3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle Communications in Highway Platooning Scenarios

Vladimir Vukadinovic¹, Krzysztof Bakowski⁶, Patrick Marsch², Ian Dexter Garcia⁷, Hua Xu⁷, Michal Sybis⁶, Pawel Sroka⁶, Krzysztof Wesolowski⁶, David Lister⁸, Ilaria Thibault⁸

¹ Nokia Networks, Wroclaw, Poland
⁶ Nokia Networks, Arlington Heights, Illinois, USA
⁷ Poznan University of Technology, Poznan, Poland
⁸ Vodafone Group R&D, Newbury, United Kingdom

Corresponding author. E-mail addresses: {vladimir.vukadinovic, krzysztof.bakowski, ian.garcia, hua.2.xu}@nokia.com, patrick.marsch@deutschebahn.com, {michal.sybis, pawel.sroka, krzysztof.wesolowski}@put.poznan.pl, {david.lister, ilaria.thibault}@vodafone.com

Abstract

The focus of this study is the performance of high-density truck platooning achieved with different wireless technologies for vehicle-to-vehicle (V2V) communications. Platooning brings advantages such as lower fuel consumption and better traffic efficiency, which are maximized when the inter-vehicle spacing can be steadily maintained at a feasible minimum. This can be achieved with Cooperative Adaptive Cruise Control, an automated cruise controller that relies on the complex interplay among V2V communications, on-board sensing, and actuation. This work provides a clear mapping between the performance of the V2V communications, which is measured in terms of latency and reliability, and of the platoon, which is measured in terms of achievable inter-truck spacing. Two families of radio technologies are compared: IEEE 802.11p and 3GPP Cellular-V2X (C-V2X). The C-V2X technology considered in this work is based on the Release 14 of the LTE standard, which includes two modes for V2V communications: Mode 3 (base-station-scheduled) and Mode 4 (autonomously-scheduled). Results show that C-V2X in both modes allows for shorter inter-truck distances than IEEE 802.11p due to more reliable communications performance under increasing congestion on the wireless channel caused by surrounding vehicles.

Keywords: Cooperative Adaptive Cruise Control; Truck Platooning; Wireless Communications; Connected Mobility; 3GPP Cellular-V2X; IEEE 802.11p;

1 Introduction

Vehicles today are equipped with a variety of on-board sensors (cameras, RADARs, LIDARs) that make them aware, to a certain extent, of what is happening in the environment around them. Wireless vehicular communication technologies have the potential to greatly enhance the vehicles’ awareness range and to allow for bi-directional communications between vehicles and any other entity that is equipped with an appropriate communications module. The term vehicle-to-everything (V2X) communications is used to refer generically to methods for passing information flows in different applications of Intelligent Transportation Systems (ITS) related to traffic safety and efficiency, automated driving, and infotainment. V2X includes (but is not limited to) Vehicle-to-Vehicle (V2V), Vehicle-to-Network (V2N), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Road Infrastructure (V2I) communications. Different standardization bodies have devoted efforts into specifying V2X wireless technologies, especially after dedicated spectrum at 5.9 GHz was allocated for ITS both in the US and in Europe in 1999 and 2008, respectively. As a result, different families of standards have been completed: the IEEE/SAE DSRC in 2010 in the US [1], the Release 1 of the ETSI/CEN Cooperative-ITS (C-ITS) in 2013 in Europe [2], and 3GPP Cellular-V2X (C-V2X) in early 2017 as a feature of Release 14 of the LTE standard [3]. DSRC and C-ITS both use the IEEE 802.11p standard [4] for the physical and data link layers, which is a short-range technology for V2V communications. 3GPP’s C-V2X specifications include short-range V2V communications, where an air interface called sidelink/PC5 is used for direct communication between vehicles, as well as wide-area V2N communication that allows vehicles to communicate with the base station (referred to as eNodeB in 3GPP). C-V2X will keep evolving in future releases of the 3GPP standard, in order to provide support for emerging use cases such as automated driving.

¹ Corresponding author. E-mail address: vladimir.vukadinovic@nokia.com
² Now with Deutsche Bahn AG, Germany
ITS applications present a variety of performance requirements for wireless V2X technologies, which are often associated with communication latency and reliability. When the latency and reliability requirements are not fulfilled, traffic safety- and efficiency-related applications will struggle to properly react to the changes in the environment. Hence it is of paramount importance to have a robust and scalable wireless communications platform that can reliably and swiftly react to potential hazardous situations. The focus of this paper is vehicular platooning, which is a promising ITS use case that has the potential to increase road capacity, reduce fuel consumption due to the reduction in air drag, and improve driver comfort. Studies have shown that platooning may double the road capacity [5]. The findings of the SARTRE project show that platooning provides fuel savings from 7% to 15% for trucks travelling behind the platoon leader [6]. Therefore, road freight transport companies would greatly benefit from platooning since fuel costs account on average for 25-30% of a truck's operational costs [7]. The fuel savings translate to a substantial reduction of CO_2 emissions. A simulation study performed in the Energy ITS project [8] has shown that, when the market penetration of truck platooning increases from 0% to 40% of trucks, CO_2 emissions along a highway can be reduced by 2.1% if the gap between trucks is 10 m, and by 4.8% if the gap is reduced to 4 m.

This paper studies the ability of different V2X technologies to improve the performance of the Cooperative Adaptive Cruise Control (CACC) algorithm, which is the key enabler for high-density platooning, as it allows close spacing to be automatically maintained between vehicles while they move at highway speeds. CACC overcomes the fact that human drivers have limited capability to safely maintain small inter-vehicle spacings. CACC adjusts the acceleration of a vehicle in a way that a certain target spacing to the vehicle in front is maintained. The adjustment is based on information supplied both by on-board sensors and V2V communication with other vehicles in the platoon. Depending on which information is transmitted between vehicles, different realizations of CACC are possible. Typically, the leading vehicle (i.e., the platoon leader) transmits its speed and acceleration to all vehicles in the platoon, allowing them to react faster to any changes in traffic conditions compared to relying on on-board sensors only. Several examples of CACC designs with different communication topologies and control policies are described in [9]-[12]. A comprehensive survey is provided in [13]. All these CACC algorithms require frequent, highly-reliable, and low-latency V2V wireless communications.

In this paper, we study the suitability of IEEE 802.11p and 3GPP C-V2X to support high-density platooning. The C-V2X considered in this paper is specified in Release 14 of the LTE standard and includes two modes for sidelink/PC5 (i.e., direct V2V) communication: Mode-3, which requires cellular infrastructure support for radio resource management, and Mode-4, which does not involve cellular infrastructure (and can hence be used in areas without cellular coverage). We will refer to them as C-V2X Mode-3 and C-V2X Mode-4. Our detailed simulation model considers a platoon of trucks driving on a highway and adjusting the speed in reaction to other vehicles. Input to the CACC controller is provided by Cooperative Awareness Messages (CAMs)⁴ that are broadcast by all vehicles on the highway. The performance metrics considered are minimum feasible (i.e., safe) inter-truck distance, CAM message latency, and CAM reception probability. We show how the performance of IEEE 802.11p and C-V2X degrades with the increasing highway traffic density that leads to the congestion on the radio channel. The communication takes place on the 10 MHz channel allocated in the U.S. (5,855 MHz – 5,865 MHz) and in Europe (5,875 MHz – 5,905 MHz) for CAMs and other traffic safety messages.

The results presented in this work show that C-V2X Mode-4 outperforms IEEE 802.11p in all of the highway traffic scenarios (except for the case where there are no vehicles other than the platooned trucks on the road, which is not a realistic case), while C-V2X Mode-3 outperforms IEEE 802.11p and C-V2X Mode-4 in all scenarios. While previous studies of C-V2X and IEEE 802.11p compared the link- and system-level performance (i.e., block error rate – BLER and packet reception ratio - PRR) of the two technologies [14]-[16], this study is the first to show how link- and system-level performance of the wireless communication technologies translate into application layer performance, i.e., inter-truck distance, for the platooning use case. The platooning/CACC performance is in fact the result of a complex interplay among V2V communications, sensing, and actuation.

The paper is organized as follows: An overview of related work is provided in Section 2. An overview of drive control algorithms for platooning and CACC in particular is provided in Section 3. Section 4 provides the necessary background on V2X technologies with focus on the recently standardized 3GPP C-V2X. The simulation model for truck platooning

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⁴ CAM messages are defined in the ETSI/CEN C-ITS standard [2]. The equivalent message in the SAE/DSRC standard is called Basic Safety Message (BSM). We will use the term CAM throughout the paper for simplicity of notation.
and the performance comparison of IEEE 802.11p and C-V2X are provided in Section 5, after which Section 6 concludes the paper.

2 Related work

A number of empirical studies have been performed to evaluate and demonstrate the performance of car/truck platooning supported by IEEE 802.11p: The SARTRE project [6], which ran from 2009 to 2012, deployed a platoon of two trucks and three cars driven autonomously in close formation. The experiments showed that the platoon could drive at speeds of up to 90 km/h with a ~5-7 m inter-vehicle gap. A platoon of three fully-automated trucks driving at 80 km/h with a 10 m inter-vehicle gap was tested on an expressway in Japan in the Energy ITS project in 2012 [8]. In the European Truck Platooning Challenge in 2016 [17], automated trucks of six major truck vendors drove in platoons on public roads from several European cities to Rotterdam in the Netherlands. While most vendors did not publish details on the underlying V2V communication equipment, it is publicly known that DAF, MAN, and Daimler trucks were equipped with IEEE 802.11p communication modules. The PATH Program led by UC Berkeley and Volvo demonstrated a platoon of three IEEE 802.11p-equipped trucks driving 15 m apart on the busy 110 Interstate freeway in 2017 [18].

While trials certainly provide valuable insight into platooning performance under realistic radio propagation conditions and with real-life vehicle dynamics, they do not account for scenarios where all vehicles on the highway are equipped with V2X radios and potentially contend for the same radio channel used for intra-platoon communication. Moreover, while this paper is being written, it is not yet possible to evaluate and compare the newly standardized C-V2X in real-world trials, since C-V2X chipsets are yet to be made commercially available. Therefore, simulations are a necessary tool to study the ability of different V2X technologies to meet the requirements of the ITS applications. As an example, [19] builds a comprehensive system simulation framework to study the CACC performance in the presence of non-ideal communications. The study shows that CAM message broadcast frequency and loss ratio have strong influence on the performance of the CACC algorithm. The performance of car platooning with Rel. 12 LTE D2D-based inter-vehicular communication, which pre-dates Rel. 14 C-V2X considered in this paper, is evaluated in [20]. A consensus-based approach to CACC where inter-vehicular communication is based on IEEE 802.11p is evaluated in [11]. A comparison of the platoon performance with IEEE 802.11p communication on a common control/safety channel and on a dedicated service channel is provided in [21]. The CACC performance with different adaptive CAM beaconing schemes implemented on top of the IEEE 802.11p protocol stack is evaluated in [22]. Further examples of simulation studies that evaluate the performance of CACC with IEEE 802.11p are given in [23], [24] and [25]. The link-level (i.e., Block Error Rate - BLER vs. Signal-to-Noise Ratio - SNR) and system-level (i.e., Packet Reception Rate - PRR vs. distance) performance of IEEE 802.11p and C-V2X have been compared in [14]-[16]. The link level results in [14] show that, for a 10% BLER target, C-V2X provides a 4-5 dB SNR gain over IEEE 802.11p in line-of-sight scenarios and a 1-3 dB gain in non-line-of-sight scenarios. The system-level results in [15] show that, for a 90% PRR target, C-V2X Mode-4 provides ~95% gain in coverage over IEEE 802.11p in freeway scenarios and ~55% in urban scenarios. The gains of C-V2X Mode-3 are even larger. None of these studies, however, show how link- and system-level gains of C-V2X translate into platoon performance, i.e., there is no mapping between the performance of the wireless technologies and the achievable inter-vehicle distance. To the best of the authors’ knowledge, this paper is the first to provide such results for the truck platooning use case.

Some examples of research studies that aim to extend and optimize the existing communication standards to better support the requirements of vehicle platooning can be found in [22], [25]-[27]. In [22], the authors propose a solution that eliminates channel contention by allowing platooned vehicles to negotiate a TDMA schedule on top of standard 802.11p channel access method. A similar approach is explored in [25], where TDMA is realized using a token passing among platoon members. Self-organizing TDMA on top of 802.11p MAC has been considered by ETSI, but eventually it was not included in ETSI C-ITS standard and is not likely to become part of any commercial ITS implementation in foreseeable future. In [26], the authors study the performance of IEEE 802.11p Distributed Coordination Function (DCF) based on a Markov chain model and propose a contention window adjustment scheme to optimize its performance in multi-platoon scenarios. The same authors proposed resource (i.e. subchannel and power) allocation algorithms for LTE-based multi-platoon communication in [27].
3 Cruise control for platooning

High-density platooning relies on automated longitudinal drive control since human drivers cannot steadily maintain short inter-vehicle distances in a safe manner. A longitudinal drive control system consists of an upper controller (i.e., a cruise controller), which calculates the desired acceleration needed to maintain a desired safety gap from the vehicle in front based on a set of inputs (e.g., from sensors and/or wireless communication), and a lower controller, which controls the actuation of the vehicle (throttle, brakes) based on the input from the upper controller, as shown in Fig. 1.

The adaptive cruise control (ACC) is a drive assistance system introduced to the market about twenty years ago. It enables automatic adaptation of acceleration so to achieve and maintain a specific constant time headway (CTH, measured in seconds) with respect to the preceding vehicle. The ACC uses input from on-board sensors such as RADAR, LIDAR, and camera, which measure the distance and relative velocity to the preceding vehicle, and calculates as output the desired acceleration that should be applied to maintain the CTH. The throttle and brake are then automatically adjusted. The CTH policy of the ACC controller does not result in constant spacing between platooned vehicles — the spacing increases and decreases with the speed. From the perspective of traffic efficiency and fuel savings, a constant spacing (CS) policy, where the objective is to maintain a constant and stable distance between vehicles, is preferred over CTH. However, since ACC is an autonomous controller (i.e., it utilizes only on-board sensors and does not depend on inter-vehicular communication or any form of cooperation with other vehicles), it is not able to provide string stable performance under CS policy, as shown in [28]. String stability means that any non-zero error in position, speed, and acceleration of an individual vehicle in the platoon does not amplify when it propagates towards the tail of the platoon. If a platoon is not string stable, a braking action of the platoon leader, for example, might introduce a disturbance in the platoon that amplifies, leading to a full standstill of following vehicles or even to a collision. The typical time headway that ensures string stable performance of ACC under CTH policy is ~1 s, which translates to 28 m when travelling at 100 km/h.

The reason why the ACC is not string stable with the CS policy and only allows for large inter-vehicle gaps is because it only uses inputs from on-board sensors and does not depend on any form of cooperation among vehicles. The information provided by on-board sensors is limited to the preceding vehicle only — there is no way to monitor vehicles that are further ahead. A change in speed/acceleration must “propagate” from the lead vehicle through the platoon to be detected. If, however, the controller could obtain inputs from the platoon leader (and possibly any other vehicle in between) via wireless communications, the ACC would be able to react much faster to those changes. This would allow reaching stability with smaller inter-vehicle gaps and with the CS policy. For this purpose, the research community started to work on an extension of the ACC algorithm called cooperative adaptive cruise control (CACC), which relies both on measurements performed by on-board sensors and on wireless communication with other vehicles in the platoon. Depending on the expected input (hence, communication pattern/topology), different realizations of CACC are possible.

Figure 1 Longitudinal drive control system. The upper (cruise) control may rely on inputs from on-board sensors only or both from on-board sensors and wireless communication.
In this paper, we study the performance of a CACC controller which is based on the well-known sliding-surface CACC controller [29] given by

$$\ddot{x}_{\text{des},i} = \alpha_1(d_d - d_r) + \alpha_2(\dot{x}_i - \dot{x}_{i-1}) + \alpha_3(\dot{x}_i - \dot{x}_1) + \alpha_4\ddot{x}_{i-1} + \alpha_5\ddot{x}_1,$$  

(1)

for \( i > 1 \) (i.e., for every vehicle behind the platoon leader), where \( \ddot{x}_{\text{des},i} \) is the desired acceleration of vehicle \( i \), \( d_d \) is the desired constant spacing between vehicle \( i \) and the preceding vehicle \( i-1 \), \( d_r \) is the distance from the preceding vehicle \( i-1 \) measured by the radar, \( \dot{x}_i \) and \( \dot{x}_{i-1} \) are the speeds of vehicle \( i \) and preceding vehicle \( i-1 \), \( \dot{x}_1 - \dot{x}_{i-1} \) is the relative speed to the preceding vehicle measured by the radar, \( \dot{x}_1 \) is the speed of the platoon leader obtained via wireless communication, and \( \ddot{x}_{i-1} \) and \( \ddot{x}_1 \) are accelerations of the preceding vehicle and platoon leader, respectively, obtained via wireless communication. The choice of weight factors \( \alpha_1, \ldots, \alpha_5 \) is discussed in [28] and [29]. CACC calculates the desired acceleration \( \ddot{x}_{\text{des},i} \) and provides it to the lower controller, which controls the actuation of the vehicle, as shown in Fig. 1. The desired acceleration is applied after a certain actuation lag \( \tau \). With this form of CACC, it is clear that wireless communication with the preceding vehicle and the platoon leader is required in order to obtain necessary input for the control algorithm. To avoid instabilities that may lead to vehicle collisions, all inputs need to be provided frequently and timely enough, which sets certain requirements on the minimum capacity, maximum message latency, and reliability of the wireless communication. The platoon leader \((i = 1)\) is typically driven either by a human or by ACC and, therefore, it doesn’t rely on wireless communication for cruise control.

The original sliding-surface CACC can be modified as follows:

$$\ddot{x}_{\text{des},i} = \alpha_1(d_d - d_r) + \alpha_2(\dot{x}_i - \dot{x}_{i-1}) + \alpha_3(\dot{x}_i - \dot{x}_1) + \alpha_4\ddot{x}_{\text{des},i-1} + \alpha_5\ddot{x}_{\text{des},1},$$  

(2)

for \( i > 1 \), where the desired accelerations of the preceding vehicle \( \ddot{x}_{\text{des},i-1} \) and the platoon leader \( \ddot{x}_{\text{des},1} \) are provided as inputs to the controller instead of the actual/current accelerations \( \ddot{x}_{i-1} \) and \( \dot{x}_1 \). This means that vehicles transmit their desired accelerations that will become effective after the actuation lag. We refer to this type of controller as “predictive CACC” since, by using the desired accelerations, it “predicts” that those will become the actual accelerations of the preceding vehicle and platoon leader after the actuation lag. In that way, the impact of the actuation lag on the CACC control loop is minimized. The actuation lag is in fact the major limiting factor for achieving very short inter-vehicle distances after having removed the reaction time of human drivers through automation. It is shown in [30] that “predictive CACC” significantly outperforms the original sliding-surface CACC, especially when the actuation lag is long. In the remainder of the paper, predictive CACC will be used according to the policy given in (2), and it will be referred to as CACC for simplicity.

4 V2X communication technologies

This section provides a brief overview of IEEE 802.11p and 3GPP/LTE-based C-V2X technologies.

4.1 IEEE 802.11p

IEEE 802.11p [4] is an adaptation of the IEEE 802.11 standard to address dynamic vehicular environments. The amendments on the MAC layer enable very efficient communication group setup without the need to establish a basic service set (BSS) as in the IEEE 802.11 MAC. Therefore, IEEE 802.11p MAC operates in so-called OCB (Outside the Context of a BSS) mode. The physical layer of IEEE 802.11p is OFDM based and similar to IEEE 802.11a, with minimal changes introduced to enable communication among fast moving vehicles. This involves the introduction of 10 MHz channels instead of the 20 MHz channels used in IEEE 802.11a to address the increased root-mean-squared delay spread in the vehicular environment. This results in the doubling of all OFDM timing parameters and halving of the maximum supported data from 54 Mb/s to 27 Mb/s. Also, more stringent receiver performance requirements in adjacent channel rejections and new spectrum masks are introduced to deal with cross-channel interference.

IEEE 802.11p has been designed to address road safety and traffic efficiency applications: \( i) \) it works in a fully distributed way and hence does not require a central controller, \( ii) \) it achieves low message latency through direct ad-hoc communication among neighboring vehicles, \( iii) \) its signaling overhead is reduced to a minimum compared to
IEEE 802.11a. However, IEEE 802.11p also inherits some legacy features that are not well-suited for vehicular communication: The synchronization and channel estimation approach is sub-optimal for highly time-variant radio channels. For example, the channel coherence time at the relative speed of 85 m/s and central frequency at 5.9 GHz equals the duration of only 75 OFDM symbols (450 bytes at 6 Mb/s). Hence, considerable time variations over a data packet can be expected, which makes channel estimation challenging at the receiver. Even more worrisome is that IEEE 802.11p relies on an un-coordinated channel access strategy based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). It is well-known that CSMA/CA does not perform well in congested scenarios and hence is not scalable to high numbers of vehicles on the road. With an increasing number of transmitters, in fact, the channel access latency and the probability of data packet collision increase. A method called Decentralized Congestion Control (DCC) [31] only partially solves the problem by reducing the transmission rate of CAMs. This however may affect the performance of some road safety and traffic efficiency applications (e.g., it has been shown in [30] that the optimal CAM rate for CACC is ~10 Hz).

4.2 3GPP C-V2X

3GPP C-V2X has been introduced in the Release 14 of the LTE standard [3]. The standard includes the support for V2V communication that is not routed via an eNodeB, but uses direct communication link (i.e., sidelink/PC5) between vehicles. It is based on the sidelink/PC5 communication for proximity services (ProSe) introduced in Release 12. Since vehicular communication has different properties and requirements compared to ProSe (e.g., in terms of node density, mobility, latency, reliability), Release 14 C-V2X introduces a number of enhancements for sidelink/PC5:

**Efficient radio resource allocation**

One of the challenges of vehicular communications is radio resource management in areas with high vehicle densities. C-V2X supports both eNodeB-scheduled resource allocation (Mode-3) and autonomous resource allocation (Mode-4) for the sidelink/PC5. With Mode-3, the network infrastructure provides centralized collision-free resource allocation to vehicles. Mode-4 supports V2V communication without network infrastructure. With Mode-4, ITS services can be supported in a distributed way, just as with IEEE 802.11p. A Semi-Persistent Transmission (SPT) mechanism in Mode-4 and a Semi-Persistent Scheduling (SPS) mechanism in Mode-3 exploit the fact that many V2X messages, such as CAMs, are generated periodically. SPT and SPS allow a vehicle to make a recurrent use of the same radio resource for a number of subsequent CAM transmissions. This avoids the need for frequent resource re-selection and allows a vehicle to predict the resource usage of surrounding vehicles based on the history of channel sensing. This differs from the purely contention-based channel access scheme used by the IEEE 802.11p. Further details of resource selection procedures in Mode-3 and Mode-4 that are necessary for understanding the results of this study are provided in Section 5.

**Mitigation of the near-far effect**

In C-V2X, sidelink/PC5 communication is broadcast-based with open-loop power control, which is inherently subject to the near-far problem and consequently unbalanced receive power at different vehicles. A key mechanism introduced in Release 14 to mitigate this undesired effect is a geographical zone-based resource usage concept (also known as geo-zoning). Geo-zoning allows a group of vehicles located in one geo-zone (e.g., a segment of a road) and other vehicle groups in neighboring zones to use radio resources in a time-multiplexed manner, based on their GPS coordinates. Geo-zones as well as the mapping between the geo-zones and sidelink/PC5 radio resource pools can be either configured by the eNodeB or pre-configured for vehicles that are out of network coverage. A vehicle determines the geo-zone identity based on the abovementioned configuration and its current location. The vehicle will then use the resource pools that are mapped to that particular zone.

**Support for high-velocity and seamless mobility**

High speeds of vehicles render channel estimation and mobility management more challenging. C-V2X increases the amount of demodulation reference symbols on the sidelink/PC5 from 2 symbols (defined for ProSe in Release 12) to 3 or 4 symbols per sub-frame to deal with large Doppler shifts. In addition, the demodulation reference symbols sequence randomization is also enhanced for better interference suppression in high vehicle density scenarios. Support for seamless mobility is also improved: When geo-zoning is used, a communication interruption may happen when a vehicle moves from one geo-zone to the other because different geo-zones are associated with different radio resource pools. To
prevent such interruptions, so-called exceptional resource pools are pre-defined and used by the vehicles that are crossing the boundaries of geo-zones.

5 Platoon performance with IEEE 802.11p and C-V2X

In this section, the performance of high-density truck platooning is analyzed using simulations. The key performance indicator that is used to measure the performance of the platoon is the average inter-truck distance. The communication between trucks is based on periodic CAMs, which contain all necessary inputs for the CACC controller defined in (2). IEEE 802.11p, 3GPP C-V2X Mode 3, and 3GPP C-V2X Mode 4 are considered as radio technologies for CAM delivery, and their performance in terms of latency, scalability, and reliability is mapped to the platoon performance.

5.1 Simulation scenario

In the considered scenario, a platoon of ten trucks is driving behind a vehicle referred to as “jammer” on one lane of a four-lane highway, as shown in Fig. 2. The speed of the jammer changes according to a pre-defined pattern shown in Fig. 3: Initially, it moves at a constant speed of 80 km/h for 30 seconds. It then decelerates to 35 km/h and accelerates again to 80 km/h within 30 seconds. The slope of the deceleration part of the jamming pattern is -0.3\text{g}, where \text{g} is the gravitational acceleration (9.8 m/s\(^2\)), which corresponds to the limit of the brake capacity of the cruise control systems (imposed by the ISO 15622:2010 standard). Therefore, it takes 4.25 seconds to decelerate from 80 km/h to 35 km/h, and it takes 25.75 seconds to accelerate from 35 km/h to 80 km/h, as shown in Fig. 3. The acceleration/deceleration pattern is periodic with a 30 second period length, which we call a “jamming cycle”. The ACC controller of the platoon leader adapts its acceleration in order to maintain a target time headway from the jammer. The CACC controllers in the trucks behind the leader need to adapt their desired accelerations to maintain a specified target inter-truck distance, in line with the CS (constant-spacing) policy described in Section 3. The particular jamming pattern is selected to stress-test the ability of the CACC to maintain the target distance without causing collisions. The speed-dependent acceleration constraints of the trucks have been modeled to account for the fact that trucks are typically not able to accelerate faster than 2 m/s\(^2\) even if a higher acceleration is determined by CACC and sent to the lower controller. The deceleration constraint is set by ISO 15622:2010 to -0.3\text{g}. The impact of the truck load and road conditions (e.g., dry or wet) on acceleration/deceleration capabilities is not modeled. The actuation lag is modeled as a first-order low pass filter applied to the output of the CACC controller. The distance and relative speed to the preceding car are assumed to be measured using a long-range radar, such as Bosch LRR3 [32] or Continental ARS 408-21 [33]. A frequency-modulated continuous wave with the cycle time of 60 ms is assumed to be used for the measurements, meaning that the distance and relative speed estimates are available at the end of the cycle, hence, every 60 ms. The accuracy of the measurements is assumed to be perfect, which is close to the reality based on the accuracies reported in [32] and [33].

![Figure 2. A platoon of ten trucks and a jammer on one lane and a configurable number of non-platooned cars on the remaining three lanes of a four-lane highway. The speed of the jammer follows a periodic pattern, as shown in a separate figure. All vehicle broadcast 300-byte CAMs every 100 ms on a 10 MHz wide radio channel.](image-url)
There is a configurable number of non-platooned cars on the remaining three lanes of the highway (0, 5, 10, or 20 cars/km/lane) to simulate different traffic intensities around the platoon. Non-platooned cars drive at a constant speed of 130 km/h. All vehicles in the scenario (trucks and cars) broadcast 300-byte CAMs every 100 ms. The CAM periods are not time-synchronized across vehicles. We assume that, both with IEEE 802.11p and C-V2X, CAMs are broadcast on a 10 MHz wide channel (5.875 GHz – 5.905 GHz) of the ITS band allocated in Europe for the transmission of safety-related messages [34]. The data load on the channel increases with the highway traffic intensity, making it challenging to provide reliable communication due to potential interference between transmissions of different vehicles. One of the main objectives of this study is to investigate the impact of traffic intensity on the CACC performance with IEEE 802.11p and C-V2X. A summary of the highway traffic and truck model parameters is provided in Table 1.

### Table 1: Highway traffic and truck model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanes per direction</td>
<td>2</td>
</tr>
<tr>
<td>Lane width</td>
<td>4 m</td>
</tr>
<tr>
<td>Trucks in the platoon</td>
<td>10</td>
</tr>
<tr>
<td>Truck length</td>
<td>16.5 m</td>
</tr>
<tr>
<td>Max. speed of trucks</td>
<td>100 km/h</td>
</tr>
<tr>
<td>Max. acceleration of trucks</td>
<td>linear decay from 2 m/s² @ 0 km/h to 0 m/s² @ 100 km/h</td>
</tr>
<tr>
<td>Max. deceleration of trucks</td>
<td>0.3g (= 2.94 m/s²)</td>
</tr>
<tr>
<td>Actuation lag of trucks</td>
<td>20 ms</td>
</tr>
<tr>
<td>Density of non-platooned cars</td>
<td>0, 5, 10, 20 cars/km/lane</td>
</tr>
<tr>
<td>Speed of non-platooned cars</td>
<td>130 km/h (constant)</td>
</tr>
<tr>
<td>Radar measurement interval</td>
<td>60 ms</td>
</tr>
<tr>
<td>CAM message interval</td>
<td>100 ms</td>
</tr>
<tr>
<td>CAM message size</td>
<td>300 bytes</td>
</tr>
</tbody>
</table>

#### 5.2 IEEE 802.11p / 3GPP C-V2X parameters and radio resource selection modes

The basic principles of radio channel access and resource selection in IEEE 802.11p and C-V2X are summarized in this section.

IEEE 802.11p uses the CSMA/CA mechanism for channel access, i.e., once a CAM is generated by the ITS application, it is then passed to the lower layers and the IEEE 802.11p autonomously decides when to transmit the CAM based on idle-channel sensing: the transmission is postponed until the channel sensing function confirms that there are no other
ongoing transmissions. The transmission uses the full 10 MHz of channel spectrum, therefore, frequency-multiplexing of multiple transmissions on the channel is not supported. In other words, the channel constitutes a single radio resource to be time-shared by all vehicles. Simultaneous transmissions from two or more vehicles lead to a collision and message loss. CSMA/CA is known to perform very well at low channel loads, but suffers from increased collision probability and latency when the load increases.

C-V2X divides the 10 MHz sidelink/PC5 channel into \( k \) sub-channels. Each CAM transmission occupies one sub-channel. Therefore, up to \( k \) vehicles can transmit their CAMs simultaneously on different sub-channels without colliding with each other. The maximum number of sub-channels \( k \) depends on the size of the CAM and the modulation and coding scheme (MCS) used at the physical layer. In this work, given that a 300-byte CAM is assumed and QPSK with code rate \( R = 1/2 \) is chosen as MCS, \( k \) is equal to 2. The transmission of a CAM occupies one transmission time interval (TTI), which is 1 ms long. The resource selection scheme determines on which sub-channel and in which TTI to transmit. As already mentioned in Section 4.2, C-V2X defines two modes for sidelink/PC5 resource selection:

- **Mode-4** for autonomous radio resource selection, where vehicles autonomously select a radio resource from the selection window, and
- **Mode-3** for eNodeB-coordinated resource selection, where the selection/scheduling of the radio resources is done centrally at the eNodeB.

**Resource selection in C-V2X Mode-4**

According to the C-V2X Mode-4 specification, radio resources are selected from a resource selection window, which can be between 20 and 100 TTIs long and composed of \( k \) sub-channels (\( k=2 \) in our setup), as shown in Fig. 4. The length of the selection window (in TTIs) is a parameter that can be set. The maximum transmission latency is limited by the length of the selection window. A shorter window provides a shorter transmission latency, but it increases collision probability under high traffic loads. In this work, the selection window size is set to 20 TTIs to minimize the CAM transmission latency. Mode-4 resource selection is designed to address periodic data, such as CAMs. Every vehicle continuously senses the radio channel to learn about the periodic transmission patterns of the neighboring vehicles. Note that this is subject to the half-duplex constraint, i.e., a terminal cannot “listen” to radio signals while it is transmitting. When a CAM needs to be transmitted, the last 1000 ms of sensing history, referred to as the sensing window, are used to determine which resources inside the resource selection window are likely to be used by other vehicles. Those resources are excluded and not further considered as candidate resources for the selection, as shown in Fig. 4. The remaining resources are sorted according to their Received Signal Strength Indications (RSSIs), which are extrapolated from the sensing window. Finally, a transmission resource is selected randomly from the bottom 20% of the sorted candidate resources with the lowest RSSI. Random selection is introduced to prevent situations where multiple vehicles select the same resource because it has the lowest RSSI. Once a resource is selected, it is used semi-persistently, meaning that a certain number of consecutive CAM transmissions will use that same resource (i.e., the same sub-channel and the same TTI measured from the start of the selection window). As briefly described in Section 4.2, this mechanism is SPT. Thanks to SPT, a vehicle is able to determine which resources shall be excluded from the selection based on the sensing history. The selected resource is released after a number of consecutive CAM transmissions using a mechanism called resource re-selection counter: When a vehicle selects an SPT resource, it also randomly picks a re-selection counter value from a pre-defined interval. With every CAM transmission, the re-selection counter is decremented. When it becomes zero, resource re-selection is triggered. The re-selection counter is important for resolving so-called “persistent collisions”, where two vehicles select the same SPT resource and, not being able to detect the collision due to the half-duplex constraint, continue to collide until the re-selection is triggered.
Resource selection in C-V2X Mode-3

According to the C-V2X Mode 3 specification, a vehicle that wants to transmit a CAM sends a sidelink/PC5 resource-assignment request to the nearest eNodeB. The eNodeB then informs the vehicle which sidelink/PC5 resource it can use for the CAM transmission by sending a resource grant message. The resource can be granted for a single CAM transmission or, in case of periodic traffic, for a number of consecutive CAMs. As briefly described in Section 4.2, this is known as SPS, and it is analogous to SPT in C-V2X Mode-4. The eNodeB may utilize the knowledge of previously issued resource grants, request patterns, vehicle-to-vehicle pathloss estimates, vehicle position reports, packet head-of-line delay, per-packet priority, scheduling queues, etc., to select the best resource and achieve the lowest transmission latency. Since transmissions are centrally scheduled, collisions can be avoided under Mode-3, at least among vehicles associated with the same eNodeB. Transmissions of vehicles associated with different eNodeBs can also be collision-free if cross-eNodeB coordination is performed.

A summary of the simulation parameters for IEEE 802.11p and C-V2X, such as spectrum band, channel models, transmission power, modulation and coding, are provided in Table 2. The ITU Vehicular-A [35] multi-path channel model is used for all V2V links (truck-to-truck, car-to-truck, and car-to-car), with fading samples generated based on the relative speed between the transmitter and the receiver. The Winner+ B1 LOS path loss model [36] assumes line-of-sight between the transmitter’s and the receiver’s antennas. This is a realistic assumption for links between trucks, which are equipped with rooftop antennas. Cars however may not necessarily have line-of-sight towards trucks and other cars. As a consequence, the impact of interference from non-platooned cars on intra-platoon communication is overestimated, leading to conservative link reliability estimates.

Table 2. IEEE 802.11p and 3GPP C-V2X configuration parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>IEEE 802.11p</th>
<th>3GPP C-V2X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum band</td>
<td>ITS-G5A (5895-5905 MHz)</td>
<td></td>
</tr>
<tr>
<td>Channel estimation</td>
<td>Ideal</td>
<td></td>
</tr>
<tr>
<td>Channel model</td>
<td>ITU Vehicular-A</td>
<td></td>
</tr>
<tr>
<td>Path loss model</td>
<td>Winner+ B1 LOS</td>
<td></td>
</tr>
<tr>
<td>Antenna height</td>
<td>3.5 m</td>
<td></td>
</tr>
<tr>
<td>Shadowing distribution</td>
<td>Log-normal</td>
<td></td>
</tr>
<tr>
<td>Shadowing standard deviation</td>
<td>3 dB</td>
<td></td>
</tr>
<tr>
<td>Decorrelation distance</td>
<td>25 m</td>
<td></td>
</tr>
<tr>
<td>TX power density</td>
<td>23 dB/m/MHz</td>
<td></td>
</tr>
<tr>
<td>Noise power</td>
<td>-174 dBm/Hz</td>
<td></td>
</tr>
<tr>
<td>Noise figure</td>
<td>9 dB</td>
<td></td>
</tr>
<tr>
<td>Number of TX/RX antennas</td>
<td>1/1</td>
<td></td>
</tr>
<tr>
<td>Power control</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>MCS</td>
<td>QPSK, R = 1/2</td>
<td></td>
</tr>
<tr>
<td>Number of used subcarriers</td>
<td>52</td>
<td>600</td>
</tr>
<tr>
<td>Subcarrier spacing [kHz]</td>
<td>156.25</td>
<td>15</td>
</tr>
<tr>
<td>FFT size</td>
<td>64</td>
<td>2048</td>
</tr>
<tr>
<td>OFDM symbol duration</td>
<td>8 µs</td>
<td>1/14 ms</td>
</tr>
<tr>
<td>Number of sub-channels</td>
<td>n.a.</td>
<td>2</td>
</tr>
<tr>
<td>Selection window size [TTIs]</td>
<td>n.a.</td>
<td>20 (Mode-4) / n.a. (Mode-3)</td>
</tr>
<tr>
<td>Resource re-selection counter</td>
<td>n.a.</td>
<td>rand[1,3] (Mode-4) / n.a. (Mode-3)</td>
</tr>
</tbody>
</table>

5.3 Performance metrics

The study focuses on the following performance metrics.

Performance metric for truck platooning:

This parameter value is not in line with C-V2X specification, which specifies the range [5,15]. It has been selected to mitigate the “persistent collisions” problem.
- **Average inter-truck spacing**: Inter-truck spacing (measured from the back bumper of one truck to the front bumper of the following truck) averaged over time, over all pairs of consecutive trucks in the platoon, and over all simulation runs for a chosen input target CACC distance. It is expected that the average inter-truck spacing closely approximates the target CACC distance. For a given traffic density on the highway and communication technology, we chose the target CACC distance as the minimum target distance that provides the *desired CACC performance*. The desired CACC performance is defined as “no more than one crash in 100 simulation runs”, i.e. ≤1% crash-rate. We assume that other crash mitigation mechanisms, such as emergency braking (not implemented in the simulator), would ensure crash-free performance in practical implementations. Therefore, it is not necessary to enforce 0% crash-rate performance with CACC alone, as this would result in a very conservative/long target distance.

Performance metrics for wireless communications:

- **CAM message latency**: Defined as transmitter-side latency measured from the moment a CAM arrives to the Layer-2/3 ingress point until it is broadcast. It includes channel access delay and transmission time. It is independent of the reception status at the receivers (i.e., it is always finite).
- **CAM reception rate**: Defined as a percentage of CAMs transmitted by vehicle A that are successfully received by vehicle B. The CACC controller in (2) relies on CAMs transmitted by the preceding truck and by the platoon leader. It is especially difficult to achieve high reception rate for the CAM transmitted by the platoon leader due to potentially long separation (i.e., high pathloss), especially for the trucks at the tail of the platoon. Therefore, we focus on the CAM reception rate from the leader, and we measure it at every truck behind the leader.

### 5.4 Simulation tools

The performance evaluation of C-V2X has been carried out with Nokia’s internal 3GPP system simulator, which has been used from the early days of LTE standardization and has been extended to include the C-V2X features introduced in Release 14 of the LTE standard. The performance evaluation of IEEE 802.11p has been carried out in a simulator initially developed by Poznan University of Technology (PUT) within the scope of a project funded by the National Science Centre of Poland in 2011. Since then, this tool has been extended to investigate the IEEE 802.11p PHY and MAC layer enhancements proposed in [37]-[39]. The same highway platooning scenario described in Section 5.1 has been implemented in both tools. The calibration of the tools has been performed in two steps: In the first step, the fact that both tools gave the same inter-truck spacing for the ideal communication case was verified (perfect communication channel with zero loss and zero latency). In the second step, the fact that both tools gave as output the same SNR for the radio channel parameters given in Table 2 was also verified.

### 5.5 Simulation Results

The minimum CACC target distance needed to achieve the desired “≤1% crash-rate” performance is found through incremental search: We have run 100 simulation runs for different input values of CACC target distances, starting from a very short distance of 0.2 m, which is then incrementally increased by 0.2 m every time more than 1 crash in the 100 runs was observed. The minimum CACC target distance for different communication technologies and highway traffic densities is shown in Table 3. The corresponding average inter-truck spacing, shown in the same table, is within ±10 cm of the target distance, confirming the accuracy of the CACC controller. When the traffic density increases from 0 to 20 cars/km/lane, the average spacing must be increased from 1 to 11 m if IEEE 802.11p is used for V2V communications. This drastic increase is due to the poor scaling of CSMA/CA when the channel load increases with the traffic density.

With C-V2X Mode-4, the spacing increases from 1.6 to 2.4 m, and it is significantly shorter than the corresponding spacing attained with IEEE 802.11p, except for zero traffic density, when IEEE 802.11p outperforms C-V2X Mode-4 (the reasons for this behavior are discussed below). Better scaling of C-V2X Mode 4 with traffic density is due to the channel access mechanism, which is based on SPT, unlike CSMA/CA, which is purely contention-based. C-V2X Mode-3 enables a very low average inter-truck spacing of 0.8 m irrespective of the surrounding traffic density. It outperforms both IEEE 802.11p and C-V2X Mode-4 due to centralized network-based sidelink/PC5 scheduling, which, in the single-cell scenario considered here, is contention-free.
Note that very low average inter-truck spacing shown in Table 3 may not be feasible in real-world platoon deployments since certain safety margins might have to be observed to allow timely reaction (e.g., emergency braking) to sudden hazardous events. The results obtained pertain to the specific jamming pattern shown in Fig. 3 and do not account for such events. This study aims in fact at exploring the limits of the considered wireless communications technologies.

Table 3. Average inter-truck spacing for the minimum CACC target distance that results in a crash-rate not higher than 1%.

<table>
<thead>
<tr>
<th>Traffic density (cars/km/lane)</th>
<th>IEEE 802.11p</th>
<th>3GPP C-V2X Mode-4</th>
<th>3GPP C-V2X Mode-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min. CACC</td>
<td>Avg. inter-truck</td>
<td>Min. CACC</td>
</tr>
<tr>
<td></td>
<td>target distance</td>
<td>spacing</td>
<td>target distance</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>3.4</td>
<td>3.4</td>
<td>2.0</td>
</tr>
<tr>
<td>10</td>
<td>5.4</td>
<td>5.4</td>
<td>2.4</td>
</tr>
<tr>
<td>20</td>
<td>11.0</td>
<td>10.9</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Table 4 and Fig. 5 provide insight into the performance of the different wireless communication technologies in terms of CAM latency and CAM reception rate. With IEEE 802.11p, the average CAM latency increases moderately with the traffic density, but remains well below 1 ms. The increase is due to the time the transmitter spends backing-off while waiting for the channel to be become idle. With C-V2X Mode 4, the average CAM latency is close to 8 ms, and it is relatively independent of the traffic density. Since a transmission resource is selected from a 20 TTIs long selection window, an average latency of 10 ms is to be expected. However, a transmitter can be configured with up to two SPT processes, out of which the one that provides lower latency is used. This helps to bring the latency below 10 ms, as shown in Table 4.

With C-V2X Mode-3, the average CAM latency is close to 7 ms for all considered traffic densities, and its variance is much lower than in Mode 4. The latency is mainly due to the time it takes to obtain a sidelink/PC5 resource grant from the eNodeB and to generate the corresponding transmission, which takes in total 5 ms. The assumption is that the eNodeB is aware of the 100 ms periodicity of the CAM message, and it pre-emptively sends the grant just-in-time when the CAMs arrive to the transmission interface, leading to lower latency. The results in Table 3 and Table 4 indicate that CAM latency does not have a critical influence on CACC performance: even though IEEE 802.11p provides the shortest latency, it in fact requires the longest inter-truck spacing to meet the desired CACC performance. The inter-truck spacing is in fact strongly influenced by CAM reliability, as discussed below, for which IEEE 802.11p proves to have the worst performance.

Table 4. Latency of CAMs generated by platooned trucks: mean, 5th percentile, 50th percentile, and 95th percentile (in milliseconds).

<table>
<thead>
<tr>
<th>Traffic density (cars/km/lane)</th>
<th>IEEE 802.11p</th>
<th>3GPP C-V2X Mode-4</th>
<th>3GPP C-V2X Mode-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean 5% 50% 95%</td>
<td>mean 5% 50% 95%</td>
<td>mean 5% 50% 95%</td>
</tr>
<tr>
<td>0</td>
<td>0.23 0.06 0.17 0.31</td>
<td>7.87 1.94 6.79 16.44</td>
<td>6.79 6.72 6.79 6.85</td>
</tr>
<tr>
<td>5</td>
<td>0.26 0.06 0.18 0.62</td>
<td>7.97 1.94 6.77 16.71</td>
<td>6.80 6.73 6.83 6.95</td>
</tr>
<tr>
<td>10</td>
<td>0.30 0.06 0.19 0.74</td>
<td>8.11 1.93 6.52 16.67</td>
<td>6.85 6.73 6.87 7.21</td>
</tr>
<tr>
<td>20</td>
<td>0.40 0.06 0.22 1.09</td>
<td>7.53 1.92 6.09 16.57</td>
<td>7.12 6.73 6.90 8.46</td>
</tr>
</tbody>
</table>

The reception rate for CAMs transmitted by the platoon leader to the rest of the trucks in the platoon is shown in Fig. 5. The number on the x-axis denotes the position of the truck inside the platoon that is receiving the CAMs from the leader, i.e. number “1” would denote the platoon leader, number “2” denotes the truck that is immediately behind the platoon leader, and so on. With IEEE 802.11p, the reception rate drops significantly with the highway traffic density, due to the increasing number of collisions caused by the well-known hidden node problem of CSMA/CA [37], where two vehicles that are out of each other’s sensing range simultaneously send a message targeted to a neighbouring vehicle that is within the transmission range of both. The reception rate for the last truck in the platoon drops below 85% for 20 cars/km/lane.

The performance of C-V2X Mode 4 is also affected by packet collisions, but to a lesser extent than IEEE 802.11p. There are two types of collisions in C-V2X Mode 4: resource-reselection collisions and persistent collisions. The resource re-
Selection collisions in C-V2X Mode 4 typically occur when two or more vehicles re-select their transmission resources within a brief period of time, i.e., within the length of the selection window (20 TTIs in this case). Those vehicles may select the same resource as there is no sensing history based on which they can learn about each other’s choices, which results in the collisions. This is why the CAM reception rate of Mode-4 for density 0 cars/km/lane is lower than the reception rate of IEEE 802.11p, and the resulting average inter-truck spacing is larger (1.6 m vs. 1.0 m). It is therefore beneficial not to re-select the resources too often, i.e., the resource re-selection counter for SPT should be initialized to a sufficiently large number. 3GPP specifies that it shall be drawn randomly from [5,15]. However, a very large re-selection counter leads to the persistent collisions problem: two vehicles that are currently outside of each other’s sensing range and are using the same transmission resource (e.g., approaching each other from opposite directions) will start colliding once they are nearby. Due to the half-duplex constraint, those collisions will persist until the re-selection is triggered at one of the vehicles. Hence, it is important to choose a re-selection counter that balances these two effects. This study shows that the “persistent collisions” have an even more adverse effect on platoon performance than the collisions caused by frequent resource re-selection. Therefore, the resource re-selection counter has been set to a lower value than the one specified by 3GPP to minimize the effect of persistent collisions, as shown in Table 2. Optimization of the resource re-selection counter remains an open issue for Mode-4.

With C-V2X Mode-3, sidelink/PC5 resource scheduling is done centrally at eNodeB. Since all the vehicles in the simulation are associated with the same eNodeB, the collisions are avoided even for the highest considered vehicle density. Since all trucks are sufficiently close to each other (i.e., link budget is good due to low pathloss) and scheduling is collision-free, the reception rate is equal to one irrespective of the traffic density, as seen in Fig. 5 (bottom). However, at extremely high vehicle densities (not simulated), higher MCS orders are required in order to divide the available spectrum into more than $k=2$ sub-channels to accommodate the increased traffic load (Fig. 4). Higher MCS orders are less robust to fading and path loss than QPSK with $R = 1/2$ used in our simulations and, therefore, it may not be possible to decode received CAMs. Congestion control mechanisms (e.g., transmission power adaptation) would then be needed at such extreme high vehicle densities to ensure reliable message delivery.

In addition to the CAMs transmitted by the platoon leader, the CACC algorithm in (2) relies on the CAMs transmitted by the preceding truck. For both 802.11p and C-V2X Mode-4, the average CAM reception rate from the preceding truck is close to 100% for the traffic density of 0 cars/km/lane, and it decreases close to 97% for the traffic density of 20 cars/km/lane. For C-V2X Mode-3, the CAM reception rate from the preceding truck is 100% regardless of the traffic density. We omit the plots for brevity.

While our simulations assume a platoon of ten trucks, the performance of shorter platoons can be inferred from the presented results since trucks at the back of the platoon do not affect the performance of trucks in-front. Fig. 5 shows that the gains of C-V2X Mode-3/4 over IEEE 802.11p in terms of CAM reception rate are smaller for the trucks closer to the platoon leader. For short platoons (e.g., of up to five trucks) and a traffic density of 20 cars/km/lane, the improvement of C-V2X Mode-4 over IEEE 802.11p is marginal. Longer platoons may benefit from C-V2X Mode-4 not only due to the lower collision probability compared to IEEE 802.11p, but also due to the better link budget and hence lower block error rate (BLER) for the same SNR, as shown in [14].
Figure 5. Reception rate for CAMs transmitted by the platoon leader in case of IEEE 802.11p (top), C-V2X Mode-4 (centre), and C-V2X Mode-3 (bottom) communication.
5.6 Future work

This section aims at providing inspiration for future work that can build on the findings of this paper.

Since a homogeneous platoon in a steady state has been considered, an immediate extension to this work would be to assume a non-homogeneous platoon where not all trucks have the same acceleration/deceleration capabilities due to, e.g., different trailer loads. This will in fact represent a more realistic scenario where trucks can dynamically join and leave a platoon at any point during their journeys (e.g., either before or after delivery of goods). Moreover, time-varying traffic densities, which may be higher than the highest density considered in this study (20 cars/km/lane), and non-periodic jamming patterns might be more adequate for representing real-life road conditions, where the platoon will encounter areas of high or low congestion according to random patterns in space and time. In such scenarios, mechanisms such as decentralised congestion control (DCC) is needed to adapt the link parameters (e.g., MCS scheme, transmission power) to the channel congestion level. In addition, the CACC algorithm may call for potential extensions to its baseline capabilities in order to handle congested highway scenarios with stop-and-go type of traffic.

For the purpose of this study, a 1% crash rate has been used as a criterion to converge to a value for the achievable inter-truck distance. However, different criteria could of course be adopted, especially if favored by truck manufacturers, and it would be interesting to investigate how the minimum CACC target distance and average inter-truck spacing of IEEE 802.11p and C-V2X change as a function of different service-level targets. In addition, taking into account the interplay between CACC and other control algorithms, such as an Advanced Emergency Braking System, in order to, for example, address the cases of very rapid and abrupt changes in speed due to emergency situations, will also have an effect on achievable inter-truck distance and link-level performance requirements for the wireless technologies. Quantifying how all these elements play a role in this scenario is indeed an interesting avenue for future research.

From the network deployment point of view, this study is focussed on a single-cell scenario, where C-V2X Mode 3 performance is evaluated in a situation where the radio resources are assigned and managed by a single entity. An obvious extension to this study would be to consider a situation where not all vehicles are associated with the same eNodeB and, therefore, there is not a single central coordination entity that allocates sidelink/PC5 radio resources. Requirements for a certain degree of inter-eNodeB coordination could then be outlined as a consequence of this extended study.

6 Conclusion

The IEEE 802.11p standard is a mature vehicular networking technology whose suitability for “day-one” V2X applications (e.g., safety use cases such as emergency electronic brake lights, left turn assist, intersection movement assist, etc.) has been tested in field-trials on many occasions. The 3GPP cellular technology that was traditionally used for mobile broadband services is now evolving to cover a much broader set of applications, with V2X being one of the key drivers. We have shown that the recently standardized 3GPP C-V2X can provide superior performance with respect to IEEE 802.11p for emerging beyond day-one applications, with particular focus on truck platooning. C-V2X Mode 3 greatly improves reliability compared to IEEE 802.11p due to centralized radio resource scheduling for the sidelink/PC5, which enables smaller inter-truck gaps that translate into higher traffic efficiency and safety. The C-V2X Mode 4, which can be deployed without network infrastructure support, may outperform IEEE 802.11p for periodic traffic due to semi-persistent resource scheduling, but resource re-selection triggers must be carefully tuned to avoid persistent collisions. Therefore, C-V2X with the combination of Mode 3 in areas covered by LTE infrastructure and Mode 4 in areas outside of the coverage is better suited for truck platooning than IEEE 802.11p from the platoon density angle. There are other angles that speak in favour of C-V2X technology: while the evolution path of IEEE 802.11p is unclear, C-V2X will be further evolved in the upcoming releases of the 3GPP standard, with a clear roadmap towards 5G-based C-V2X, which will complement LTE-based C-V2X to provide ultra-high reliability and ultra-low latency performance required by the most demanding V2X applications. In March 2017, 3GPP approved a work item [41] on C-V2X evolution (labelled as “3GPP V2X Phase 2”) for advanced V2X services categorized into four use case groups: advanced vehicle platooning, extended sensors, advanced driving, and remote driving [42]. The work item is expected to end by June 2018. Other considerations that will affect the choice of the communications technology for the commercial deployment of platooning, such as the deployment cost, spectrum, and regulatory aspects, are discussed in the white papers published by
the 5G Automotive Association (5GAA) [43], [44]. Several authors of this work are members of 5GAA and their views are reflected in those white papers.

References


