study of the communication protocol proposed by the ENSEMBLE project. For this we did an extensive performance evaluation, showing that the protocol, even with packet loss, works reliable in all tested scenarios, and guarantees a certain level of road safety. Considering the protocol performance from the application layer perspective, we evaluate how effective the protocol fulfills the requirements of the controller. By doing that, we additionally provide a key performance indicator to measure how well the protocol ensures constant information flow. That can be used to determine whether a different controller would be reliable with the proposed communication protocol.

Chapter 2

Fundamentals

In this chapter, we will describe the fundamentals on which this thesis is based. We start by describing the most important aspects of platooning, including mobility and vehicular communication (Section 2.1). Then, we will give an overview of the content of the proposed communication protocol itself (Section 2.2) and finally, briefly describe the simulation framework PLEXE, which was used in the implementation (Section 2.3).

2.1 Platooning

Platooning is an application fully relying on IVC, which at its core coordinates a group of vehicles called a platoon. For platooning to be able to build and maintain a platoon, multiple technologies are necessary. Essential are two components, which work closely together. The first one is the control algorithm, which is needed to, e.g., regulate the relative inter-vehicle gap and coordinate all vehicles in order to stabilize the platoon. The second one is the communication network, which is needed to exchange information between the vehicles. [11] The control algorithm is realized with a specific type of cruise control, which in order to function properly relies on data received from other vehicles in the platoon. This causes the need for communication between these vehicles. The design of the control algorithm itself defines the *control topology* [11]. It indicates which data from which vehicle the controller takes into consideration, e.g., if the controller exploits data from the leader, the front vehicle or even of vehicles behind.

In the following sections, we will first consider platoon control in Section 2.1.1 and 2.1.2 and then the communication network in Section 2.1.3 and 2.1.4.

2.1.1 Platoon Control

Platoon control consists of two fundamental components, longitudinal and lateral control. These are the two main aspects forming the regulation control of an automated vehicle. Longitudinal control is about maintaining a desired speed and inter-vehicle gap, and lateral control is about lane keep and lane change. As described in Section 2.2, the ENSEMBLE project defines different levels of platooning, focussing on platooning level A first. It describes longitudinal automation but not lateral automation yet, for which reason the lateral control is out of scope for this thesis. The main control aim in platooning regarding longitudinal control is to ensure that all vehicles move at almost the same speed while maintaining a given inter-vehicle distance. Therefore the ENSEMBLE project defines Adaptive Cruise Control (ACC) for the leader of the platoon and CACC for the following vehicles in the platoon. ACC is an advanced longitudinal control system. It adapts the vehicle's velocity to the desired velocity or if there is a vehicle driving in front of it, to a velocity that yields a desired distance to the preceding vehicle. To detect vehicles in front and measure the relative velocity as well as the inter-vehicle distance the ACC uses a radar or a scanning laser (lidar). [12] CACC is an enhanced version of ACC and additionally uses wireless communication, so that information such as speed and acceleration can be shared among multiple vehicles. This enables the possibility to reduce the inter-vehicle gap without compromising safety. [11] In general, it is expected that vehicles that can build a platoon will always have both CACC and ACC functionalities.

Two essential performance indicators for the control of CACC are the level of string stability and how well the controller handles actuation lag. Actuation lag is defined as the time between a control impulse and the point in time where the desired effect occurs, e.g., the time between the controller deciding to accelerate and the actual acceleration of the vehicle. Actuation lag occurs because of factors like a delay of sensors, engine response time and sampling delay, etc., which need to be considered. [12], [13] A platoon is considered string stable if any error in position, velocity, or acceleration of an individual vehicle is not amplified towards the end of the platoon. [14], [15] A consequence of a lack of string stability would be that errors are amplified within a platoon, such that the traffic flow, fuel consumption, and the scalability concerning platoon length might be negatively affected. Various CACCs can be found in the literature, which differ in design, requirements, and characteristics [11]–[13], [16], [17]. As a result, the performance indicators, e.g., how much errors are attenuated, differ between CACCs.

2.1.2 Cruise Control: CACC

In the following, we will describe the CACC selected for analyzing the proposed communication protocol in detail. The protocol itself specifies that the leader is using an ACC and the followers are using CACCs, but it does not define which controllers in particular to use. A decisive aspect of the protocol is that it defines the inter-vehicle gap as a time period instead of a length unit, for which reason we chose the CACC described in [12]. This controller defines distances in the same way as a *headway time*, which is the time a vehicle needs to travel a certain distance at the current speed. Its main objective is that each vehicle follows its preceding vehicle at the desired distance. The controller design is based on a standard ACC system and the most common spacing policy [18]. This spacing policy is defined with a constant part and a velocity part and determines the desired distance $d_{r,i}$ for a given point in time. The desired distance is

$$d_{r,i} = r_i + hv_i, \qquad 2 \leq i \leq m, \tag{2.1}$$

where m is a string of vehicles, h is the headway time, v_i is the velocity of vehicle i, and r_i is the constant part defined as the desired distance at standstill [12]. Due to this spacing policy the string stability of the controller is ensured. The control law for the CACC is defined as [12]

$$\dot{u}_i = \frac{1}{h}(-u_i + k_p(x_{i-1} - x_i - (r_i + hv_i)) + k_d(v_{i-1} - v_i - hz_i) + u_{i-1}), \tag{2.2}$$

where u_i is the control input (i.e., desired acceleration) for the i-th vehicle in the platoon, which is received by means of wireless communication. x_i is the position of the i-th vehicle in the platoon in m, v_i is the velocity of the i-th vehicle in m/s, $z_i$is the acceleration of the i-th vehicle in the platoon in m/s^2, and k_p and k_d are gains used to tune the behavior of the controller. The controller defines that each vehicle exploits only the data of the preceding vehicle and of the leader of the platoon. The distance and relative speed are obtained from the radar and the desired acceleration is received via the radio interface. By using wireless communication, there is an advantage in system reactivity because each vehicle receives information on the future actions of other vehicles.

2.1.3 IEEE 802.11p

In the following, we will consider the communication network, more precisely the IVC. Even though there are various short-range radio technologies, which can be used for IVC, we are only introducing those used in the proposed communication protocol and their main aspects. The proposed communication protocol uses the higher layer protocol stack ETSI ITS-G5 [19], based on IEEE 802.11p [20]. IEEE 802.11p, in turn, is an amendment to IEEE 802.11 [21], also called Wireless LAN (WLAN), which adds missing parts of the functionality needed for an efficient IVC. This is, for instance, and most importantly, the operation at around 5.9 GHz.

First, we will look at some important aspects of wireless LAN (WLAN), which have been adopted to IEEE 802.11p. This mainly affects the data transmission. In the MAC layer, WLAN uses a network multiple access method, called Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). CSMA/CA means that devices, e.g., vehicles, try to avoid collisions by only starting to transmit after they sensed the channel to be idle for the duration of an interframe space (IFS). Therefore they have to continuously observe the channel to identify whether that is the case or not.

In the case a device wants to start a transmission but cannot yet transmit, because, e.g., the channel is not idle yet or the channel is idle but the IFS is not over yet, a backoff procedure is initiated, and the frame gets queued. This ensures that as soon as the channel becomes idle, synchronous access will be avoided. To do so, a random backoff time from a pre-configured interval called contention window gets drawn. During every interval, the channel is idle this backoff time is decremented until it reaches zero, or the channel becomes busy again. If the backoff time reaches zero, the transmission can be performed, and in the case the channel becomes busy, the reduction of the backoff time pauses until the channel becomes idle again for an IFS. At the same time, the contention window is increased if a transmit attempt fails. As soon as the transmit attempt succeeds, the contention window is reset. If a transmission is finished, the backoff procedure gets invoked as well, so other vehicles frames, which are still in backoff, get a chance to be transmitted. [22]

Another important aspect is Enhanced Distributed Channel Access (EDCA). EDCA provides Quality of Service (QoS) mechanisms, which by setting levels of priority enables to differentiate better between high-priority and low-priority data. These levels of priority are called Access Categorys (ACs) and are divided into AC_VO, AC_VI, AC_BE, and AC_BK, AC_VO being the one with the highest priority. The channel-access parameters, e.g., minimum and maximum contention window size and the IFS length, corresponding to the ACs are set according to its priority and, therefore, according to the traffic expected in each AC. This is done so that higher-priority frames can access the channel more likely as well as are retried sooner than others. Therefore new introduced IFS lengths are called AIFS or arbitration interframe space. As shown in Figure 2.1, every AC has its own queue with its own backoff timer in which the frames will be stored. In the case that two or more backoff timers are reaching zero simultaneously, this will be handled like a collision by the

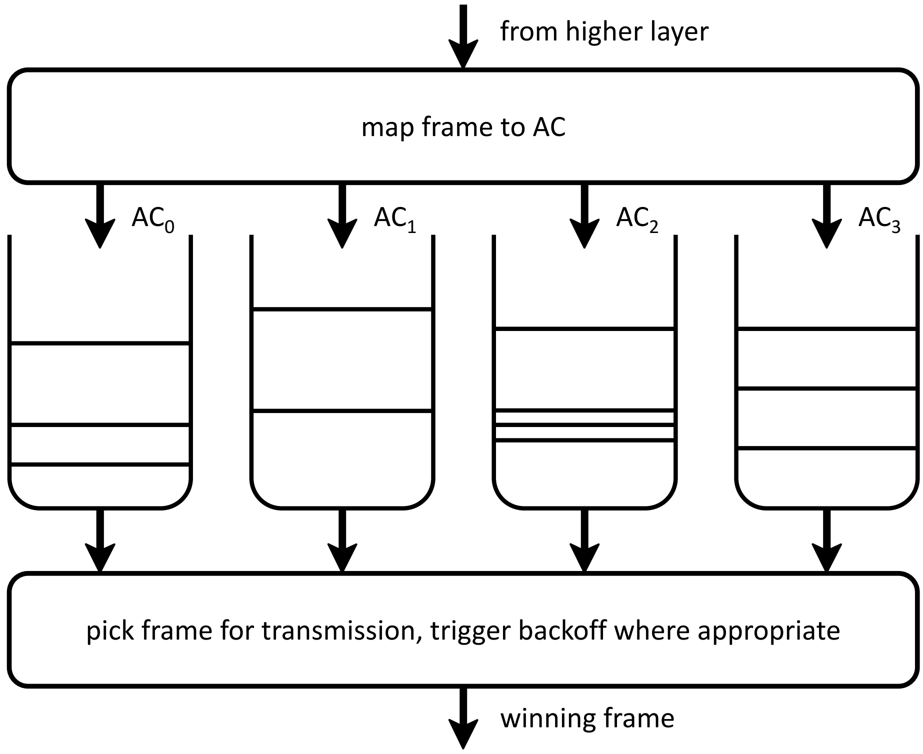


Figure 2.1 – An illustration of the EDCA queue management from [22].

lower-priority queue.

Before IEEE 802.11p got developed, the available bandwidth was too little to support some of the existing ITS applications and also the spectrum had to be shared with other applications. In order to solve this problem, the 5.9-GHz frequency band and thus a dedicated spectrum for ITS applications got reserved. The exact partitioning of it differs in the respective areas of application. In Europe, three 10-MHz channels (176, 178, and 180) for safety-related communications and two (172 and 174) for non-safety communications were reserved. An overview of the channel allocation is given in Figure 2.2. To use the new frequency band efficiently, the amendment IEEE 802.11p was developed. It contains the necessary adjustments to IEEE 802.11, not only for an efficient use of the 5.9-GHz band but also to fulfill the requirements of vehicular networks.

2.1.4 ETSI ITS-G5

Worldwide three different IVC protocol stacks for Europe [19], Japan [23], and the USA [24] have been developed, which mainly differ in their number of available channels. Because we are looking at a communication protocol proposed for Europe,

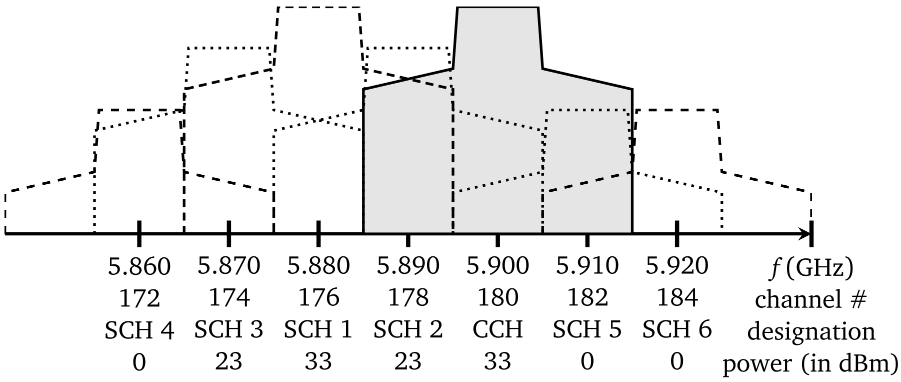


Figure 2.2 – Frequencies and maximum transmit power as assigned in Europe according to ETSI EN 302 663. The spectral masks are not to scale. [22]

we will only consider the European protocol stack for IVC, leaving the others out of scope. The protocol stack for Europe got standardized by ETSI and is called ETSI ITS. Regarding the available channels, the Electronic Communications Committee (ECC) has allocated up to five dedicated channels in the 5.9 GHz band for ITS. As mentioned earlier, ETSI ITS is based on IEEE 802.11p and, therefore, on IEEE 802.11 WLAN. These have been adapted to the ECC regulations, and by that got extended to a family of standards, which gets referred to as ETSI ITS-G5. To avoid any confusion, we will call it from now on ETSI ITS-G5 as well.

Another important aspect that distinguishes ETSI ITS-G5 from the other protocol stacks is that it utilizes a multi-radio multi-channel system. This means that it assumes that multiple channels are available. Regarding the multi-radio, ETSI ITS has defined that a vehicle wanting to exchange safety information shall be additionally equipped with an ETSI ITS-G5, i.e., an IEEE 802.11p, transceiver, which is constantly tuned to the Control Channel (CCH) (a.k.a. channel 180). Service Channels (SCHs) on the other hand can freely be used by additional IEEE 802.11p transceivers, to e.g., use services offered via regular WiFi or cellular technologies. [22]

Figure 2.3 shows the different layers of the ETSI ITS protocol stack. ETSI ITS abstracts from channel-access technologies, i.e., the used MAC and physical layers of the various installed transceivers, introducing the concept of an *access layer*. Part of the *access layer* is the Decentralized Congestion Control (DCC) access control mechanism, which was also standardized by ETSI [25]–[27]. Because it is a rather complex set of different concepts, we will only briefly outline the main idea behind it. The objective of DCC is to prevent the channel from being overloaded and therefore provide congestion control. To do so, the wireless channel's access becomes restricted and depends on the current channel state. This is done by the ETSI ITS DCC access control mechanism [25]. The algorithm is based on a state machine, consisting of three states between which the state machine is switching, RELAXED, ACTIVE, and

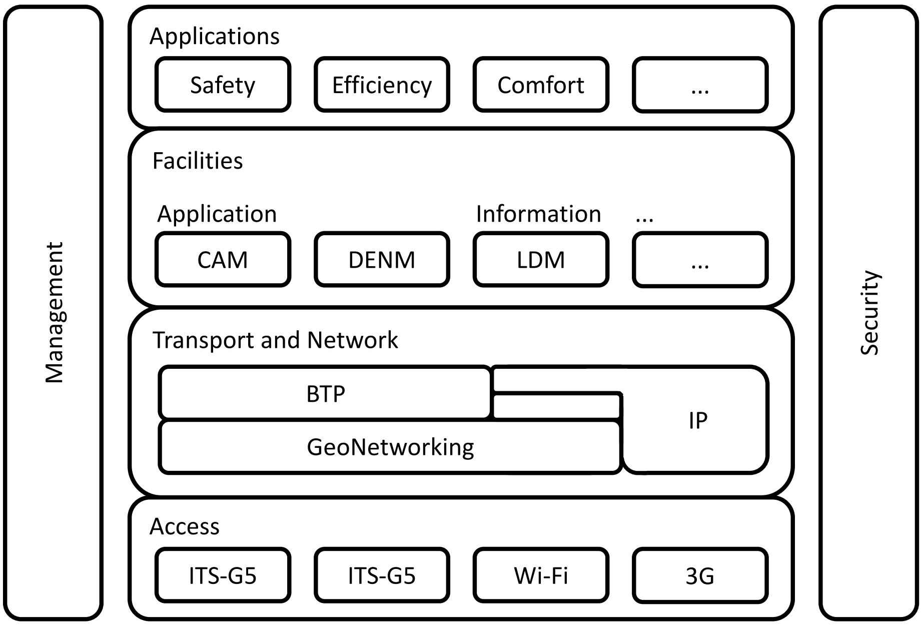


Figure 2.3 – An excerpt from the ETSI ITS protocol stack from [22].

RESTRICTIVE. Each state uses a different transmit power, modulation, beacon rate, and Clear Channel Assessment (CCA). Depending on the observed Channel Busy Ratio (CBR) the current active state is decided. The *management* and *security layers* are available to all layers of the protocol stack and are therefore depicted vertically in Figure 2.3. They provide cross-layer services for, e.g., choosing an access technology or changing pseudonyms at ideal times. Above the *access layer* is the *networking and transport layer*. On the one side, it provides TCP/UDP over IP services, and on the other side, the Basic Transport Protocol (BTP) over a GeoNetworking (GN) service. [22] BTP is a connectionless transport protocol to pass protocol data units (PDU) to the GN protocol and, therefore, to the network layer. GN itself supports different kinds of communication technologies. Two crucial aspects of these technologies are the geographical addressing, which means that for forwarding packets among ITS stations, the addresses are based on geographical positions of the ITS station and that the forwarding relies on each station knowing its environment in the network. The next layer on top of the *networking and transport layer* is the *facilities layer*. Subdivided into information support, communication support, and application support, the facility layer provides common support functionality for all layers of the ETSI ITS stack. For example, Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs) are about the sending and receiving of generic messages. As an example there are CAMs and DENMs, which are about the sending and receiving of generic messages. CAMs, for example, ensure that vehicles on the road and infrastructure beside it are informed about each other's dynamics, position, and attributes. A vehicle, by receiving CAMs, can detect approaching vehicles not yet seen by the driver or by line-of-sight sensors such as radar and camera. [26] DENMs, on the other side, are triggered on behalf of an ITS application when other in-vehicle sensors detect a dangerous situation. [28]

2.2 ENSEMBLE: Platooning protocol definition and Communication strategy

The ENSEMBLE project is an EU co-funded project coordinated by TNO, the Netherlands Organisation for Applied Scientific Research. Their main objective is, do fundamental work to enable the adoption of multi-brand truck platooning in Europe. They try to do this by unifying and standardizing Platooning within Europe. The project started in June 2018 and is officially a 3.5 year EU project. At the time this thesis was written, the project did a public demonstration taking place in Barcelona of trucks from seven different manufacturers driving in a fully coordinated platoon for the first time [1]. This demonstration offered the opportunity to perform various measurements. As a next step, the ENSEMBLE project is doing an impact analysis to predict the effect of platooning on traffic flow, fuel consumption, as well as studies into the experience of drivers and other road users.

The ENSEMBLE project itself is structured in 6 work packages, illustrated in Figure 2.4. With regard to the simulation study in this thesis, the focus is on WP2 and WP5. WP2 defines the specifications of the multi-brand truck platooning concept and WP5 the testing, validation, and demonstration of the multi-brand platoon implementation. The current status of the work packages is published in deliverables on which this thesis is based. In these deliverables, ENSEMBLE notes that they constantly validate and modify the specification during the whole project, for what reason they announced to publish updated versions of the deliverables. We use only the deliverables existing at the time of writing this thesis. Therefore future modifications can not be included.

[1] https://platooningensemble.eu/events/23-september6054b64811568

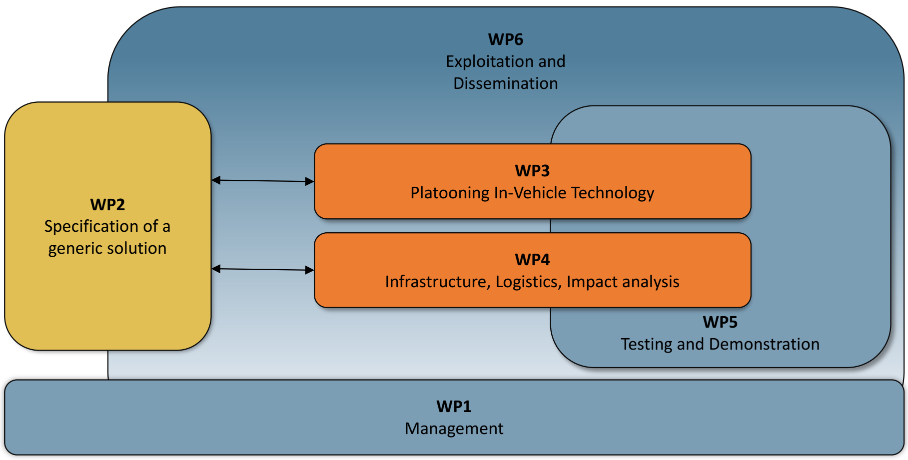


Figure 2.4 – Project structure of ENSEMBLE. [29]

The ENSEMBLE project defines three different platooning levels in order to break down the complexity and enabling a stepwise approach of the deployment of multi-branded truck platooning. [30] These levels are called platooning level A, B, and C. The project describes platooning level A, which is implemented first. For platooning level B and C only an initial outlook is given and these will be build on top of level A. Platooning level A is defined with a manual or advanced assist system (e.g. ACC) for the leading truck of the platoon and an autonomous longitudinal control (e.g. CACC) for the following vehicles. The lateral functions are not coordinated on platoon level. The inter-vehicle distance is at minimum 0.8s at maximum cruise velocity as long as string stability and vehicle performance is given. ENSEMBLE considers up to 7 trucks as a maximum number for platooning level A. Which means that for simulation and testing purposes a maximum number of 7 trucks will be considered.

The proposed communication protocol itself is a proposal for a concrete implementation of communication for truck platooning in Europe and is defined in document D2.8 [29]. The proposed communication protocol describes a facilities layer protocol to support the platooning application using the wireless technology ITS-G5 (i.e. IEEE 802.11p) at 5.9 GHz band (see Figure 2.5). This protocol utilizes functionality such as CAMs or DENMs from ETSI ITS-G5, while using the same lower layer protocols as for transmitting CAMs and DENMs. A vehicle is announcing its platooning capability in its CAMs, which for that reason, are extended by a platooning container. Therefore to enable the functionality of platooning, a set of preconditions must be fulfilled. If that is the case and a vehicle wants to platoon,

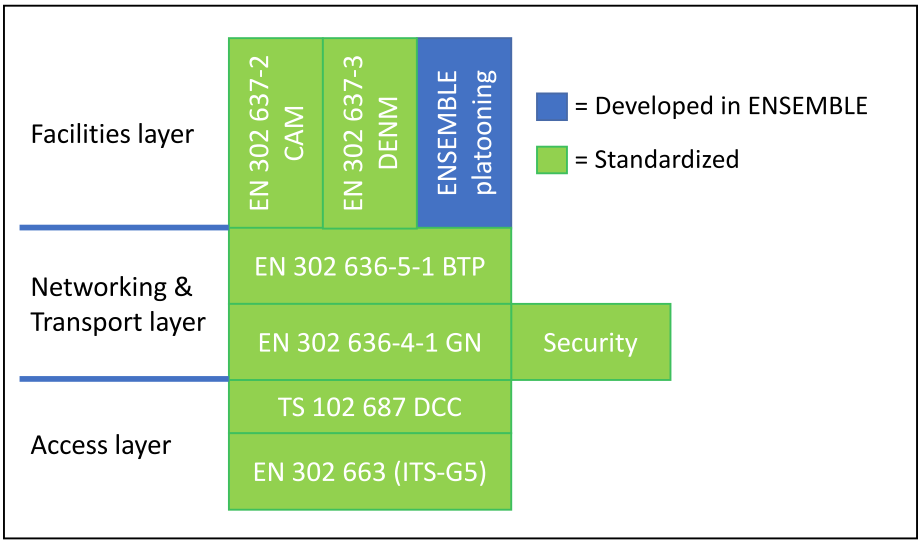


Figure 2.5 – C-ITS protocol stack with standardized protocols and the ENSEMBLE platooning protocol. [29]

the vehicle will indicate this through the CAM. In the following, we will describe this procedure in detail. The protocol itself consists of four components, which are IDLE, JOIN, PLATOON, and LEAVE. The IDLE mode is for individual operation

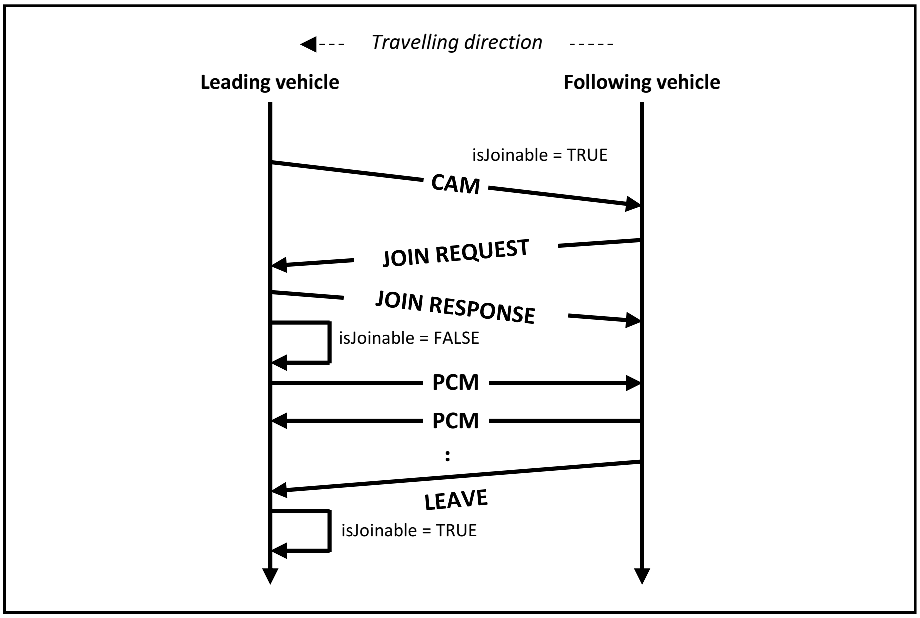


Figure 2.6 – Overview of the platooning procedure from join to leave according to the proposed communication protocol in [29].

with regular CAMs or for looking for a platoon to join. Therefore the newly added container of the CAM includes the flag *isJoinable* stating if the vehicle is interested in receiving join requests or not. In the JOIN mode platoons are built by performing join maneuvers. They are sending JOIN REQEUSTs and JOIN RESPONSEs as well as setting the *isJoinable* Flag. In the PLATOON mode, Platoon Control Messages (PCMs) are getting exchanged continuously between members of the platoon to share information about the current state and which actions should be performed. If vehicles in the platoon do not receive PCMs for a certain amount of time the platoon must dissolve and re-initiate again. In the LEAVE mode vehicles separate from the platoon and continue on an individual basis by sending a LEAVE message and setting the *isJoinable* flag to its desired state, which will bring them back to IDLE mode.

The protocol defines the message types control and management and new data elements. The management frames include join request, join response and leave messages and the control frame consists of the described PCMs, which contain the signals for the operations performed by the platoon. For the content of the messages the protocol defines existing DE (data elements) and DF (data frames) from TS 102 894-2 [31], as well as new data elements introduced by the platooning protocol.

With respect to security the ENSEMBLE project published a separate document (D2.9 [32]), in which they describe that the protocol will be part of the public key infrastructure (PKI) developed for C-ITS where messages are signed and verified using a temporarily authorization ticket. In addition, the PCMs will also be encrypted using symmetric keys. Because the security is out of scope we will not go into details here.

2.3 Simulation Framework: PLEXE

We decided to use the simulation software PLEXE[2] [33], [34], which is an extension of the simulation framework Veins [3] [35], adding platoon support. Veins itself is used for running vehicular network simulations. Therefore it couples networking from OMNeT++ [4] [36] and mobility from Simulation of Urban MObility (SUMO) [5] [37] and extends these to offer several models for the IVC simulation, such as IEEE 802.11p [20] and IEEE 1609.4 [38]. OMNeT++ is an event-based network simulator to model communication networks, written in C++ [36]. It can be used to design and evaluate, e.g., wired and wireless networks as well as communication protocols. With SUMO on the other side, realistic vehicle mobility and traffic simulation are possible. It provides routing algorithms, vehicle definitions, and car-following models, e.g., the car-following model by Krauss [39], which with some modifications is the default model used in SUMO. Scenarios with road networks of varying scope with not only vehicular but also human traffic can be simulated. [37] For a better understanding of how these simulators are working together, Figure 2.7 shows a schematic overview. Veins creates a network node in OMNeT++ for each vehicle in SUMO. Each of these nodes is associated with a network stack. This includes an IEEE 802.11p wireless network interface, plus a beaconing protocol and one or more applications running on top of it. The communication between the network and the traffic simulator takes place via the TraCI interface provided by SUMO. On the one side, whenever vehicles are moved in SUMO Veins mirrors that movement in the corresponding OMNeT++ nodes, and on the other side, Veins can query SUMO regarding the current simulation status (e.g., speeds, positions, number of vehicles, etc.), or change traffic dynamics by, for example, re-routing vehicles via TraCI. [33] Furthermore, PLEXE extends TraCI interactions to access vehicle data from SUMO as well. These, for instance, can be used by platooning protocols and applications, meaning such data can be sent to e.g., the CACCs in SUMO, if a vehicle, equivalent to an OMNeT++ node, receives it.

The main arguments for using PLEXE are that the most common controllers are already implemented and come with the WLAN 802.11p as a basis. Furthermore, the ability to perform mixed traffic scenarios and the realistic simulation of both wireless networking and vehicle dynamics will be beneficial.

[2] http://plexe.car2x.org
[3] http://veins.car2x.org
[4] https://omnetpp.org
[5] https://www.eclipse.org/sumo/

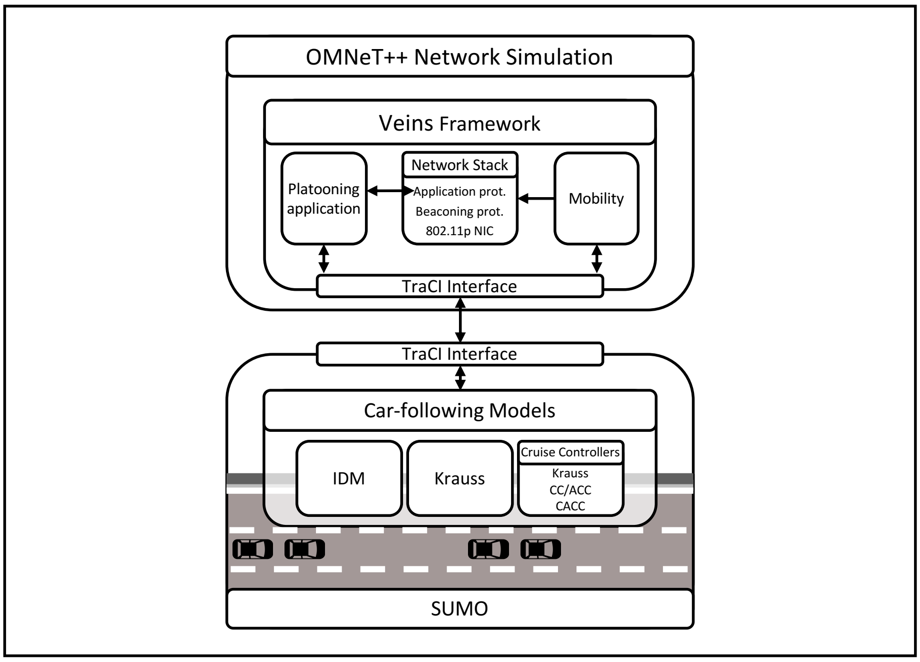


Figure 2.7 – Schematic structure of the simulator. [33]

2.4 Related Work

In this chapter we describe the work that has been made in the field of analyzing communication protocols for platooning based on IEEE 802.11p/IEEE 1609.4 PHY/MAC, as well as evaluating the impact of communication on the performance of CACC. In [40] the authors discuss different beaconing solutions for platooning by comparing four proposed approaches with adaptive beaconing protocols, i.e., DynB [41], [42] and ETSI DCC [25]–[27]. For the proposed approaches they introduce a standard static beaconing approach with and without transmit power control, called STB and STBP, as well as a slotted approach with and without transmit power control, called SLB and SLBP. They investigate these different communication strategies comparing the network and application layer performance by taking the requirements of the controller, transmit power adaptation, and using synchronized communication slots into account. As a result they demonstrate that even on very crowded freeway scenarios the approach of having synchronized communication slots with transmit power adaptation is well suited for platooning. Furthermore, they prove, that the consideration of high-level requirements from the application layer perspective can improve the performance, while also avoiding network congestion, and, finally, they investigate the impact of the communication on the CACC performance. In order to do that they considered an emergency brake scenario and obtained the requirements of the CACC application. As metric they consider the minimum inter-vehicle gap after the platoon stands still in relation to the beacon interval for different leader decelerations, showing that the maximum tolerable delay depends on the dynamics of the maneuver and that the maximum delay should not be bigger than 0.2 to 0.3 s.

Another analysis using similar methods has been made in [43]. In which another dynamic beaconing approach for platooning, called Jerk Beaconing, was developed. Jerk Beaconing is coupled with a reliable delivery mechanism and uses the vehicle dynamics to only send beacons when needed. While analyzing it, they compare the protocol with commonly used 10 Hz static beaconing using similar methods as in [40], considering, e.g., the CBR or the inter-message delays. Additionally, they also compute the minimum distance between any pair of consecutive vehicles, to analyze the safety. As a result, compared to static beaconing, Jerk Beaconing shows benefits regarding network resource saving, safety and also in keeping the inter-vehicle distance closer to the desired one even in highly demanding scenarios. The work in this paper raises the further question, if a theoretical link between the performance of the controller and the beacon interval can be found. This could lead to the development of an optimal algorithm, which could be configured according to the desired performance of the controller.

In the literature there has also been done some work explicitly regarding the impact of communication on the CACC performance. In [44] the authors consider the impact of dynamic wireless channel conditions on the CACC performance. They provide an insight in the performance of 802.11p protocol, characterizing the performance in terms of different metrics, using the CBR, latency, throughput, packet loss, mean burst length and reliability. As a result their initial tests show the performance of throughput and latency of 802.11p radios. Furthermore, from a testbed on a campus they depict metric results and thus show proof for correlated loss. By that they confirm that assumptions in studies about a Bernoulli loss process are not realistic. This leads to the idea of developing robust loss models, which can parameterize the range of expected loss process dynamics.

In [45] the authors discuss the impact of communication explicitly on the string stability of CACC. To do so they evaluate its performance with various beaconing intervals, packet loss ratios, and time headways. As a result they show that lower beaconing intervals and/or higher packet loss ratios prevent vehicles from receiving new information, which lowers the performance of the controller on string stability. Therefore the beaconing interval and packet loss ratio have a significant influence on the performance. Given a required time headway, the beaconing interval as well as the packet loss ratio have to be set according to it, to be able to guarantee string stability.

The proposed communication protocol by ENSEMBLE is another static beaconing approach for platooning, which hasn't been analyzed yet. Even though we won't compare the protocol to other ones, we will use similar methods in the scope of this thesis to evaluate it with regard to the network layer and application layer performances as well as the impact of communication on the CACC performance.

Chapter 3

Implementation

In the following chapter we will describe how we extended the implementation of PLEXE by the proposed communication protocol and how we tested the implementation as well as validated the protocol. The following implementations rely on PLEXE version 3.0, based on Veins 5.1, SUMO 1.4.0, and OMNeT++ 5.6.2.

3.1 Implementation in PLEXE

3.1.1 Platoon Control Message (PCM)

As mentioned in Chapter 2.2 PCMs are continuously getting send during the PLATOON mode and therefore are building the core of the proposed communication protocol. For this reason we extended PLEXE by that message type. The start time of the PCM transmissions depends on the time of the join procedure. From there on the PCMs are getting send at a rate of 20Hz, i.e., every 50 ms to every platoon member. However, since no join procedures are used in the simulation, the start time is set randomly. In general the PCMs of one vehicle are always getting send to every member of the platoon. The protocol defines that no Acknowledgements (ACKs) are used and instead refers to implicit ACKs, implying that around every 50 ms a vehicle of the platoon can expect a new message from all the other platoon members.

The PCM itself contains all necessary data for the longitudinal as well as lateral control of the vehicle. In the document D2.8 [29] the ENSEMBLE project provides a first draft of an ASN.1 file describing the content of the PCM in detail. However, since most of the data contained in the PCMs is regarding geographical information or, e.g., is a preparation for the lateral control being used in the future, these are values which are not necessary for the simulation and wouldn't be used. For that reason we implemented the PCM only with values which are relevant in the simulation. To create a realistic simulation, the packet size of PCMs got set to a realistic value.

With regard to the packet size of PCMs the proposed communication protocol doesn't define a size or size range for it and there couldn't be found any studies regarding it neither. Therefore we determined a realistic packet size by encoding a PCM created after the given ASN.1 schemas. To do so we used the *ASN.1 Playground* of the OSS Nokalva website [6], which is a program to compile, encode and decode ASN.1 schemas. To encode these messages different encoding rules exist. The proposed communication protocol doesn't define any encoding rules for the ASN.1 structure containing the PCMs, however in document D2.9 [32] the encoding rule for the security information is given as COER. Therefore we assume this encoding rule is used for the PCMs as well. In addition the PCMs will be encapsulated in lower layers headers and trailers which results in a larger packet size of the actual send message. Figure 3.1 shows an overview of the packet encapsulation of the platooning PDU. As mentioned in Chapter 2.3 Veins as part of PLEXE contains an implementation of 802.11p, for what reason regarding the PHY and MAC header and trailer the PCM will be encapsulated as required. However, the other headers shown in Figure 3.1 are not implemented in the simulation and would only be used to add on to the packet size, but not be used at any other point. That's why we summed up the remaining header sizes as defined by the protocol and added it as a total to the packet size of the PCMs. This is shown in detail in Table 3.1. For that we used the headers as outlined in document D2.8 [29]. For the security of platooning, the PCMs are getting encrypted using a symmetric encryption key. Even though the security aspect is out of scope, this is adding up on the packet size of the PCMs as well, for what reason this must be taken into account. The security is part of the GN headers (GN secured header) and are described in detail in document D2.9 [32]. Regarding the *security certificates* as shown in Figure 3.1 no further details could be found for what reason it got left out of the computation. For each of the listed parameters in Table 3.1 we chose the maximum possible values to get a rather larger PCM packet size. In order for the vehicles to be able to send and receive PCMs in the

[6] https://asn1.io/asn1playground/

Parameter	*Value*
PCM/Platooning PDU	126 Bytes
LLC header	8 Bytes
GN headers	105 Bytes
BTP header	4 Bytes
Total	243 Bytes

Table 3.1 – Values for the computation of the PCM packet size.

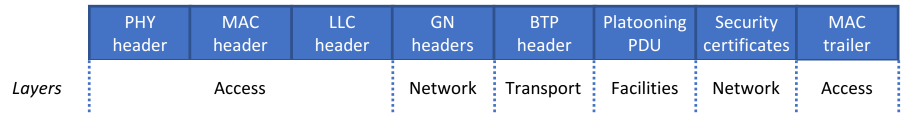


Figure 3.1 – Packet encapsulation of the platooning PDU. [29]

simulation, a protocol and application specifically for sending and receiving PCMs got implemented as well.

3.1.2 Requirements

In addition to the structure of the proposed communication protocol itself the ENSEMBLE document D2.8 [29] describes 25 requirements which need to be fulfilled according to the ENSEMBLE project specifications. There are some preliminary requirements only used for the ENSEMBLE project, which will be modified for the regular use of the proposed communication protocol. Requirement REQ001, e.g., defines that no DENMs will be implemented, because they are not necessary during platooning for the proposed communication protocol, however in real life applications vehicles might have the capabilities to receive and transmit DENMs. In requirement REQ002 it is defined that no DCC will be implemented. This is because the ENSEMBLE project assumes that the DCC algorithm will not be activated due to very low CBR values. Again for real life applications DCC needs to be investigated for platooning.

The proposed communication protocol assumes that the channel load on channel 180 (CCH) will be high due to many ITS-G5 equipped vehicles transmitting CAMs and DENMs. Therefore the DCC will reduce the number of packet transmissions. To avoid disrupting the platooning application the protocol defines a separate channel for the platooning communication, i.e., the PCMs. For this purpose they propose channel 176 (a.k.a., Service Channel 1 (SCH1)). This will not be the case in the ENSEMBLE projects test scenarios, therefore requirement REQ006 defines that all communication will take place on channel 180 (CCH). However, since the protocol defines the use of two separate channels for real life applications, we assumed the use of two channels as well. Since we focus on the PLATOON mode and CAMs as well as DENMs are transmitted on a separate channel we won't implement any other message type than PCMs. Hence, we will drop all requirements regarding CAMs and DENMs. The same applies to requirements regarding the security as well as platoon management messages. Latter are as mentioned in Section 2.2, e.g., join or leave messages, which are not part of the PLATOON mode neither. The requirements we took into account are listed in Table 3.2 as defined in the document [29].

Requirement No.	*Description*
REQ001	No specific triggering of DENMs will be implemented in ENSEMBLE.
REQ002	No DCC will be implemented in ENSEMBLE.
REQ003	The output power is set to 23 dBm e.i.r.p.
REQ004	The ENSEMBLE platooning communication system needs to follow the duty cycle requirements outlined in Clause 4.2.10 of EN 302 571 V2.1.1.
REQ005	The ENSEMBLE platooning communication system needs to implement the database solution found in TS 102 792 V1.2.1.
REQ006	All ITS-G5 communication in ENSEMBLE will take place on channel 180 (CCH).
REQ010	Platooning PDUs shall use the BTP-B header.
REQ012	Platooning control PDU shall set the field destination port TBD and destination port info to 0.
REQ013	The single-hop broadcast packet header as outlined in Clause 9.8.4 of ETSI EN 302 636-4-1 V1.3.1 shall be used.
REQ014	The parameter setting of the single-hop broadcast packet with its different headers shall be as outlined in Table 2.
REQ015	The LLC and SNAP headers as outlined in Table 3 shall be used.
REQ016	The default rate for all messages transmitted in ENSEMBLE is 6 Mbps.
REQ017	The platoon control message shall use access category AC_VO.

Table 3.2 – Selected requirements as defined by [29].

3.1.3 Communication

As defined in requirement REQ017 the PCMs are using access category AC_VO, being the messages with the highest priority. Additionally, we set the bitrate to 6 Mbit/s and the transmit power to 200 mW. By reading the standards mentioned in the requirements of the proposed communication protocol, several values regarding the communication, which were not defined by the protocol, needed to be set as well. This concerns parameters like sensitivity, noise floor or CCA-threshold, which got set according to values defined by underlying standards. These values are summarized in Table 4.1 together with all necessary network simulation parameters.

3.1.4 Mobility

As mentioned in Chapter 2.1 the CACC described in [12] will be used as the controller. This controller is already implemented in PLEXE and only its parameters need to be set. The two gain values k_p and k_d are set to 0.2 and 0.7. The headway time h as specified by the protocol is set to 0.8 s and the actuation lag τ is set to 0.5 s. This time constant was chosen as a worst-case delay, taking the delay of sensors,

Parameter	*Value*
Path loss model	Free space ($\alpha = 2.0$)
PHY/MAC model	IEEE 802.11p/1609.4 single channel
Frequency	5.89 GHz (CCH)
Bitrate	6 Mbit/s
Access category	AC_VO
MSDU size	200 B
Transmit power	200mW
Sensitivity	-94 dBm
Noise floor	-95 dBm
CCA-threshold	-65 dBm
PCM frequency	20 Hz

Table 3.3 – Network simulation parameters.

response of the engine, sampling delay, etc. into account. [12] The desired distance at standstill r_i is set to 2 m, which also defines that the inter-vehicle distance will be the headway time plus the 2 m distance at standstill.

In order to simulate trucks a couple of parameters like the truck size or the engine characteristics are needed to be set and as described later on in Chapter 3.2 there is not only one type of truck, but at least seven different truck types needed. As an orientation and for the first test cases we used the default values of the vehicle type *truck* given by SUMO [7], which are defined as shown in Table 3.4. Based on these values, we created the other truck types, whose values may differ due to different truck loads or engine characteristics. Overall, we try to create a range of values which cover most of the cases. The truck with the worst values has an acceleration of 0.8 m/s^2 and a deceleration of 4 m/s^2 and the one with the best values has an

[7] `https://sumo.dlr.de/docs/Vehicle_Type_Parameter_Defaults.html`

Parameter	*Value*
vClass	truck
length	7.1 m
width	2.4 m
height	2.4 m
minGap	2.5 m
a_{max} accel	1.3 m/s^2
b decel	4 m/s^2
b_e emergency decel	7 m/s^2
v_{max} maxSpeed	130 km/h
speed deviation	0.05

Table 3.4 – Default values of the vehicle type *truck*.

acceleration of 1.6 m/s^2 and a deceleration of 6 m/s^2. All 7 different truck types are defined with values evenly distributed within these boundaries. Since the default value for the deceleration of trucks given by SUMO is already 10 to 20 % under the minimum deceleration stated by the StVZO in Germany (§41 Abs. 4 S. 1 StVZO, §41 Abs. 9 S. 1 StVZO), we used 4 m/s^2 as the worst value.

3.2 Testing and Validating

To test the implementation of the proposed communication protocol and to validate, whether the protocol in its execution delivers the results as ENSEMBLE claims, we implemented several test cases defined by the ENSEMBLE project. Document D5.1, called "*First version Demonstration and test plan*" [46], published by the ENSEMBLE project, defines the first states of their test plan, including a list of test cases. These test cases are subdivided into three different levels:

- Mono-brand testing
- Three-brand testing
- Multi-brand testing

The *Mono-brand testing* contains test cases, which are defined for a platoon with vehicles of only one brand, the *Three-brand testing* defines a platoon with vehicles of three different brands and the *Multi-brand testing* defines a platoon with vehicles of multiple brands. The main idea behind these testing levels is to ensure the interoperability between different brands on the road. This aspect can not be tested in a simulation, but testing the interaction between vehicles with different parameters is reasonable as well. By setting different values for the engine characteristics, it is possible to simulate vehicles with different engines or loads. This lets us evaluate how the protocol is behaving under different vehicle conditions. The different vehicle parameters were set as described in Section 3.1.4. The Mono-brand testing is using the vehicle with the default values, while the remaining vehicles are distributed randomly on the other testing levels.

The following Table 3.5 shows the test cases, which have been chosen to test the implementation and validate the proposed communication protocol. The test cases 0.2, 1.2, 1.3 and 1.7 are from Mono-brand testing, 2.2, 2.3 and 2.12 are from Three-brand testing and 2, 5 and 7 are from Multi-brand testing. They were classified into three categories: *Steady State Platooning*, *Acceleration/Deceleration* and *Emergency Brake*. Steady State Platooning stands for regular platooning without any influencing factors, Acceleration/Deceleration includes a couple of test cases regarding accelerating and decelerating during platooning and Emergency Brake describes an emergency brake test case for each level. The test cases will be described in the following sections in detail. They were chosen to cover the same aspects for each level, which except of minor exceptions is the case. ENSEMBLE for instance doesn't define a Steady State Platooning test case for Three-brand testing. As shown in the following, these test cases make it possible to test and validate the mobility and network behavior during regular platooning, acceleration and decelerations as well as during an emergency brake.

The test document D5.1 defines, according to the official description of platooning level A (D2.2 [30]), a couple of general conditions, which apply to all of the test cases: A platoon consists of 7 trucks, which are driving with a minimum headway time of 0.8 seconds at maximum cruise velocity on a highway. The maximum cruise velocity is depending on country regulations. In Germany the speed limit for trucks is 22.22 m/s, for what reason the maximum cruise velocity in the test cases will be 22.22 m/s as well.

3.2.1 Test Cases: Steady State Platooning

Steady State Platooning is defined by ENSEMBLE as a platoon operating with a short inter-vehicle distance and within the longitudinal control limits described for platooning. To test Steady State Platooning and hence regular platooning, the test cases 0.2 and 2 got chosen. Test case 0.2 is defined at design gap (0.8 s) and at maximum design speed (22.22 m/s). Test case 2 is defined in the same way, except for speed, which is set to 25 m/s. Because this exceeds the maximum cruise velocity of 22.22 m/s we defined in the previous section (Section 3.2), this test case was performed at 22.22 m/s instead. As mentioned in Section 2.1.2 the chosen controller

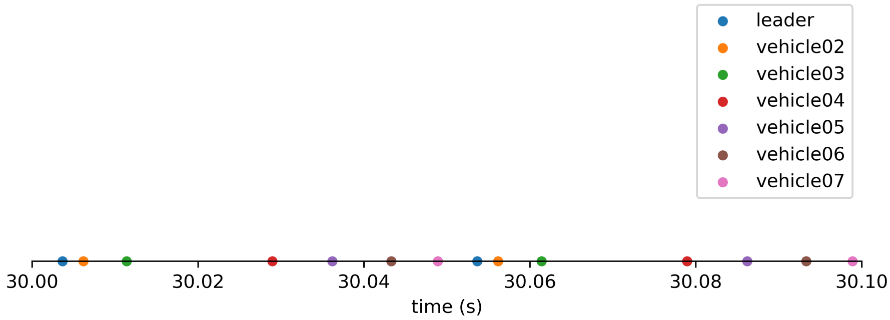
Name	No./ID	Testing Level
Steady State Platooning	0.2	Mono-brand testing
	2	Multi-brand testing
Acceleration/Deceleration	1.2	Mono-brand testing
	1.3	Mono-brand testing
	2.2	Three-brand testing
	2.3	Three-brand testing
	5	Multi-brand testing
Emergency Brake	1.7	Mono-brand testing
	2.12	Three-brand testing
	7	Multi-brand testing

Table 3.5 – Test cases selected from the test document D5.1 [46].

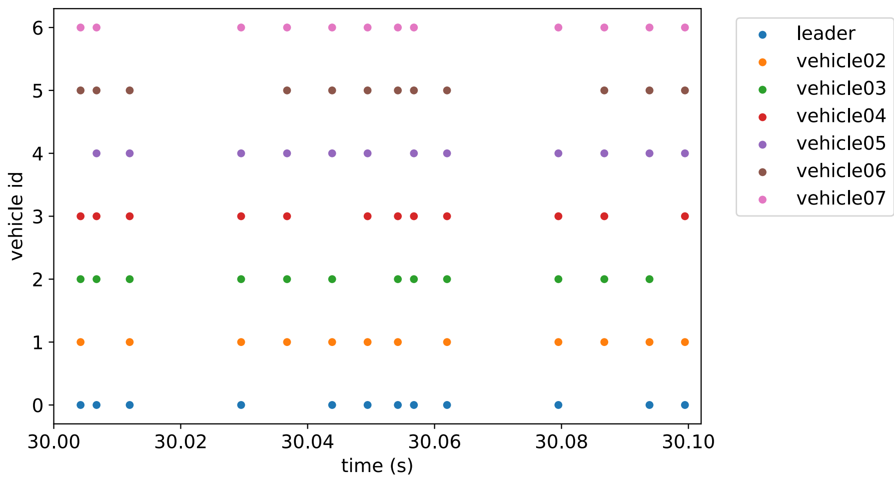
requirers a set *desired distance at standstill*, which we set to 2 meters. These 2 meters will be added to the expected inter-vehicle gap, which results in

$$r_i + h \cdot v_i = 2m + (0.8s \cdot 22.22m/s) = 19.77m. \tag{3.1}$$

First of all it is necessary to look at the communication between the vehicles of the platoon and check if it is working as expected by the protocol. Therefore we will consider the sending and receiving of PCMs. As mentioned in Section 2.2 the proposed communication protocol defines that each vehicle of a platoon is sending a PCM every 50 ms to every other member of the platoon. Figure 3.2a shows a section



(a) sending PCMs

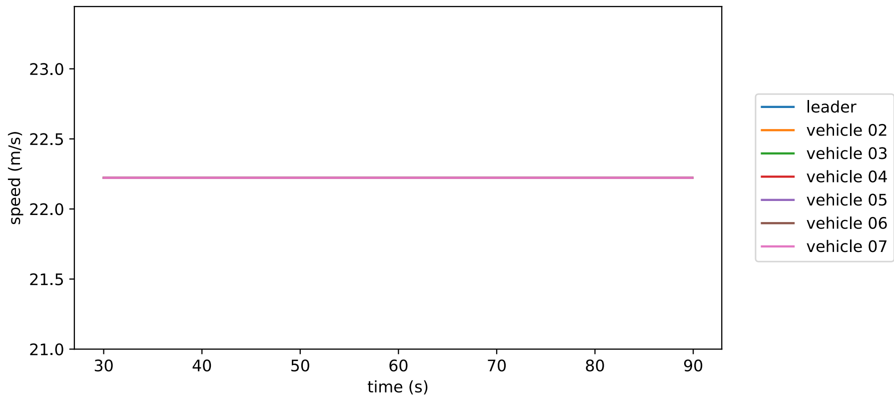


(b) receiving PCMs

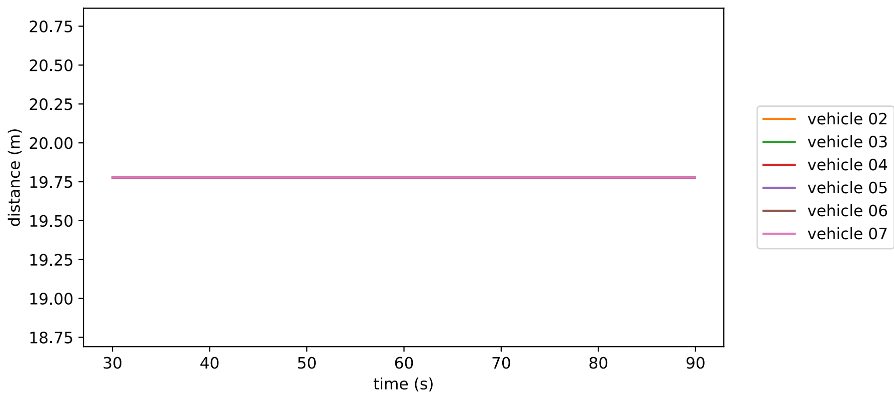
Figure 3.2 – An excerpt of the vehicle communication showing the sending and receiving of PCMs. Plot (a) showing the timestamps PCMs send by each member of the platoon within 100 ms; plot (b) showing the PCMs received by each member of the platoon within 100 ms. A missing point indicates that the vehicle self was sending.

of the timeline indicating which vehicle sent a PCM at what time. Looking at it, it is clear to see that every vehicle is sending messages every 50 ms. Outside the cut-out the values looked the same. Figure 3.2b shows related to the sent PCMs at what time which vehicle is receiving them. The horizontal axis represents the time (s) and the vertical axis the vehicle id of the receiving vehicle, starting at 0 for the leader vehicle. It can be seen that the sending vehicle is sending the PCM to every other vehicle of the platoon (in this case 6) and each one of these vehicles is receiving the messages as expected. This also implicates that no messages were lost during these test cases. Furthermore, no collisions appeared.

We were able to verify that the communication functions independent from the mobility by comparing the communication of test cases with different mobility behavior. As a result the communication was behaving exactly the same in every test



(a) speed



(b) distance

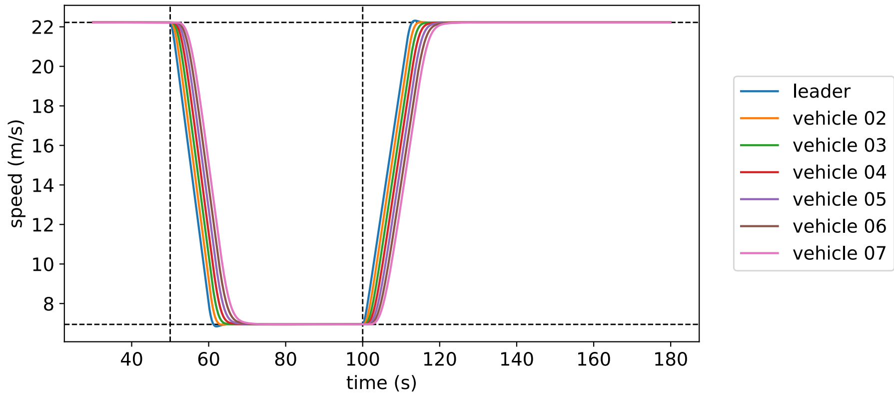
Figure 3.3 – Vehicle dynamics of test case 0.2 (Steady State Platooning). Plot (a) shows the speed of each vehicle; plot (b) shows the distance to the respective front vehicle.

case. Therefore the verification of the working communication is representative for all test cases and it is not considered in the remaining test cases, assuming it works properly.

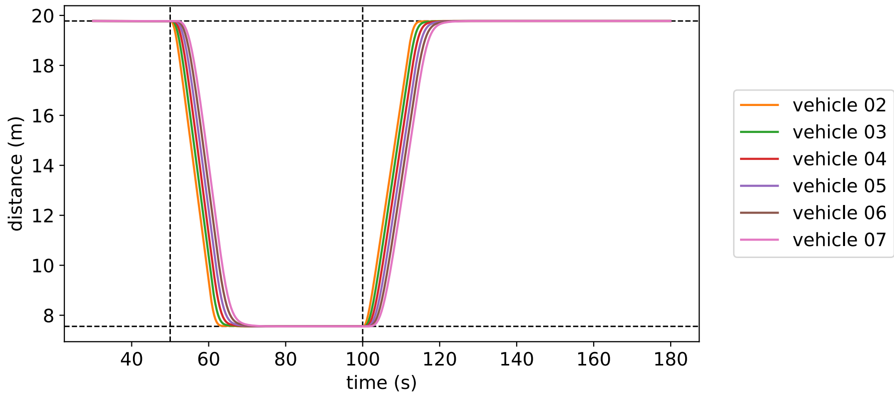
Regarding the mobility aspects, in Figure 3.3 the results of test case 0.2 are depicted. As shown in Figure 3.3a the speed of all 7 vehicles of the platoon is as expected constantly at 22.22 m/s, keeping the inter-vehicle distance of 19.77 m as shown in Figure 3.3b.

3.2.2 Test Cases: Acceleration/Deceleration

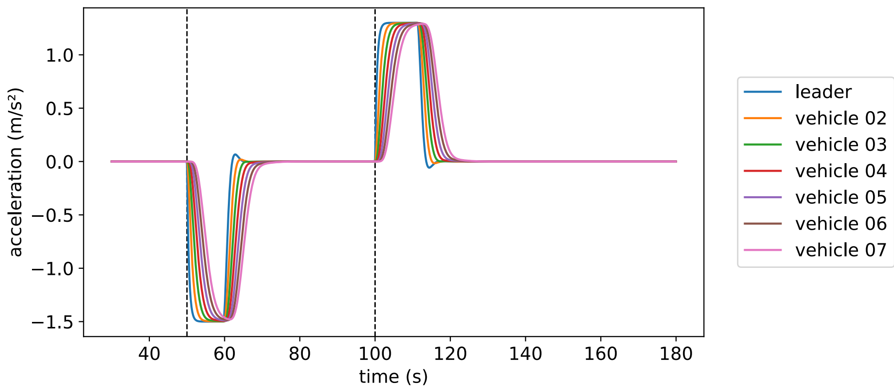
For testing accelerating and decelerating during platooning the test cases 1.2, 1.3, 2.2, 2.3 and 5 were chosen. Test cases 1.2 and 2.2 as well as 1.3 and 2.3 describe the same scenario, which differs only in the number of brands that are part of the platoon. In the cases 1.2 and 2.2 the leader of the platoon decelerates from 22.22 m/s to 16.67 m/s and in the cases 2.2 and 2.3 the leader accelerates from 16.67 m/s back to 22.22 m/s. Test case 5 however is defined as the leader of the platoon decelerating from 22.22 m/s to 6.94 m/s and then accelerating back to 22.22 m/s. Because test case 5 turned out to be a more interesting case to look at, we additionally implemented it for the Mono-brand and Three-brand testing. In the following we will look at its results for the Mono-brand testing, which can be seen in Figure 3.4. The description of test case 5 doesn't define any point in time at what the deceleration is supposed to start and no amount of time after which the leader of the platoon is supposed to accelerate again. Therefore we chose appropriate values and implemented the test case such that the platoon drives at a velocity of 22.22 m/s until it starts its deceleration after 50 seconds. After another 50 seconds the leader starts to accelerate again to get back to its original velocity of 22.22 m/s. For a better evaluation of the graphs these time points, as well as the target speed and distance of the vehicles, were marked with a dotted line in the graphs. These target values for speed are 22.22 m/s and 6.94 m/s and for distance are 19.77 m and 7.56 m. Figure 3.4a and Figure 3.4b respectively show these results. Here we can see that it took approximately 15 seconds to get from 22.22 m/s to 6.94 m/s. Looking at the leader after the deceleration process in Figure 3.4a, the speed is 0.1 m/s below the target speed and at the end of the acceleration process it is exceeding the target speed by 0.9 m/s before it gets corrected. Compared to the other vehicles regulating their speed perfectly, this is a noticeable behavior. It can be explained by the fact, that the leader is using an ACC whereas the following vehicles are all using CACCs. The control algorithm of the controllers in general computes the control input, i.e., the acceleration of the vehicle, based among other on the target speed. The ACC does not regulate without errors, which is why we have these outliers.



(a) speed



(b) distance



(c) acceleration

Figure 3.4 – Vehicle dynamics of test case 5 for Mono-brand testing (Acceleration/Deceleration). Plot (a) shows the speed of each vehicle; plot (b) shows the distance to the respective front vehicle; plot (c) shows the acceleration of each vehicle.

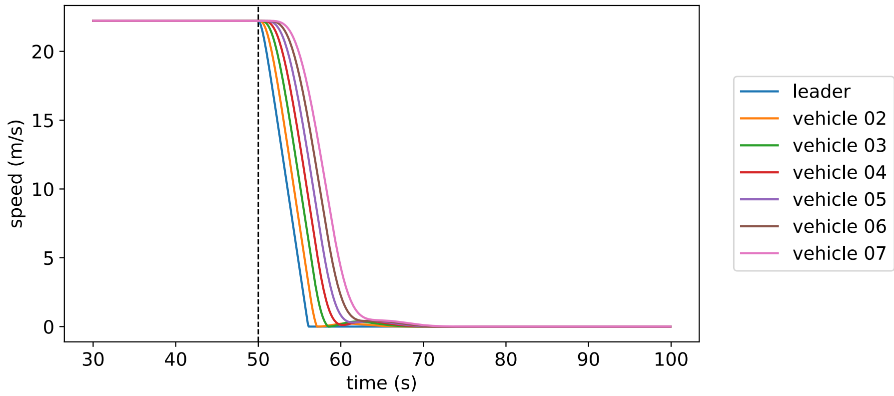
Doing multiple tests with a platoon consisting only of the leader, the same behavior can be observed. Therefore we can assume that it is due to the controller.

3.2.3 Test Cases: Emergency Brake

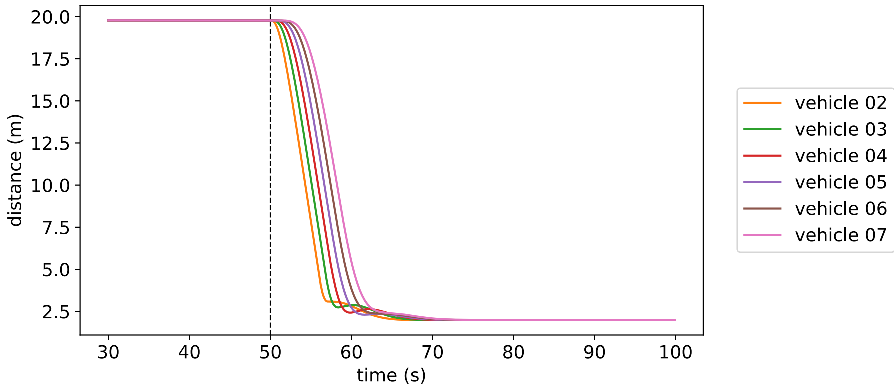
The test cases 1.7, 2.12 and 7 are describing an emergency brake for each testing level. They are defined as a platoon which drives at a speed of 22.22 m/s, where the leader of the platoon performs an emergency brake. The other vehicles of the platoon follow that behavior and perform an emergency brake as well until every vehicle stands still (0 m/s). The braking acceleration is defined as $-5m/s^2$. These test cases got implemented as defined, except of the acceleration value. The defined acceleration of $-5m/s^2$ is a better value than the default truck value for what reason we used the default. As mentioned in Section 3.2.1 we set the *desired distance at standstill* to 2 meters, for what reason we expect a distance at standstill of 2 meters also after an emergency bake and therefore no accidents.

Figure 3.5 shows the results of test case 1.7 in three different graphs. Again we marked the point in time, where the leader of the platoon starts the emergency brake with a dotted line at second 50 after simulation start. First of all the test case can be classified as successful. Every vehicle comes to a stop (see Figure 3.5a) with a distance at standstill of 2 meters (see Figure 3.5b) and no accidents occur. The emergency brake itself is performed within approximately 20 seconds. Looking at Figure 3.5c between second 58 and second 65 every vehicle, except of the leader of the platoon, is again accelerating after the emergency brake was performed. This behavior can be explained by the desired distance at standstill of the controller. After performing an emergency brake the inter-vehicle distance is greater than 2 meters for what reason after the vehicles have come to a stop they accelerate again to reach their desired distance at standstill of 2 meter.

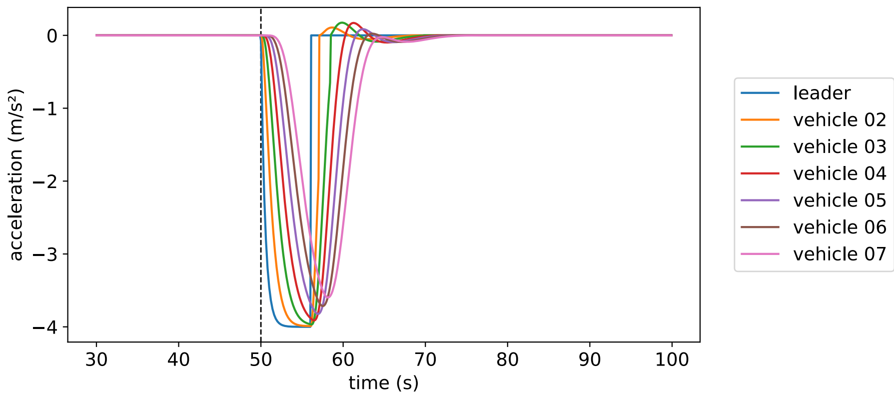
In conclusion the testing and validation has proven, that the communication between the vehicles is working as defined by the proposed communication protocol. All PCMs are getting send and received as they are supposed to be and the mobility of the platoon in different scenarios is working as well. The behavior of speed, distance and acceleration is as expected and no accidents occur during the emergency scenarios. It is important to say that in some test cases we could see a noticeable behavior of the controller, which is due to the CACC and ACC controller we chose. With different versions of the controllers a different mobility behavior could occur. With these results, we will now proceed with the evaluation.



(a) speed



(b) distance



(c) acceleration

Figure 3.5 – Vehicle dynamics of test case 1.7 (Emergency Brake). Plot (a) shows the speed of each vehicle; plot (b) shows the distance to the respective front vehicle; plot (c) shows the acceleration of each vehicle.

Chapter 4

Evaluation

The main goal of this chapter is to evaluate the proposed communication protocol and to gain insights in how well the communication performs in different scenarios. As mentioned before the focus of our analysis will be on regular operation leaving other aspects defined by the protocol, e.g., security and maneuvers out of scope. First, we will describe a general simulation setup, which is used for all following scenarios (Section 4.1), followed by a description of the used metrics (Section 4.2). We will then go through the different scenarios, first looking at scenarios regarding the network layer and application layer performance (Section 4.3) and second at scenarios regarding the impact of communication on the CACC performance (Section 4.4), finished by a discussion (Section 4.5).

4.1 Simulation Setup

All of the following scenarios take place on a highway with four lanes. The duration of the simulations is 90 seconds, in which the vehicles are driving straight ahead the entire time. Since we only look at scenarios for the PLATOON mode and as mentioned in Section 3.1.2 CAMs as well as DENMs are transmitted on a separate channel, it won't be necessary to add additional road traffic. We are using a warm-up period of 30 seconds to not include interfering factors at the beginning of the scenarios, that occur due to possible deviations during the spawning process. In each scenario we are doing 30 simulation runs to obtain statistical confidence for the results. These are done with the same parameters but different random number seeds. The most relevant network and road traffic simulation parameters are summed up in Table 4.1.

Parameter	*Value*
Path loss model	Free space ($\alpha = 2.0$)
PHY/MAC model	IEEE 802.11p/1609.4 single channel
Frequency	5.89 GHz (CCH)
Bitrate	6 Mbit/s
Access category	AC_VO
Transmit power	200 mW
Sensitivity	-94 dBm
Noise floor	-95 dBm
CCA-threshold	-65 dBm
PCM frequency	20 Hz
Number of lanes	4
Number of trucks	7, 21, 42 and 63
Platoon size	7
Truck length	7.1 m
Intra-platoon distance	19.78 m
Inter-platoon distance	21.78 m
Leader's average speed	22.22 m/s
Max acceleration	1.3 m/s^2
Max deceleration	4 m/s^2
Oscillation frequency (sinus. scenario)	0.1 Hz
Oscillation amplitude (sinus. scenario)	1.39 m/s
ACC headway time h	0.89 s
CACC headway time h	0.8 s
CACC k_p	0.2
CACC k_d	0.7
CACC actuation lag τ	0.5 s
CACC desired distance at standstill r_i	2 m
Simulation time	90 s
Warm-up period	30 s
Repetitions/Number of seeds	30

Table 4.1 – Network and road traffic simulation parameters.

4.2 Evaluation Metrics

With regard to getting a holistic insight on the performance of the communication and the impact of the communication on the CACC performance we chose the following metrics:

- *Channel busy ratio (CBR):* The CBR is a value between zero and one representing the fraction of time that a single radio channel is declared busy with transmissions by the physical layer with respect to a given time interval. In the simulation each vehicle determines the CBR for time intervals of 10 ms. This resolution is sufficient to detect the PCMs that are sent every 50 ms.

- *Latency:* An important metric to evaluate the communication quality is the latency. We measure the time between the moment the message gets created and send and the moment it gets received and encapsulated. Messages which are not arriving are not getting recorded at this point.

- *PCM-loss ratio:* As a reliability metric for the communication we chose the PCM-loss ratio. Over a recorded simulation time of 60 seconds each vehicle sends 1200 PCMs, meaning that a vehicle should receive in average 7200 PCMs of other members of its platoon. For the calculation of the PCM-loss ratio we count the number of sent PCMs as well as the number of the received ones. Afterwards, we compute the proportion of lost PCMs for each vehicle within a platoon. Therefore we get one representative value for each vehicle per seed. To aggregate these values we took the arithmetic mean value.

- *Inter-message delay:* For each vehicle we record the timestamps when a PCM from within the platoon is received. This enables us to determine, how long it has been since the last message arrived. By doing that we can see for how long in a row the controller does not get any information from, e.g., the leader.

- *Safe time ratio:* The safe time ratio r_{safe} is an application layer metric developed by [40] measuring the amount of time a vehicle is in a safe state depending on the delay requirement δ_{req} of the controller. It is defined as

  $$r_{safe} = \frac{\sum_{d_s \in D_{safe}} d_s}{\sum_{d \in D} d} \tag{4.1}$$

  where D is the set of all inter-message delays collected by a vehicle. D_{safe} is the subset of D satisfying the delay requirement defined as

  $$D_{safe} = \{d : d \in D \wedge d \leq \delta_{req} + \Delta\} \tag{4.2}$$

  δ_{req} is the maximum tolerable delay and Δ is a small grace period that accounts for uncertainties like MAC layer backoffs. As an example, if all delays in D are 200 ms long and the delay requirement δ_{req} is 300 ms, the resulting safe time ratio would be $r_{safe} = 1$, meaning that all information was received in time. They consider the safe time ratio for leader as well as preceding vehicle messages.

- *Error:* The error is intended to show deviations in the mobility behavior. It is computed by comparing separately each vehicle of a platoon with the vehicles of the reference platoon at the same position. We calculate for each timestamp the absolute difference in speed and then aggregate these errors over all 30 simulation runs and every timestamp by calculating the arithmetic mean.

- *Inter-vehicle gap:* As a road safety metric, we chose the inter-vehicle gap. For the evaluation we record the minimum inter-vehicle gap among any pair of consecutive vehicles.

4.3 Network Performance

In this section we want to analyze the communication of the proposed protocol looking at the network layer and the application layer performance. Therefore we are looking at a scenario with one platoon first to evaluate how the network is behaving. Afterwards, in Section 4.3.2, the goal is to understand the characteristics and the behavior of the protocol and network in a more stressful condition. Therefore we add more platoons to the highway, looking at scenarios with three, six, and nine platoons. By using a dedicated platooning channel, as defined by the protocol, we can ease the interpretation of the results. We analyze the scenarios considering the network metrics: CBR, latency, PCM-loss ratio, inter-message delay and the safe time ratio.

4.3.1 Scenario: One Platoon

In the first scenario we implemented, similar to Section 3.2.1, a Steady State Platooning scenario with one platoon. While doing that we are looking more closely at the communication during regular platooning. Here, we maintain a constant speed to focus on network analysis only. With one platoon we have seven vehicles transmitting their PCMs every 50 ms on the channel. Looking at the CBR first, we have a channel load span from 0 %, in the best case, to 33.61 % in the worst case, with a median of 5.6 %. These results are depicted in Figure 4.1.

As mentioned in Section 3.1.2 in REQ002 the ENSEMBLE project does not implement DCC for now, because they assume that the CBR values will be too low to activate any DCC algorithm. We want to look into this statement by comparing our CBR results with the default threshold values of the DCC given in [25]. As defined in Section 2.1.4 there are three different states between which the state machine is switching, RELAXED, ACTIVE and RESTRICTIVE. According to [25] the default threshold values for G5CC, i.e. CCH, as well as G5SC, i.e. SCH, are defined differently, as shown in Table 4.2. The ENSEMBLE project so far only proposed SCH1

	RELAXED	*ACTIVE*	*RESTRICTIVE*
G5CC	0 - 15 %	15 - 40 %	40% or higher
G5SC	0 - 20 %	20 - 50 %	50% or higher

Table 4.2 – DCC thresholds of the state machine according to [25].

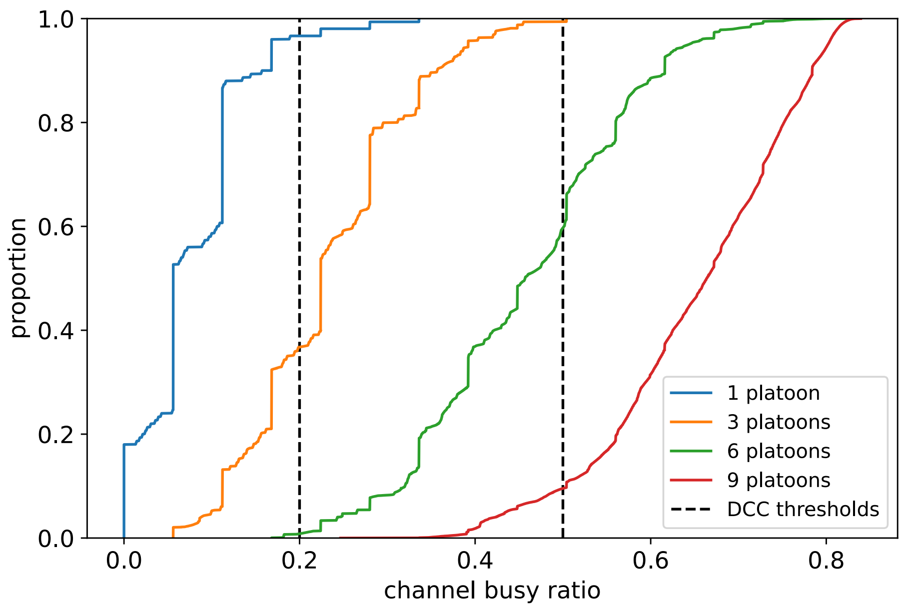


Figure 4.1 – eCDF showing the CBR results of each scenario, including the DCC thresholds dividing the graph into the states RELAXED, ACTIVE, and RESTRICTIVE.

for transmitting PCMs, while CAMs as well as DENMs are send on CCH. Therefore it makes sense to use the threshold values defined for SCH. Additionally, these threshold values are higher than those for CCH, which raises the possibility that if SCH thresholds got exceeded, the CCH thresholds would have been exceeded as well. Even though the ACTIVE state of SCH is subdivided into up to 4 sub states, we will only consider the threshold values for the three main states, leaving the sub states out of scope. As shown in Table 4.2, the state machine for G5SC switches to the RELAXED state for channel loads lower than 20 %, to the ACTIVE state for channel loads between 20 % and 50 % and to the RESTRICTIVE state for channel loads higher than 50 %. With respect to the results of the CBR values, we would be in 96.66 % of the cases in the RELAXED state, and in 3.34 % of the cases switching to the ACTIVE state. With a maximum of 33.61 % we would not reach the RESTRICTIVE state.

Due to the high transmission power of 200 mW (23 dBm, REQ003) as set by the proposed communication protocol, every vehicle in the simulation is recording the same CBR at each timestamp. With a platoon of 7 trucks with a length of 7.1 m and a distance of 19.78 m between the trucks, we reach a total length of 188.16 m. In the following scenario with nine platoons, where we have at maximum three platoons driving behind each other, we reach a total length of 608.04 m. From [47] we know that with a transmission power of 100 mW (20 dBm) a transmission of nearly 600 m is possible and therefore a transmission with 200 mW over the length of three consecutive platoons is likely possible. In the simulation this conjecture could be confirmed by each vehicle measuring the same CBRs, which are then distributed as shown in Figure 4.1. This means that no PCM is lost due to the transmission distance and no collisions through hidden terminal problems should appear.

Next to the CBR we recorded the latency of the PCMs, which in 94.5 % of the cases is at 0.57 ms and in 5.5 % between 0.57 ms and 2.07 ms (see Figure 4.2). Outliers in the latency with, for example, 2.07 ms are due to the randomly set start times of the PCM transmissions, which can result in vehicles sending their PCMs quite close to each other and therefore having an overlay or almost overlay when sending. As a possible result they spend more time in backoff and, hence, have a larger latency. However, most latencies are near the average of 0.58 ms and overall platooning is not effected by the smaller proportion of high latency messages.

As the third metric we consider the PCM-loss ratio, which in 93.33 % of the vehicles in all 30 simulation runs is 0 %. For the remaining 6.67 % it is between 1.01 % and 2.39 % as depicted in Figure 4.3. The upper 6.67 % of PCM-loss ratios are on the one side due to signal-to-noise-plus-interference-ratio (SNIR) packet losses, which are collisions and bit errors, and on the other side due to messages not getting received because vehicles were sending while receiving, which we will call TXRX packet losses. These are distributed as shown in Figure 4.4, in which we can see that the packet loss due to SNIR packet loss is significantly higher than due to TXRX packet loss. As a result of the high transmission power the PCM-loss is approximately

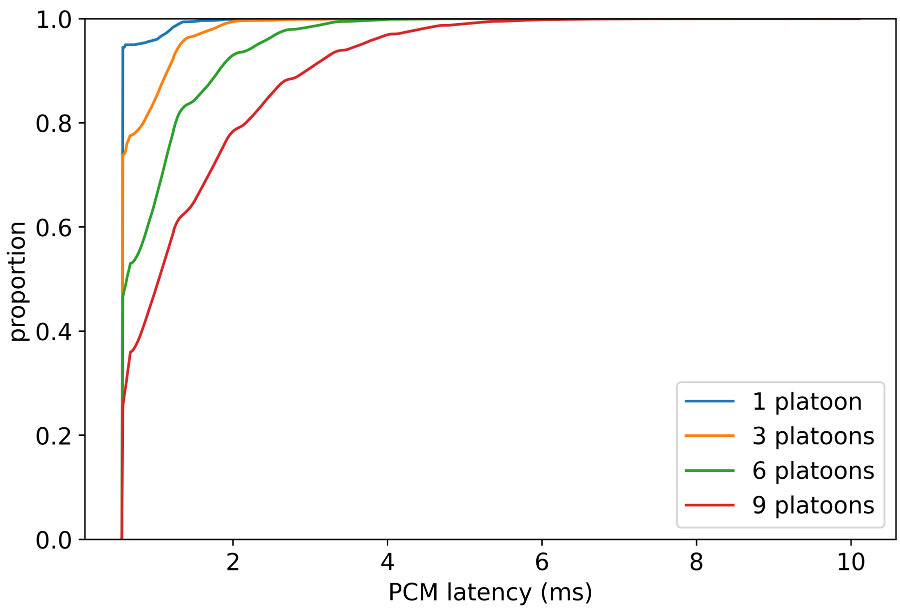


Figure 4.2 – eCDF showing the PCM latency results of each scenario.

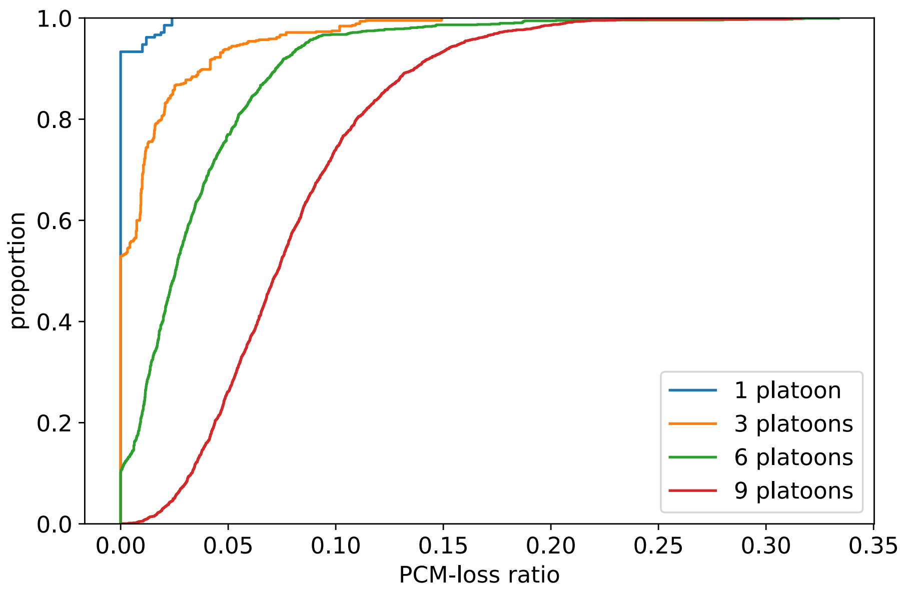


Figure 4.3 – eCDF showing the PCM-loss ratio results of each scenario.

equally distributed over the vehicles, meaning that there are no positions within a scenario with multiple platoons where the PCM-loss is significantly higher. In general, the PCM-loss ratio is for the most part at zero and the remaining cases still have a low PCM-loss ratio, so there are no effects on the platooning.

4.3.2 Scenario: Three, six, and nine Platoons

After looking at the network performance during regular platooning with one platoon, we want to evaluate the behavior of the protocol and network in a more stressful condition. For this purpose we add more platoons to the highway, creating scenarios with three, six, and nine platoons, which results in a density of 21, 41, and 63 vehicles. The goal of this configuration is to simulate the most common realistic scenarios on highways with up to 3 lanes for each direction and also worst case scenarios to push the protocol's limits. By doing that no requirements of the proposed communication protocol are getting violated.

As a result the CBR, as depicted in Figure 4.1, is increasing with the density of the scenarios. Compared to one platoon with a channel load being at 0 % in 18 % of the cases, with three platoons driving next to each other, the CBR is already starting with a channel load of 5.6 %, having its median at 22.4 %, and a maximum at 50.41 % . When the amount of platoons on the highway is doubled from three to six platoons, having two rows of three platoons driving next to each other, the minimum CBR is 16.8 %, its median is at 45.68 %, and the maximum at 82.18 %.

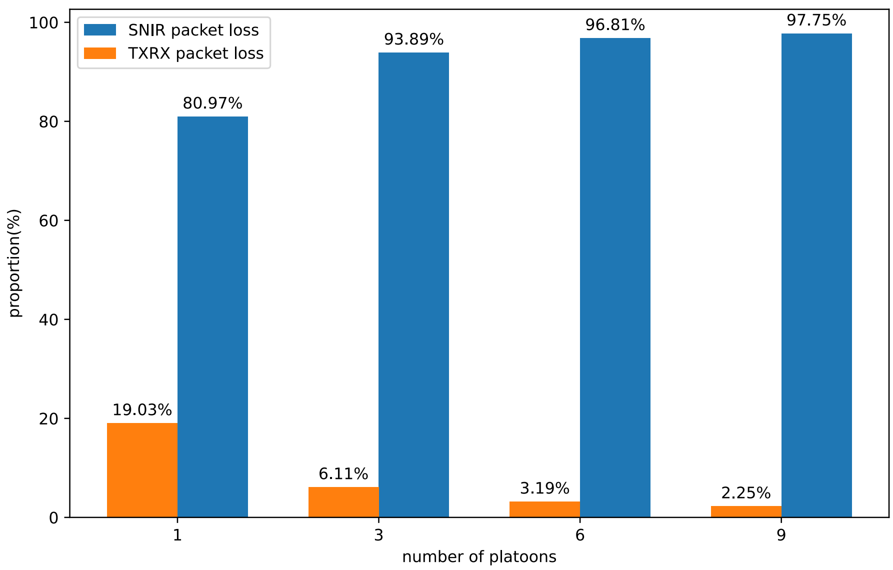


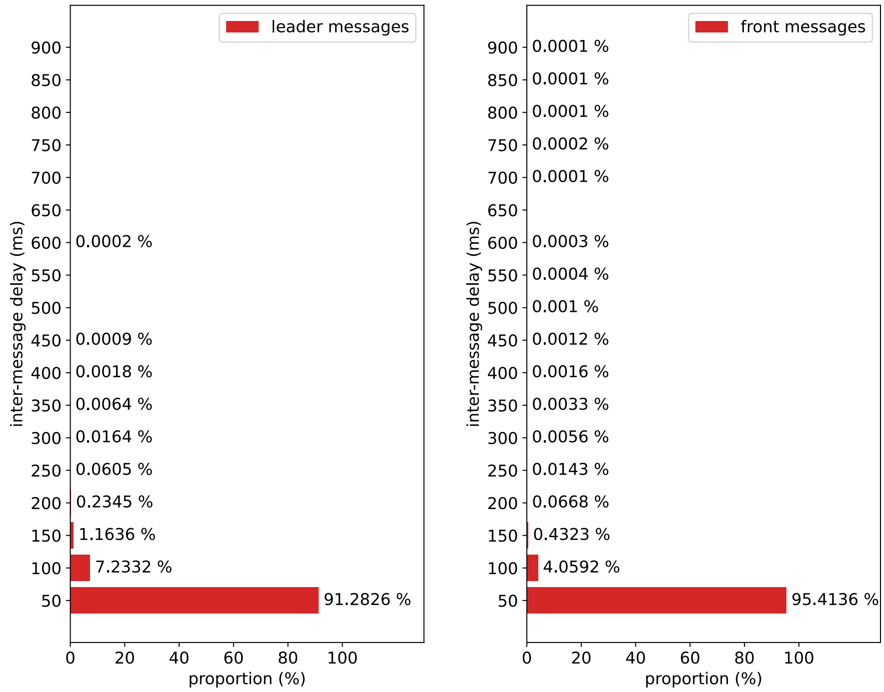
Figure 4.4 – Plot showing the ratio of SNIR packet loss and TXRX packet loss within the PCM-loss ratio for each scenario.

As the scenario with the highest density we have nine platoons, where three rows of three platoons driving next to each other. These result in the highest channel load, starting at 24.67% and going up to 83.93 %.

With respect to the DCC and considering three platoons, we would be in the RELAXED state in 36.75 % of the cases, in the ACTIVE state in 62.66 % of the cases, and with a maximum channel load of 50.41 % in 0.59 % of the cases in the RESTRICTIVE state. Looking at six platoons, we already have a CBR of 16.8% as the minimum and, thus, are in 0.83 % of the cases in the RELAXED state. In 58.87 % of the time we are in the ACTIVE state and in 40.3 % in the RESTRICTIVE state. The channel load of nine platoons is even higher, starting with a minimum of already 24.67 % and, therefore, is never in the RELAXED state. In 9.55 % of the cases we are in the ACTIVE state and in 90.45 % of the cases in the RESTRICTIVE state.

Having a higher channel load, the latency of the PCMs increases. Instead of a latency of at most 0.57 ms in 94.5 % of the cases, adding two more platoons, as shown in Figure 4.2, lowers that value to 74.8 % of the cases. This value goes further down with an increasing amount of platoons on the highway. Hence, we have a latency of 0.57 ms in the six platoons scenario in 47.7 % and in the nine platoons scenario only in 25.57 % of the time. Looking at three platoons, in 20.2 % the PCM latency is between 0.57 ms and 1.31 ms and the upper 5 % are between 1.31 ms and the maximum latency of 3.96 ms. With six platoons in 47.3 % the PCM latency is between 0.57 ms and 2.24 ms and the upper 5 % are between 2.24 ms and the maximum latency of 6.22 ms. Due to the fact that nine platoons created the highest channel load, we are having the highest PCM latency as well. Therefore in 69.43 % the PCM latency is between 0.57 ms and 3.65 ms and the upper 5 % are between 3.65 ms and the maximum latency of 10.11 ms. As we will see in Section 4.4 missing PCMs and therefore an inter-vehicle delay of 100 ms or higher does not have a significant influence on the mobility. Therefore if the PCM is received with a latency of over 10 ms in the worst case scenario, this is a small value compared to the larger inter-message delays, when PCMs are lost.

With regard to the PCM-loss ratio a similar behavior can be seen in Figure 4.3. In general, the higher the number of platoons the higher the PCM-loss ratio. As a result of one platoon we had a PCM-loss ratio of 0 % in 93.33 % of the cases. With three platoons this value decreases to 52.86 % of the cases. The 95 % quantile is at 5.86 % and the last 5 % of the distribution rise up to 14.93 %. Considering six platoons, the PCM-loss ratio is in 10.16 % of the cases at 0 %. The 95 % quantile is at 8.61 % and the upper 5 % are between 9.13 % and the maximum of 33.61 %. With nine platoons, the PCM-loss ratio starts at 0.07 %, has its 95 % quantile at 15.82 % and the maximum at 31.6 % . These packet losses are again due to SNIR packet losses and TXRX packet losses, whose distribution within the PCM-loss is shown in Figure 4.4. Here we can observe that the distribution with the growing density of the scenario is changing to an increase in SNIR packet loss and decrease in TXRX packet loss. Therefore we can say that with a higher channel load a larger share of the PCM-loss is due to SNIR packet losses, having relatively more bit errors and collisions appearing. To further evaluate the PCM-loss ratio we are going to look at the resulting inter-message delay for the highest density scenario. The controller we are using, as defined in Section 2.1.2, exploits data from the leader of the platoon and the vehicle driving immediately in front. Therefore missed or omitted messages by them can be harmful for the platooning application. We recorded the amount of missing messages of the leader and front vehicle, to be able to see for how long the controllers are actually staying without information and how much of the PCM-loss is a loss of leader and of the front vehicle messages. For that reason the metric is split between the messages of the leader of the platoon and the messages of the vehicle driving directly in front. The results are shown in Figure 4.5a for the leader messages and in Figure 4.5b for the messages of the vehicle in front. They show the distribution of how long vehicles didn't receive a PCM from the leader or the vehicle immediately in front, respectively. As we can see the PCMs from the leader and vehicle in front were received after 50 ms in 91.28 % and 95.41 % of the cases, respectively, which is the time interval defined by the proposed communication protocol. The remaining PCMs were received after more than 50 ms in 8.72 % and 4.59 %, respectively. The PCM-loss from the leader or the vehicle immediately in front is not necessarily happening at the same time, except for the second vehicle of

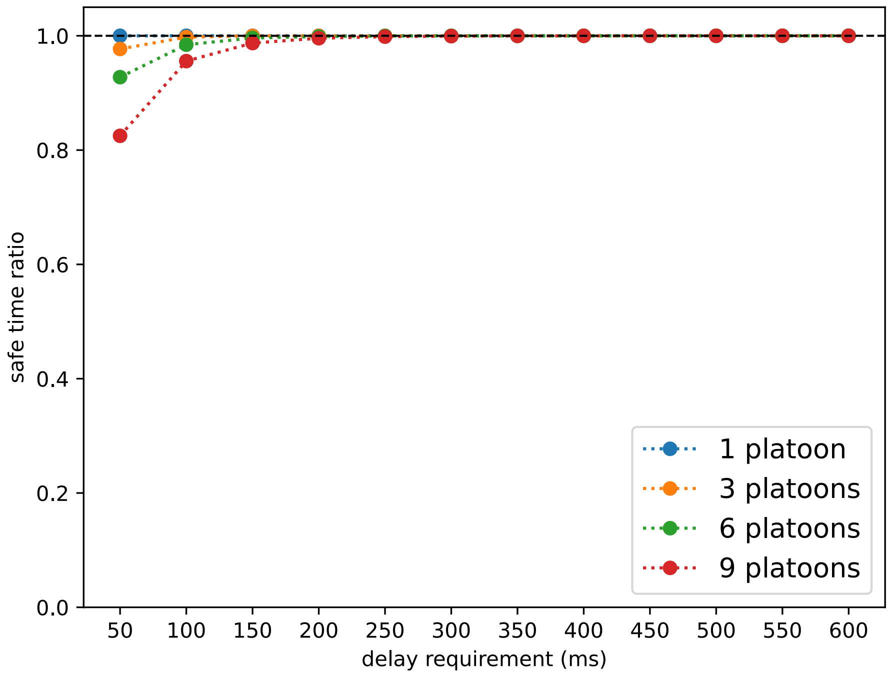


(a) inter-message delay (leader) **(b)** inter-message delay (front)

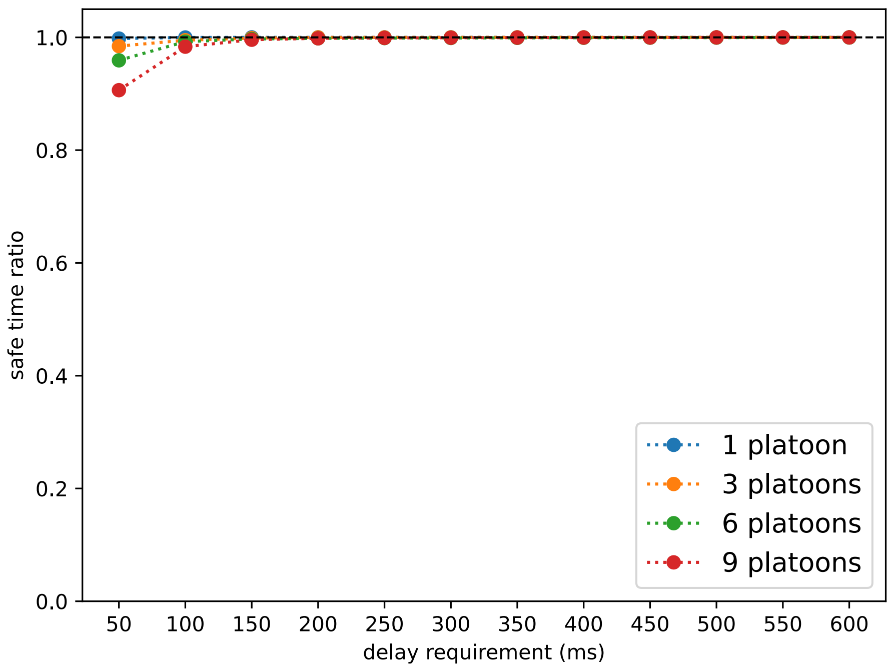
Figure 4.5 – Horizontal bar plot showing the the inter-message delay for the leader messages and for the messages of the vehicle immediately in front of the scenario with the highest density (nine platoons).

a platoon, which ensures that the controller still gets information, even though a larger inter-message delay occurs. In Section 4.4 we will further evaluate the impact a higher inter-message delay can have on the platooning application.

To understand the effectiveness of the protocol from the application layer perspective, we want to use the application layer metric by [40], called safe time ratio r_{safe}. Therefore we will use the results of the inter-message delay and choose $\Delta = 10ms$, i.e., the CACC controller sampling time [12], [33]. The safe time ratio r_{safe} measures the amount of time a vehicle is in a safe state, meaning that their requirements of how often PCMs are received are fulfilled. The results of the leader and the vehicle in front messages are depicted in Figure 4.6. These show the safe time ratio with respect to the delay requirement given by a controller for each scenario (one, three, six, and nine platoons). Considering the scenario with the highest density, having a delay requirement of, e.g., 50 ms, the proposed communication protocol ensures that vehicles are in a safe state 82.5 % of the time regarding the leader messages. For a delay requirement of 100 ms and 150 ms the safe time ratio is at 95.57 % and 98.73 %, respectively. All safe time ratios of higher delay requirements are approximately or equal to 1. Considering the messages of the vehicle immediately in front vehicles are in a safe state 90.64 % of the time and for a delay requirement of 100 ms as well as 150 ms the safe time ratio is at 98.35 % and 99.58 %, respectively. In the scenarios with less platoons, the protocol manages to deliver the leader and front vehicle messages even more reliable.



(a) leader messages



(b) front messages

Figure 4.6 – Safe time ratios for both leader and front messages of all four scenarios with one, three, six, and nine platoons.

4.4 Impact of Communication on CACC Performance

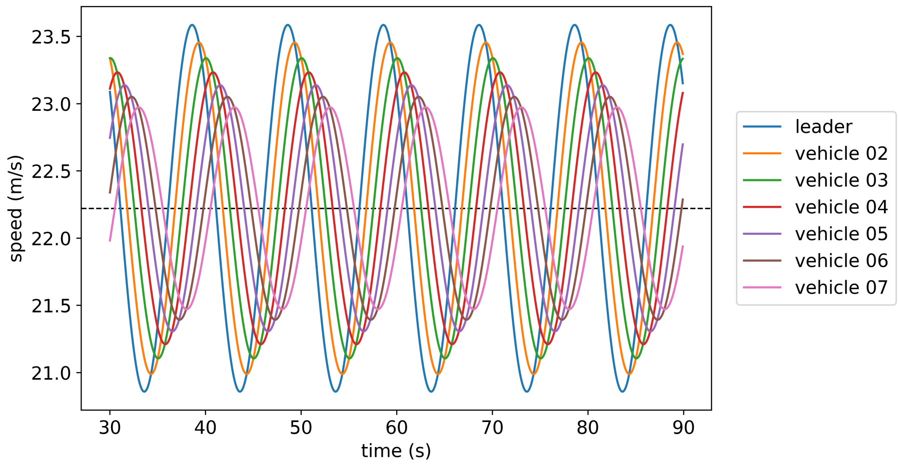
In the following sections we want to evaluate the impact of the communication designed by the proposed communication protocol on the CACC performance and therefore on the mobility. In principle, an important aspect in traffic is road safety. When a new technology is introduced, it has to be ensured that even under worst case conditions a certain level of safety is guaranteed. As shown in the previous section PCM-loss ratios of over 30 % were observed, potentially leading to situations in which the controller doesn't get any information. In that case CACC would perform a blind control action, i.e., assume that the input variables are unchanged. This could result in instabilities or crashes. Hence, we need to evaluate if road safety can be ensured under such conditions.

4.4.1 Scenario: Sinusoidal

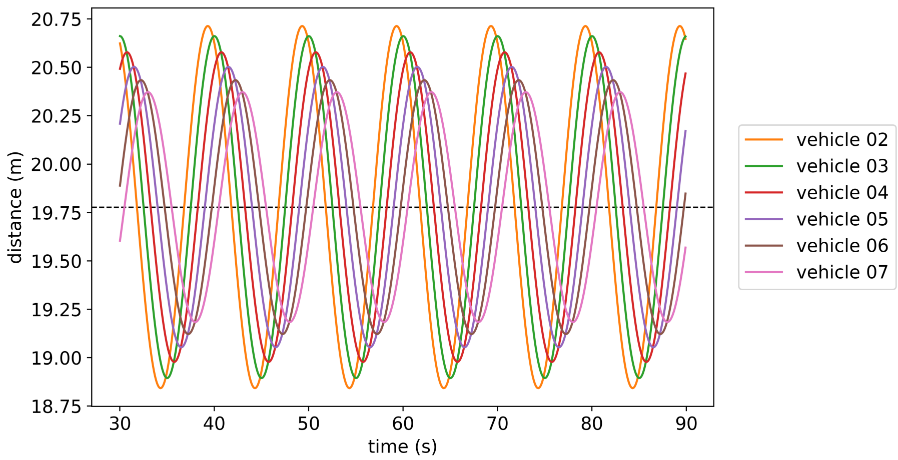
We implemented a sinusoidal scenario for nine platoons with the objective to investigate, if the higher load on the channel and, associated with it, the higher PCM-loss has any effects on the mobility of the vehicles in the platoons.

A sinusoidal scenario is described as a scenario where the leader of a platoon gets the instructions to alternately accelerate and decelerate by the same value in a specified period, which creates a sinusoidal input for the controllers of the platoon members. The reason we chose this kind of scenario is, that because of the repeating accelerating and decelerating, there are more often changes in the driving behavior than during regular platooning. A higher number of missing messages could show a bigger impact on the mobility in a sinusoidal scenario than during regular platooning. At the same time the response of a controller to a sinusoidal input is a standard approach to analyze string stability.

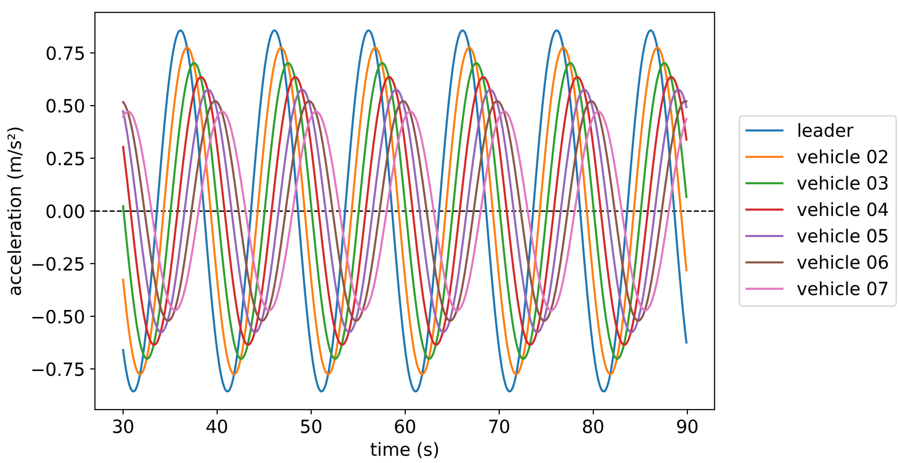
In the implemented sinusoidal scenario the platoon is traveling on a highway at a speed of 22.22 m/s. Since the platoon consists of trucks, which have worse engine characteristics than, e.g., passenger cars, we implemented a sinusoidal scenario adjusted to these values. Therefore the leaders speed follows a sinusoidal disturbance profile with a frequency of 0.1 Hz and an amplitude of 1.39 m/s, which the followers will try to adapt. A frequency of 0.1 Hz gives the vehicles enough time to reach the speed goal of 23.61 m/s or 20.83 m/s, respectively. Additionally this goal can be reached without using the full acceleration power of 1.3 m/s^2 the entire time, but with 0.86 m/s^2. These results are depicted in Figure 4.7. They show the speed, distance, and acceleration of the sinusoidal scenario with one platoon, which will be used as a point of comparison. With respect to the string stability, as shown in Figure 4.7a, the oscillation of the speed between the first and second vehicle is attenuated by the following vehicles of the platoon. Therefore the controller is string stable.



(a) speed



(b) distance



(c) acceleration

Figure 4.7 – Vehicle dynamics of the sinusoidal scenario with one platoon. Plot (a) shows the speed of each vehicle; plot (b) shows the distance to the respective front vehicle; plot (c) shows the acceleration of each vehicle.

To be able to evaluate the mobility behavior in a sinusoidal scenario under a high channel load we need to look at the mobility behavior under normal conditions as a reference. Therefore we implemented the sinusoidal scenario for one platoon, as well. Now, we need to compare each platoon to the reference platoon in the following way. We compare the vehicles within the platoon separately and for that chose the vehicle in the reference platoon at the same position. In this comparison we first calculate for each timestamp the absolute difference in speed and then aggregate these errors over all 30 simulation runs and every timestamp by calculating the arithmetic mean. Overall, the errors are so small, that there is no significant impact on the mobility. The results from the platoon with the highest errors, together with the corresponding relative errors, are shown in Table 4.3. The low error values can be explained due to inter-message delays of leader and front vehicles being not necessarily synchronous, which means that the controller still receives information.

4.4.2 Scenario: Emergency Brake

To gain more insights in the possible impact of communication on the CACC performance we implemented an emergency brake scenario with nine platoons. Again following the idea, that if it works reliable in the high density scenario, we can assume it will work in scenarios with a lower density as well. After looking at the results of the sinusoidal scenario, having a small error value at continuously changing the driving behavior, an emergency brake at a randomly set timestamp would not show any impact on the mobility, except when the emergency brake happens at the exact point in time where the inter-message delay is very high. This leads us to the question how harmful the impact of PCM-loss can be to the CACC performance if a large inter-message delay from the leader and preceding vehicle at the same time appears. Even though these cases may be rare, they can still occur, which is why we want to evaluate, what impact they might have on the CACC performance and, furthermore, possibly on the road safety. To construct this scenario, we picked the

Vehicle ID	*Absolute Error (m/s)*	*Relative Error (%)*
Leader	0.0276	0.12
Vehicle 02	0.0281	0.13
Vehicle 03	0.0283	0.13
Vehicle 04	0.0295	0.13
Vehicle 05	0.0295	0.13
Vehicle 06	0.03	0.14
Vehicle 07	0.03	0.14

Table 4.3 – The average absolute and relative error in speed, with respect to the reference platoon, of the platoon from the nine platoons scenario with the highest errors.

second vehicle of a platoon with the highest inter-message delay (300 ms), having the exact same PCM-loss for the leader as well as the vehicle in front messages. We implemented the emergency brake scenario to start at the exact point in time where the 300 ms time interval without any messages starts. The platoons drive with a cruise velocity of 22.22 m/s and perform a full-stop braking maneuver. As a reference we considered an emergency brake scenario with one platoon, at a simulation run with no extraordinary PCM-loss, and recorded the distance to the preceding vehicle at standstill to compare it. The results regarding the mobility of this reference scenario are shown in Section 3.2.3 in Figure 3.5. Looking at the second vehicle of the platoon, after performing the braking maneuver, we can see that the vehicle comes down to an inter-vehicle distance of 3.08 m and then more slowly adjusts to a minimum inter-vehicle distance of 2 m, which is the same as the desired distance at standstill. For the constructed emergency brake with nine platoons, starting the maneuver at the exact point in time, where an inter-message delay of 300 ms for the second vehicle of a platoon exists, a minimum inter-vehicle distance of 1.63 m was recorded.

Even with an PCM-loss of 300 ms no crash occurred and the remaining distance at standstill of 1.63 m has still an acceptable size. This scenario is a constructed worst case scenario, unlikely to happen, to demonstrate what kind of impact the communication can have on the mobility. With the inter-vehicle gap as defined by the proposed communication protocol the mobility can cope with that kind of message loss. If one wants to reduce the inter-vehicle distance further, this would have to be investigated again.

4.5 Discussion

When we look at the results of the network layer performance we see, as expected, that there is a positive correlation between the number of platoons and the recorded network metrics. Due to more vehicles on the highway sending PCMs, the CBR, latency as well as the PCM-loss ratio increases. The objective of the DCC is to prevent the channel from being overloaded and therefore provide congestion control. The CBR results of the scenario with one platoon show, that the DCC state machine would have switched to the ACTIVE state and therefore would have started to regulate the channel. This is something the ENSEMBLE project claims to not happen. They expect the CBR values to be too low to activate any DCC algorithm. On the other hand, considering the results of this thesis, we would not reach the RESTRICTIVE state with one platoon. A realistic real life scenario in the near future could be three platoons driving on the highway behind each other. With three platoons we would reach the RESTRICTIVE state in 0.59 % of the cases, which could be avoided by using DCC.

The vehicles in a platoon only need to share their information with the vehicle immediately behind. Therefore the leader is the only one needing to reach every vehicle in the platoon, which raises the question if a transmit power that high is necessary. A lower transmit power could reduce the interference domain, i.e., avoid to transmit on the channel from other platoons nearby, which would not have any use in receiving such data, and, therefore, increase the spatial reuse of the channel. It can also be differentiated between the transmit power of the leader and the followers, having the leader use a higher power to reach all vehicles of the platoon. Segata et. al. [40], [48], [49] investigate the use of adaptive transmit power control in the context of platooning and show that the use can be very beneficial. This could be further investigated for the proposed communication protocol.

As mentioned in the first scenario, outliers in the latency can be explained due to randomly set start times resulting in a possible overlay or almost overlay transmitting PCMs. This and additionally having a higher density on the highway resulting in a higher channel load in the other scenarios (three, six, and nine), leads to PCMs spending more time in backoff and therefore having a larger latency. This could be avoided by spacing out the start times within the PCM interval of 50 ms. However, the latency of over 10 ms in the worst case scenario is compared to the lager inter-vehicle message delays an insignificant small value.

The PCM-loss ratio is due to SNIR and TXRX packet losses, in which especially the share of SNIR packet loss and, therefore, the bit errors and collisions increases with an increase of the channel load. To discuss the PCM-loss it must be seen in context of its effects. Considering the protocol performance from the application layer perspective, we can see that the proposed protocol manages to deliver leader messages within 150 ms in 98.73 % of the cases and front messages in 99.57 % of the cases in the scenario with the highest density. In the scenario with one platoon, the protocol manages to deliver the leader and front vehicle messages even more reliable. These results additionally provide a key performance indicator to measure how well the protocol ensures constant information flow, which can be used to determine whether a different controller would be reliable with the proposed communication protocol.

To investigate further into the possible impact of the communication on the CACC performance and therefore on the mobility, the sinusoidal scenario shows that the resulting errors are too small to have a significant impact on the mobility behavior of platooning. The emergency scenario, on the other hand, is a forced worst case scenario, proving that the PCM-loss can have an impact on the mobility. Due to how the proposed protocol is defined, with an inter-vehicle gap of 0.8 s, this doesn't effect the road safety. Apart from the fact that this scenario is unlikely to happen. The scenarios regarding the impact of communication on the CACC performance show that there can be an impact in rare worst case scenarios, whereas in general, the impact is not harmful to platooning. This is shown for the scenarios with the highest road density and therefore we can conclude that the impact in scenarios with less density would be even less. Overall, we can conclude that the proposed communication protocol works reliable.

Chapter 5

Conclusion

In this thesis, we present a first simulative performance analysis of the proposed communication protocol for multi-brand truck platooning in Europe published by the ENSEMBLE project. The aim of the thesis is to evaluate the network layer and application layer performance in a normal as well as in a high density condition. Additionally, we investigate the impact of the communication on the CACC performance and therefore on the mobility aspects. By using the simulation framework PLEXE we implement the proposed protocol and simulate several scenarios. In order to analyze them, often used metrics for platooning were chosen.

Our analysis shows that the proposed communication protocol works reliable. Even with a higher amount of platoons on the highway sending PCMs and therefore increasing the CBR, latency and PCM-loss ratio, the communication functions reliable. In the scenario with the highest density the protocol manages to timely deliver, i.e. 150 ms, the for the controller necessary information in 98.73 % of the cases regarding the leader messages and in 99.58 % of the cases regarding the messages of the vehicle immediately in front. Considering these results for one platoon, we have an even more reliable information flow with 100 % of the PCMs being transmitted within 50 ms. These results additionally provide a key performance indicator to measure how well the protocol ensures constant information flow, which can be used to determine whether a different controller would be reliable with the proposed communication protocol. A similar result is also reflected in the scenarios regarding the impact of the communication on the CACC performance. The sinusoidal scenario performed under the same level of density shows that the resulting error in the mobility behavior is too small to have a significant impact on it and the emergency brake scenario shows that there can be an impact in constructed worst case scenarios, but road safety was not effected. Therefore, the proposed communication protocol seems to be safe even with a high density of platoons on the highway.

With respect to the DCC the ENSEMBLE project states that it is applicable, but would need investigation. The results of this thesis show, that the proposed communication protocol does work without DCC, even in the most demanding scenario. An investigation of the proposed communication protocol using DCC as a preventive measure could still give insights in its impact on the network performance. Additionally, to be able to better classify the protocol itself, a comparison with other protocols, similar to what was done in [40], [43], can be made. Furthermore, the protocol uses a transmit power, which reaches over the length of three platoons driving behind each other. This raises the question, if a transmit power that high is necessary. Especially, because research shows, that an adaptive transmit power control can be very beneficial in the context of platooning. This is an aspect which could be investigated for further improvements of the proposed communication protocol.

List of Abbreviations

AC	Access Category
ACC	Adaptive Cruise Control
ACK	Acknowledgement
BTP	Basic Transport Protocol
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
CCA	Clear Channel Assessment
CCH	Control Channel
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance
DCC	Decentralized Congestion Control
DENM	Decentralized Environmental Notification Message
EC	European Commission
ECC	Electronic Communications Committee
EDCA	Enhanced Distributed Channel Access
GN	GeoNetworking
ITS	Intelligent Transportation System
IVC	Inter-Vehicle Communication
LLC	Logical Link Control
OEM	Original Equipment Manufacturer
PCM	Platoon Control Message
QoS	Quality of Service
SCH	Service Channel
SCH1	Service Channel 1
SUMO	Simulation of Urban MObility

List of Figures

List of Tables

Bibliography

[1] "Energy, transport and environment statistics – 2020 edition," European Commission, Luxembourg City, Luxembourg, Product Code KS-DK-20-001, Nov. 2020. DOI: 10.2785/522192.

[2] European Automobile Manufacturers' Association, "Vehicles in use Europe," *acea.auto*, pp. 1–20, Jan. 2021.

[3] European Commission. (2017). "Hours spent in road congestion annually," [Online]. Available: https://ec.europa.eu/transport/facts-fundings/scoreboard/compare/energy-union-innovation/road-congestion_en#2017 (visited on 06/04/2021).

[4] C. Bergenhem, H. Pettersson, E. Coelingh, C. Englund, S. E. Shladover, and S. Tsugawa, "Overview of Platooning Systems," in *19th World Congress on Intelligent Transport Systems (ITS 2012)*, Vienna, Austria: Transportation Research Board, Oct. 2012.

[5] U. Franke, F. Bottiger, Z. Zomotor, and D. Seeberger, "Truck Platooning in Mixed Traffic," in *IEEE Intelligent Vehicles Symposium (IV 1995)*, Detroit, MI: IEEE, Sep. 1995. DOI: 10.1109/ivs.1995.528248.

[6] S. E. Shladover, C. A. Desoer, J. K. Hedrick, M. Tomizuka, J. Walrand, W.-B. Zhang, D. H. McMahon, H. Peng, S. Sheikholeslam, and N. McKeown, "Automated Vehicle Control Developments in the PATH Program," *IEEE Transactions on Vehicular Technology (TVT)*, vol. 40, no. 1, pp. 114–130, Feb. 1991. DOI: 10.1109/25.69979.

[7] Kraftfahrt-Bundesamt, "Verkehr in Kilometern - Inländerfahrleistung (VK)," *kba.de*, pp. 1–9, 2020.

[8] A. A. Alam, A. Gattami, and K. H. Johansson, "An Experimental Study on the Fuel Reduction Potential of Heavy Duty Vehicle Platooning," in *13th IEEE International Conference on Intelligent Transportation Systems (ITSC 2010)*, Funchal, Portugal: IEEE, Sep. 2010, pp. 306–311. DOI: 10.1109/ITSC.2010.5625054.

[9] X.-Y. Lu and S. E. Shladover, "Automated Truck Platoon Control," University of California, Berkeley, Berkeley, CA, Research Report UCB -ITS -PRR -2011-13, Jun. 2011.

[10] S. Tsugawa, S. Jeschke, and S. E. Shladover, "A Review of Truck Platooning Projects for Energy Savings," *IEEE Transactions on Intelligent Vehicles (T-IV)*, vol. 1, no. 1, pp. 68–77, Mar. 2016. DOI: 10.1109/tiv.2016.2577499.

[11] S. Santini, A. Salvi, A. S. Valente, A. Pescapè, M. Segata, and R. Lo Cigno, "A Consensus-based Approach for Platooning with Inter-Vehicular Communications," in *34th IEEE Conference on Computer Communications (INFOCOM 2015)*, Hong Kong, China: IEEE, Apr. 2015, pp. 1158–1166. DOI: 10.1109/INFOCOM.2015.7218490.

[12] J. Ploeg, B. Scheepers, E. van Nunen, N. van de Wouw, and H. Nijmeijer, "Design and Experimental Evaluation of Cooperative Adaptive Cruise Control," in *14th IEEE International Conference on Intelligent Transportation Systems (ITSC 2011)*, Washington, D.C.: IEEE, Oct. 2011, pp. 260–265. DOI: 10.1109/ITSC.2011.6082981.

[13] R. Rajamani, Vehicle Dynamics and Control, 2nd ed. Springer, 2012, p. 498. DOI: 10.1007/978-1-4614-1433-9.

[14] A. Bose and P. Ioannou, "Analysis of Traffic Flow with Mixed Manual and Intelligent Cruise Control Vehicles: Theory and Experiments," University of California, Berkeley, Berkeley, CA, California PATH Research Report UCB-ITS-PRR-2001-13, Apr. 2001.

[15] D. Swaroop and J. Hedrick, "String Stability of Interconnected Systems," *IEEE Transactions on Automatic Control*, vol. 41, no. 3, pp. 349–357, Mar. 1996.

[16] A. Ali, G. Garcia, and P. Martinet, "The Flatbed Platoon Towing Model for Safe and Dense Platooning on Highways," *IEEE Intelligent Transportation Systems Magazine*, vol. 7, no. 1, pp. 58–68, Jan. 2015. DOI: 10.1109/MITS.2014.2328670.

[17] V. Milanés, S. E. Shladover, J. Spring, C. Nowakowski, H. Kawazoe, and M. Nakamura, "Cooperative Adaptive Cruise Control in Real Traffic Situations," *IEEE Transactions on Intelligent Transportation Systems (TITS)*, vol. 15, no. 1, pp. 296–305, Feb. 2014. DOI: 10.1109/TITS.2013.2278494.

[18] G. J. Naus, R. P. Vugts, J. Ploeg, M. Van de Molengraft, and M. Steinbuch, "String-stable CACC Design and Experimental Validation: A Frequency-domain Approach," *IEEE Transactions on Vehicular Technology (TVT)*, vol. 59, no. 9, pp. 4268–4279, Nov. 2010. DOI: 10.1109/TVT.2010.2076320.

[19] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band," ETSI, ES 202 663 V1.1.0, Nov. 2009.

[20] IEEE, "Wireless Access in Vehicular Environments," IEEE, Std 802.11p-2010, Jul. 2010. DOI: 10.1109/IEEESTD.2010.5514475.

[21] ——, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE, Std 802.11-2016, Dec. 2016. DOI: 10.1109/IEEESTD.2016.7786995.

[22] C. Sommer and F. Dressler, Vehicular Networking. Cambridge University Press, 2014. DOI: 10.1017/CBO9781107110649.

[23] ARIB, "700 MHz Band Intelligent Transport Systems," ARIB, Chiyoda, Japan, STD T109-v1.3, Jul. 2017.

[24] IEEE, "IEEE Guide for Wireless Access in Vehicular Environments (WAVE) - Architecture," IEEE, Std 1609.0-2013, Mar. 2014. DOI: 10.1109/IEEESTD.2014.6755433.

[25] ETSI, "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part," ETSI, TS 102 687 V1.1.1, Jul. 2011.

[26] ——, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service," ETSI, TS 302 637-2 V1.3.1, Sep. 2014.

[27] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band," ETSI, TS 102 724 V1.1.1, Oct. 2012.

[28] ETSI, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specification of Decentralized Environmental Notification Basic Service," ETSI, TR 302 637-3 V1.2.1, Sep. 2014.

[29] B. Atanassow and K. Sjöberg, "Platooning protocol definition and Communication strategy," HORIZON 2020 project ENSEMBLE, Deliverable D2.8, Dec. 2018, pp. 1–55.

[30] J. Vissers, J. Banspach, V. Liga, T. Tang, H. Nordin, S. Julien, S. Martinez, and C. Villette, "V1 Platooning use-cases, scenario definition and Platooning Levels," HORIZON 2020 project ENSEMBLE, Deliverable D2.2, May 2020, pp. 1–51.

[31] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary," ETSI, TS 102 894-2 V1.2.1, Sep. 2014.

[32] B. Atanassow, P. Sandström, D. Millard, R. Alieiev, S. Gherekhloo, R. Prenzel, W. Whyte, J. van Doorn, S. Guarnich, and A. Manilla, "Security framework of platooning," HORIZON 2020 project ENSEMBLE, Deliverable D2.9, May 2020, pp. 1–30.

[33] M. Segata, S. Joerer, B. Bloessl, C. Sommer, F. Dressler, and R. Lo Cigno, "PLEXE: A Platooning Extension for Veins," in *6th IEEE Vehicular Networking Conference (VNC 2014)*, Paderborn, Germany: IEEE, Dec. 2014, pp. 53–60. DOI: 10.1109/VNC.2014.7013309.

[34] M. Segata, "Platooning in SUMO: An Open Source Implementation," in *SUMO User Conference 2017*, Berlin, Germany: DLR, May 2017, pp. 51–62.

[35] C. Sommer, R. German, and F. Dressler, "Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis," *IEEE Transactions on Mobile Computing (TMC)*, vol. 10, no. 1, pp. 3–15, Jan. 2011. DOI: 10.1109/TMC.2010.133.

[36] A. Varga, "The OMNeT++ Discrete Event Simulation System," in *European Simulation Multiconference (ESM 2001)*, Prague, Czechia, Jun. 2001.

[37] D. Krajzewicz, G. Hertkorn, C. Rössel, and P. Wagner, "SUMO (Simulation of Urban MObility); An Open-source Traffic Simulation," in *4th Middle East Symposium on Simulation and Modelling (MESM 2002)*, Sharjah, UAE, Sep. 2002, pp. 183–187.

[38] IEEE, "IEEE Standard for Wireless Access in Vehicular Environments (WAVE) - Multi-channel Operation," IEEE, Std 1609.4-2010, Feb. 2011.

[39] S. Krauß, "Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics," PhD Thesis, Mathematical Institute, Köln, Germany, Apr. 1998.

[40] M. Segata, B. Bloessl, S. Joerer, C. Sommer, M. Gerla, R. Lo Cigno, and F. Dressler, "Towards Communication Strategies for Platooning: Simulative and Experimental Evaluation," *IEEE Transactions on Vehicular Technology (TVT)*, vol. 64, no. 12, pp. 5411–5423, Dec. 2015. DOI: 10.1109/TVT.2015.2489459.

[41] C. Sommer, S. Joerer, M. Segata, O. K. Tonguz, R. Lo Cigno, and F. Dressler, "How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help," in *32nd IEEE Conference on Computer Communications (INFOCOM 2013), Mini-Conference*, Turin, Italy: IEEE, Apr. 2013, pp. 110–114. DOI: 10.1109/INFCOM.2013.6566745.

[42] ——, "How Shadowing Hurts Vehicular Communications and How Dynamic Beaconing Can Help," *IEEE Transactions on Mobile Computing (TMC)*, vol. 14, no. 7, pp. 1411–1421, Jul. 2015. DOI: 10.1109/TMC.2014.2362752.

[43] M. Segata, F. Dressler, and R. Lo Cigno, "Jerk Beaconing: A Dynamic Approach to Platooning," in *7th IEEE Vehicular Networking Conference (VNC 2015)*, Kyoto, Japan: IEEE, Dec. 2015, pp. 135–142. DOI: 10.1109/VNC.2015.7385560.

[44] A. Rayamajhi, Z. A. Biron, R. Merco, P. Pisu, J. M. Westall, and J. Martin, "The Impact of Dedicated Short Range Communication on Cooperative Adaptive Cruise Control," Kansas City, MO, USA, Tech. Rep., May 2018, pp. 1–7. DOI: 10.1109/ICC.2018.8422309.

[45] C. Lei, E. van Eenennaam, W. Wolterink, G. Karagiannis, G. Heijenk, and J. Ploeg, "Impact of Packet Loss on CACC String Stability Performance," in *11th International Conference on Intelligent Transportation Systems Telecommunications (ITST 2011)*, Saint Petersburg, Russia, Aug. 2011, pp. 381–386. DOI: 10.1109/ITST.2011.6060086.

[46] J. Blasco, N. Parera, X. Sellart, H. Nordin, S. Ellwanger, J. Stephane, V. Liga, D. Willemsen, and J. Allard, "First version Demonstration and test plan," HORIZON 2020 project ENSEMBLE, Deliverable D5.1, May 2020, pp. 1–55.

[47] B. Bloessl and A. O'Driscoll, "A Case for Good Defaults: Pitfalls in VANET Physical Layer Simulations," in *IFIP Wireless Days (WD 2019)*, Manchester, United Kingdom: IEEE, Apr. 2019. DOI: 10.1109/WD.2019.8734227.

[48] M. Segata, B. Bloessl, S. Joerer, C. Sommer, M. Gerla, R. Lo Cigno, and F. Dressler, "Towards Inter-Vehicle Communication Strategies for Platooning Support," in *7th IFIP/IEEE International Workshop on Communication Technologies for Vehicles (Nets4Cars 2014-Fall)*, Saint Petersburg, Russia: IEEE, Oct. 2014, pp. 1–6. DOI: 10.1109/Nets4CarsFall.2014.7000903.

[49] M. Segata, "Safe and Efficient Communication Protocols for Platooning Control," PhD Thesis, Institute of Computer Science, Innsbruck, Austria, Feb. 2016.