Performance evaluation of C-ACC/platooning under ITS-G5 communications

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Abstract

Intelligent Transport Systems (ITS) are aiming to provide innovative services related to different modes of transport and traffic management, and enable various users to be better informed and make safer, more coordinated and smarter use of transport networks. Cooperative-ITS (C-ITS) support connectivity between vehicles, vehicles and roadside infrastructure, traffic signals as well as with other road users. In order to enable vehicular communications European Telecommunication Standards Institute (ETSI) delivered ITS-G5 – a of set of C-ITS standards. Considering the goals of C-ITS, inter-vehicle communications should be reliable and efficient.

In this thesis we study the performance, efficiency, and dependability of ITS-G5 communications for Cooperative adaptive cruise control (C-ACC) and platooning C-ITS applications. We provide an overview of currently available and ongoing standardization targeting communications in C-ACC/platooning. We study the performance of ITS-G5 beaconing in a C-ACC/platooning scenario, where we show that its performance may deteriorate when implemented in cooperative driving applications due to the kinematic-dependent design of the message triggering mechanism. We explain in detail the cause of this phenomenon and test it for a wide range of parameters. Also, we study the influence of different available ITS-G5 legitimate setups on the C-ACC/platooning fuel efficiency and demonstrate that proper communication setup may enhance fuel savings. This thesis also proposes a jamming denial-of-service attack detection algorithm for platooning. The main advantage of our detector is its short learning phase that not exceed a second and low detection delay of a few hundreds of milliseconds. Under some assumptions, the proposed algorithm demonstrates the ability to detect certain types of attacks with average probability above 0.9.
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This thesis is a result of two years of my studies at Halmstad University at the School of Information Technology within the Computer Communication group.

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Chapter 1
Introduction

1.1 Motivation

Road users’ awareness of each other is supposed to become the basis for a number of road safety and traffic efficiency applications [4]. It is achieved by regular exchange of information among vehicles (V2V, in general all kind of road users) and between vehicles and road side infrastructure (V2I and I2V). This communication exchange is enabled by the means of Vehicular Ad-Hoc Networks (VANETs). ETSI defines the cooperative awareness within road traffic as when road users and roadside infrastructure are informed about each other’s position, dynamics and attributes. Road users in this context are all kind of road vehicles like cars, trucks, motorcycles, bicycles or even pedestrians, and roadside infrastructure equipment [8].

Cooperative adaptive cruise control (C-ACC) and platooning are two emerging automotive ITS applications. In this thesis, we will refer to that class of automotive systems as C-ACC/platooning. In C-ACC/platooning the leading vehicle is driven by a human, while the following vehicles automatically maintain the velocity of the leading one, but their directions are still controlled by the drivers. Platooning is aiming to reduce the air-drag in the caravan of heavy-duty vehicles, which could significantly benefit from the fuel consumption point of view, while C-ACC is mostly oriented towards increasing the driving experience enabling comfort semi-autonomous driving [38]. The cooperation between the vehicles in the C-ACC/platooning is achieved by the frequent exchange of periodic broadcast messages, which we refer to as beacons. Beacons may contain various related information like vehicle’s ID, kinematic information of a vehicle, such as its current speed, position, direction, etc.

To enable inter-vehicle communications in the Dedicated Short Range Communications (DSRC) 5.9 GHz band, IEEE 802.11p, which is currently integrated into the recent IEEE 802.11-2012 standard, has been introduced by Institute of Electrical and Electronics Engineers (IEEE). IEEE 802.11p provides the medium access control (MAC) and physical (PHY) layers for wireless
communications in a vehicular environment. The IEEE 1609 working group has defined the protocol stack IEEE 1609.x, also known as WAVE (Wireless Access in Vehicular Environment). The scope of these standards is the extension of the IEEE 802.11p MAC layer functions for multi-channel operation as well as the specification of the upper layers, functionality in security and management planes.

At the same time, European Telecommunication Standard Institute (ETSI) delivered the first release of the C-ITS standards under European Commission Mandate M/453. ETSI specified the first set of ITS-G5 communication protocols and architecture regulating operation in the 5 GHz spectrum for C-ITS. ITS-G5 reuses the IEEE 802.11p PHY and MAC layers of the IEEE 1609 framework.

Considering the goals of C-ITS, inter-vehicle communications should be reliable and efficient. Obviously, C-ITS communications became a field of intensive research activities. However, there are still a lot of open issues and white spots in the field of assessing the performance of C-ITS protocols and approaches. The goal of this licentiate thesis is to study the performance, efficiency, and dependability of ITS-G5 vehicular communications.

1.2 Problem statement

Reliable real-time beacon delivery is crucial for the operation of C-ACC and platooning applications in order to support its efficiency, safety and reliability. The beacon delivery might be poor due to the congested vehicular communication channel, improper design of communication protocols or even become a target for different malicious intrusions, Figure 1.1. Thus, we identify three main research areas targeting the aforementioned: studying the performance of ITS-G5 beaconing protocols; studying the performance of ITS-G5 congestion control mechanisms; and studying the sources of Denial-of-Service (DoS) attacks, corresponding DoS attacks detection methods and countermeasures.

In the ITS-G5 framework ETSI defines the Cooperative Awareness Message (CAM) to support beaconing. It is worth noting, that Cooperative Awareness basic service is mandatory for all kind of ITS-stations (ITS-S) operating in ITS-G5 [8]. In order to support C-ACC/platooning CAM should demonstrate performance that is sufficient to enable coordination among its member vehicles. Thus, the assessment of CAM performance in C-ACC/platooning is of high importance.

Decentralized Congestion Control (DCC) is also a mandatory component of ITS-G5 stations operating in the ITS-G5 band [5] and will accordingly affect the communication exchange of CAMs in C-ACC/platooning. Despite the main objective of DCC to control channel occupancy and support fair access for all the ITS-S, improper DCC configuration may have a negative influence on the C-ACC/platooning efficiency and stability.
Vehicular networks will become a basis for a number of safety and time-critical applications. It is obvious, that even a short period of communication loss in a C-ACC/platooning beaconing exchange may be crucial for its stability and safety. Current end-to-end latency requirement for a road hazard signaling application is 300 ms, which may be further reduced for C-ACC/platooning applications [38]. DoS attacks on the communication channel may disrupt the communication significantly. It is worth considering also, that various types of DoS attacks could be rather intelligent and not easy to detect. Thus, there is a strong demand in methods to detect DoS attacks in cooperative driving applications and in appropriate countermeasures.

The main goal of my research is to provide reliable and secure Vehicle-to-vehicle (V2V) delivery of beacons. This can be further broken into three following problems:
1. What is the performance of the currently issued ITS-G5 beaconing approach and its applicability to support C-ACC/platooning vehicular applications?

2. What is the performance of the ITS-G5 decentralized congestion control mechanisms when applied to C-ACC/platooning scenarios?

3. What methods could be applied to detect DoS attacks in cooperative driving applications and what corresponding countermeasures could be designed?

1.3 Methodology

In scope of VANETs and, especially, C-CACC/platooning systems the real-world measurements and testbeds become highly expensive and are possible only after a thorough simulation study. To study the IEEE 802.11p wireless communications standard there are several well-known established network simulators can be utilized. Two examples are: Network Simulator 3 [1], OMNeT++ [2]. Also, depending on the research goal, self-written simulators that can be utilized. Simulation studies of wireless communications allow to assess the performance of various communication technologies, standards and protocols in a controlled environment/setup. Based on the simulation result conclusions on the effectiveness, reliability and how various parameters affect the communication performance can be done. However, due to the specific properties of VANETs, its complex behavior and extremely high mobility, simulation platforms that combine mobility and communications are necessary. Moreover, in case of the C-ACC/platooning systems, the simulator should be able to support cooperation between vehicles in real-time, relying on the data exchange via wireless communications. Veins [37] and VSimRTI [3] are two widely-used platforms that allow to model V2V and V2X communications and to some extent provide the implementation of WAVE and the C-ITS protocol stack. However, necessary for C-ACC/platooning simulation, real-time interaction with the vehicles’ control system is not implemented in these frameworks.

In C-ACC/platooning the design of most communication mechanisms and protocols is based on the information on dynamics of the originating ITS-S, which make it unrealistically to model communication and mobility parts separately. In order to model C-ACC/platooning systems realistically there are several systems that should be coupled: communication simulator, mobility simulator and control system simulator. To the best of our knowledge, there is only one simulation framework that provides all of the aforementioned functionalities, Plexe. Plexe is an C-ACC/platooning extension for the Veins simulator [36]. Plexe allows to model and measure the communication performance of automotive driving systems enabled by inter-vehicle communications closely coupled with the control system of the vehicle. The Plexe simulator provides a detailed implementation of the two bottom ITS-G5 MAC and PHY layers. To
better comply with ITS-G5 we also implement ETSI DCC and CAM. Thus, in our framework we closely follow the ITS-G5 framework coupled with the vehicle dynamics. However, so far Plexe uses a simple path-loss channel model to simulate signal propagation, which could be seen as a potential source of channel condition overestimation. In scope of this thesis we use extensive realistic simulations using both a self-written detailed simulator and Plexe, and through analytical models.

1.4 Contributions

Contributions of this thesis are directly related to the three problems we are focusing on, Figure 1.2. Paper I is related to all the research problems, providing a study of the C-ACC/platooning standards and requirements. Paper II studies beaconing in platooning, while Paper III covers both beaconing and congestion control. Finally, Paper IV treats the problem of jamming DoS in C-ACC/platooning.

![Figure 1.2: Overview of papers](image)

Paper I [38] is a tutorial article explaining the principles of C-ACC and platooning, describing related ongoing ITS-G5 standardization activities, and presenting performance evaluation of the underlying communication technology.

In Paper II [30] the communication performance of the ETSI EN 302 637-2 CAM [8] (Cooperative Awareness Message) beaconing in the C-ACC/platooning scenario is studied. Paper II is related to the first research problem (see Fig-
In this study we have discovered that the improper choice of the sampling rate value may increase the number of collisions between CAMs at the IEEE 802.11p medium access control layer and, therefore, diminish the efficiency of beaconing in a platoon. The paper gives an explanation of the specifics in the CAM triggering mechanism design that leads to a grouping of CAMs that, as a consequence, causes degradation in the communication performance.

In Paper III we take an attempt to evaluate the performance of platoons enabled by ITS-G5 vehicular communications through a number of simulation experiments. We assess the influence of different ITS-G5 communication setups on C-ACC/platoon fuel efficiency. ETSI Decentralized Congestion Control is an essential part of the ITS-G5 protocol stack. In our study we show that the choice of ETSI DCC setup may directly influence the platooning efficiency. This study is related to both problem one and two, Figure 1.1.

In Paper IV [31] we study jamming attacks in VANETs with focus on the platooning scenario. The paper treats the third research problem, Figure 1.1. Paper IV proposes a simple algorithm for real-time detection of jamming attacks against beaconing in IEEE 802.11p vehicular networks. The proposed algorithm is able to detect unlikely loss of beacons in the platooning communication exchange in real time after a short training period.

1.5 Organization of Thesis

The rest of the thesis is organized as follows. Background material and literature review are presented in Chapter 2. Chapter 3 overviews the Papers I-IV. Chapter 4 discusses future studies and concludes the thesis.
Chapter 2
Background and Related Works

The section is organized in accordance with the three main research problems, divided into corresponding subsections.

2.1 State-of-the-art beaconing approaches

To support cooperative awareness within ITS-G5, ETSI delivered EN 302 637-2, the standard defining Cooperative Awareness Messages (CAMs) [8]. Note, that Cooperative Awareness basic service is mandatory for all kinds of ITS-stations (ITS-S) operating in ITS-G5. Each ITS-S puts kinematic and other related data into periodically sent CAMs. The content of the message may vary depending on type of the ITS-S. In this thesis we focus on the cooperative awareness on the road and a vehicles as an ITS-S. The standard defines a kinematically-driven mechanism to trigger CAMs. This means, that each vehicle generates a new CAM depending on its current position, speed and direction. The vehicle compares its current kinematic measurements with the ones it put into the last generated message and, if the difference between one of them is above some specified threshold, the vehicle has to trigger next CAM. The reasoning behind that is to allow the vehicle to trigger more messages when its behaviour is highly dynamic and vice versa. In other words, the vehicle will transmit less messages when its behaviour is predictable and more messages, when accelerating/decelerating, turning or driving at high speed. However, as a consequence, the ETSI CAM protocol has a behaviour that is much more difficult to analyse in comparison to a traditional beaconing approaches that have a fixed frequency for the message generation process.

In [27] Liu showed that even small information delays in a platoon may lead to its string instability. Information delay in this context is a time between two subsequent inputs into the controller, which is directly related to the time between two subsequent received beacons from the same vehicle. Traditionally, the operation of a C-ACC/platoon control algorithms is considered either under assumption of a TDMA-like slotted beaconing [22] or CSMA/CA having a
fixed beaconing rate [12, 17]. However, ETSI CAMs have much more complex and unpredictable behaviour, which make it difficult to analyse and predict actual informational delay to design an appropriate controller. Moreover, the standard contains a number of parameters with non-specified values, that also need to be tested.

Many studies applying CAMs are either not considering kinematic rules [17, 24, 23] at all or implement CAM according to the standard, but are testing their content structure applicability and not the performance of the mechanism itself. There are very few studies focusing on assessing the effectiveness of the rules proposed by ETSI for CAM generation. The performance evaluation of CAM beaconing under various parameters set has been studied in [25, 21, 35, 16]. In [19], the authors evaluate the CAM rules to understand the actual beaconing rate and corresponding channel load in a highway scenario. In [28], the authors present more the detailed study of the CAM kinematic rules. This paper attempts to find optimal parameters’ thresholds to enhance the network performance in terms of packet delivery ratio (PDR), channel load and message age. In [14] the applicability of ETSI EN 302 637-2 CAM to support platooning was studied. The main conclusion was that CAM may support cooperative autonomous driving, while having gaps at application functionality: support of platooning merging/disaggregation, and most important the lack of appropriate authentication mechanism that can be used for secure platooning aggregation. The study concludes that improvements of the CAM data structure are necessary.

The authors of [15] present results of an extensive measurement study estimating the performance of CAM cooperative awareness in terms of neighborhood awareness ratio and packet delivery rate. The paper provides substantial results on CAM ability to support awareness at certain level depending on different factors (environment, transmission power level, beaconing generation frequency, etc.). However, the study discuss the results in terms of averaged performance metrics and does not focus on the CAM generation mechanism’s functioning itself.

In [29, 30] a side effect of CAM synchronization in a platooning scenario was discovered, it was shown that in a string of vehicles under synchronous acceleration/deceleration maneuvers CAM generation times may synchronize, which lead to an increase in CAM collision rate. Current manuscript studies the side effect under typical mobility patterns of cooperative and semi-autonomous systems under various set of CAM parameters. We make conclusion on the strength of the effect under various conditions and give recommendations on how to possibly avoid it.

2.2 Decentralized congestion control mechanisms

Considering the number of stations in a VANET and limited frequency resources, congestion control (CC) mechanisms are necessary. Since a VANET is
an ad-hoc network and does not have a centralised infrastructure, the operation of the CC mechanism should be performed by each vehicle independently from each ITS-S. To cope with these requirements ETSI issued technical specifications defining a decentralized congestion control (DCC) mechanism [9, 7, 5]. Each ITS-S will perform the DCC algorithm independently from the other stations (which makes it fully distributed and decentralized), but since its operation relies on the measured channel load, neighboring vehicles are supposed to have a fair access to the channel resources. Note that in EU, DCC will be a mandatory component of all stations operating in ITS-G5 5.9 GHz frequency band to maintain network stability, throughput efficiency and fair resource allocation, which makes this mechanism a component of key importance.

DCC operates as the gatekeeper on the access layer. DCC is based on the state-transition automate which, by default, switches between three states: Relax, Active and Restrictive. The choice of the current DCC state is performed based on the measurements of Channel Busy Ratio (CBR). Each ITS-S periodically takes the channel probes and counts the average CBR during the measuring interval, which is typically equal to 1 s. Each transition in the state machine has an appropriate CBR value as threshold. In each state of the DCC the restrictions on the ITS-S’s transmission parameters are defined. DCC considers five mechanisms to control the vehicle’s channel access: "Transmit Power Control" (TPC), "Transmit Rate Control" (TRC), "Transmit Datarate Control" (TDC), "DCC Sensitivity Control" (DSC) and "Transmit Access Control" (TAC).

Note, that the standard also allows the DCC state-machine’s configuration containing a set of sub-states in the Active state [9, 7]. Implementing this approach may allow to achieve finer granularity and control over sharp changes in DCC behavior when state transition occurs. The transitions among states are meshed, i.e. transitions are possible between any two states and depend only on the channel busy measurements history. Thus, DCC-configurations with reasonable number of sub-states may help to avoid rapid changes in ITS-station behavior keeping the targeted level of CBR. The performance of different DCC configurations has, according to our knowledge, not been studied in the literature. Depending on the application and environment, the optimal configuration for DCC could also vary. In scope of our studies we are aiming to identify and evaluate the DCC configuration, that will be optimal for C-ACC/platooning application.

The design of the DCC assumes that it may react sharply (that was partly shown in [26]) on the changes in the channel busy ratio. It is shown that basic DCC configuration with three states may introduce unfairness in the resource distribution among ITS-Ss. This is caused by the significant differences in the restrictions different DCC states imply on the behavior of an ITS-S. Presented observations arise from the fact that basic DCC does not support smooth transition of TRC thresholds between states.
According to [5], ETSI DCC will be the mechanism that each ITS-S should follow. Despite the importance of the DCC, there has been done quite few studies on its performance. The authors of [13] present the performance evaluation of the DCC under various levels of channel load. The authors also determine the impact of different parameters that are affected by DCC operation on overall VANET performance. Based on the simulation results, the paper provides discussion on the effectiveness of ETSI DCC from the communication and application point of view.

In [26] the performance of ETSI DCC in dense environment, where the number of vehicles in the same communication range is relatively high, was studied. The simulations show that since DCC is decentralized (each vehicle performs algorithm independently without any coordination) an ITS-S may experience unfairness in terms of channel access. The reason for that is a situation when two neighboring vehicles (that are in the same communication range) are placed in different states of the DCC state-machine.

### 2.3 Denial-of-service attacks detection approaches

Since the IEEE 802.11p medium access control (MAC) protocol specifies random access, during its normal operation the beacons can be lost either due to the wireless channel impairments or due to collisions (overlapping transmissions of beacons from several vehicles). The probability of collisions can be reduced by the proper choice of the MAC protocol parameters [20]. However, the beacons can also be intentionally corrupted by malicious node in case of a jamming Denial of Service (DoS) attack [32]. To support safety applications in a vehicular environment with extremely high mobility of the wireless nodes, inter-vehicular communications should provide a relatively high level of reliability. Various types of DoS attacks could significantly compromise the reliability of the communications. Obviously, DoS attacks may have different types/sources of intrusion. The most relevant types of DoS attacks for vehicular environments are summarized in [11] (a short summary is given later in this section). In scope of this study we focus on radio jamming attacks. A jamming DoS attack it is usually defined as the situation when a malicious node (hereafter, jammer) emits according to some jamming strategy aiming to disrupt the exchange of messages over the communication channel. The jammer can damage certain messages/parts of the messages or jam the communication channel completely depending on its own goals and strategy [32]. It was experimentally shown in [34], that jamming may have significant influence on the stability of the communications in vehicular environments.

According to TS 101 559 – 1 (RHS) [6], the end to end latency of CAM should be less than 300 ms for a road hazard signalling application. In the presence of a jamming node, the loss of a few subsequent beacons will lead to the failure of the requirements. For platooning and C-ACC applications, this end to end latency requirement may be further reduced. Thus, to reduce
the air-drag in the platoon of heavy-duty vehicles (which would significantly reduce the fuel consumption), the inter-vehicle gap in the platoon should be in the order of several meters [10]. This means that the reaction time of the vehicles in the platoon will be very tight and interruption in the beacons’ exchange might compromise security of the automotive systems and endanger the safety of road traffic.

In [34], the influence of the jamming on the platoon was studied. The authors present the outcomes from an outdoor experiment in the presence of constant, periodic and reactive jammers. The results show that the presence of a jammer may drastically decrease PDR, which could potentially significantly compromise the reliability and security of the C-ACC/platooning system.

In [11] the authors consider various types of potential scenarios when communications between autonomous vehicles participating in C-ACC/platooning are compromised. Throughout the paper they classify possible security attacks on a C-ACC/platooning vehicle stream by the influence on different levels of the communication stack:

- Application layer attacks are oriented to disrupt the functionality of applications, like C-ACC/platoon beaconing exchange or the management protocol. The adversary can use message falsification (modification), spoofing (masquerading), or replay attacks to maliciously affect the vehicle stream. In the case of a message falsification attack the adversary starts listening to the wireless medium and, upon receiving each beacon, manipulates the content meaningfully and rebroadcasts it. Spoofing assumes that the adversary impersonates another vehicle in the C-ACC/platoon stream in order to inject fraudulent information into a specific vehicle. During replay attacks the adversary receives and stores a beacon sent by a member of the C-ACC/platoon stream and tries to replay it at a later time with malicious intent – the replayed beacon contains old information, which can lead to hazardous effects.

- Network layer attacks have a focus to affect not a particular application, but multiple applications by violating the TCP/IP stack operation. Examples of network layer attacks could be various denial-of-service (DoS) or distributed DoS (DDoS), like radio jamming on the control channel (CCH) [31]. Another possible example is enormous number of messages emitted on the CCH by the adversary, which cause an enormous number of CPU-intensive operations (due to the complexity of cryptographic operations). That kind of attacks may make CACC/platoon members unable to support proper communications in a vehicle stream.

- System level attacks are characterized as a tempering with vehicle hardware or software, which can be performed by a malicious insider at the manufacturing level or by a malicious outsider. In that case even if V2V communication is stable and secure, tampered hardware/software can
provide wrong/incorrect information to the vehicle itself or to another CACC/platoon member via communication facilities.

- Privacy leakage attacks. Due to the periodic beaconing exchange in the C-ACC/platoon systems there is a possibility for an intruder for eavesdropping. Each message may contain various information about the originating vehicle and the C-ACC/platoon system in general (vehicle ID, speed, position, acceleration and others), which could be further potentially used by the malicious node for its own benefits.

The authors also present simulation results showing the stability of the C-ACC/platooning system under message falsification and network layer DoS attacks through the set of simulations. In both cases C-ACC/platooning experiences significant downgrade in the performance from the longitudinal stability (inter-vehicle gap), which shows the actuality of the attacks on security in that type of systems.

In [33] a jamming-detection method based on machine learning algorithms is presented. The authors propose to use the following metrics:

- channel busy ratio;
- channel noise;
- inactive time;
- packet delivery ratio.

The proposed method is splitted into 2 phases: training and detection. During the training phase, a number of training sequences are obtained under controlled experiments that should be performed both with and without the presence of the jamming node. This result could then be used to construct a Random Forest [18] classifier that later can be used as a classifier in the detection phase. The authors tested the performance of the detector in the presence of constant and reactive jammers. Experiments showed a detector accuracy of over 90%. The main drawback of the proposed method is its high dependency on the training sequences. All the metrics that have been used for decision tree construction are highly dependent on the current VANET conditions, which are constantly influenced by high dynamics. That fact makes offline training of the proposed system almost an impossible task. Although, the authors do not posses their method as an real-time solution. If the considered VANET has a relatively static behaviour like platoon/C-ACC, the detector can be trained offline, and the proposed method may have potential application in the scope of such type of systems.
Chapter 3
Summary of Appended Papers

The section presents a summary of the appended papers. In Paper I we provide an overview of the current ETSI ITS-G5 standardization activities aiming to support CACC/platooning, while Paper II-IV are related to the research problems 1-3 accordingly, as illustrated in Figure 1.2.

3.1 Paper I

ITS-G5 defines the overall vehicular communication protocol stack. So far there has been no dedicated message type or DCC configuration standardized for platooning. However, there is currently pre-standardization activity (ETSI TR 103 301, TR 103 299) studying how to apply currently available standards for a platooning application. In Paper I we give a brief description of C-ACC and platooning, also depicting major differences between these applications. In compliance with the idea of using current standards in order to enable CACC/platooning operation, Paper I provides results of a simulation study. In this study communication exchange in platooning is enabled by currently available ETSI EN 302 637-2 CAM. In scope of the simulation setup we tested both CAM kinematically driven message triggering and a fixed beaconing rate of 10 Hz. To estimate the information delay, data-age metrics has been used as a performance metrics. Based on the results, the paper concludes that fixed beaconing with a proper message generation frequency outperforms CAMs in terms of data-age. Our conclusion is that the current CAM rates could be insufficient to support platooning requirements. Moreover, due to the dynamic-dependent nature of CAM generation, the data-age may vary significantly depending on the mobility pattern of the platoon. It is worth to be noted here, that DCC operation was disabled in scope of this study, so the results could be generalized and extended to a system supporting both CAM and DCC.
3.2 Paper II

In this paper we evaluate the performance of ETSI EN 302 637-2 CAM in the platooning scenario. CAM triggering conditions [8] are based on the dynamics of an originating vehicle. These conditions are checked repeatedly with a certain sampling rate. An ITS-S generates CAM whenever the kinematic event occurs, with an upper bound of 10 messages/second (10 Hz). If no kinematic event is observed for 1 second after the last CAM generation, the ITS-S should also generate a message, which corresponds to a lower bound of 1 message/second (1 Hz). By kinematic event it is meant here that the ITS-S tracks its current speed, position and direction and compares them to the values sent in the last triggered CAM. If the differences exceeded any of the pre-defined thresholds, a kinematic event is detected and a CAM is generated. In the scope of the study we consider a platoon, following disturbance mobility pattern, where information exchange is enabled by CAM. Disturbance mobility pattern is when a vehicle (platoon) performs acceleration/deceleration maneuvers, which is aiming to emulate a slower vehicle in front. The slower vehicle may appear due to a lane changing process (e.g. the vehicle is trying to take off-ramp) or it could be considered as a vehicle coming from metering ramp, etc. Our simulation setup shows, that due to the design of kinematic rules, CAM triggering times of different platoon members may become synchronized in time domain after subsequent maneuvers. We show that the CAM synchronization effect may further lead to increased CAM collision rate on the wireless channel and subsequent communication performance degradation. The paper describes the mechanism leading to the occurrence of the negative CAM synchronization effect, and proposes a framework allowing to analyze the strength of the effect. Also we study the influence of various CAM sampling rates on the communication performance and make appropriate conclusions.

3.3 Paper III

In this paper we make an attempt to estimate the potential influence of the communication system on the efficiency of the platooning. V2V communications, stability and fuel efficiency in a platoon are closely coupled. Proper communication setup can make a platoon follower maintain a desired distance to its predecessor while reducing acceleration and braking frequencies. We evaluated the performance of C-ACC/platoon enabled by ITS-G5 communication standards through a number of simulation experiments. As it was noted in Paper I there are no dedicated communication standard for platooning available, however current ETSI standardization activities are focused around applicability of the existing ITS-G5 set to enable platooning. In conformity with aforementioned, in Paper III we implement and apply ETSI EN 302 637-2 Cooperative Awareness Messages [8] together with DCC to confirm to the ITS-G5 stack. Note, that according to [5]: "Decentralized congestion control
(DCC) is a mandatory component of ITS-G5 stations operating in ITS-G5A and ITS-G5B frequency bands to maintain network stability, throughput efficiency and fair resource allocation to ITS-G5 stations”. In Chapter 2 it was described that there are several DCC state-machine configurations currently available in the documents. Thus, we compared the potential fuel consumption reduction, when platooning is enabled by two different DCC setups available in ITS-G5. To be able to test influence of ITS-G5 on potential fuel savings, the simulation framework that incorporates a communication simulator with a mobility simulator and uses communication as an input to a platooning control part. To cope with this requirements we use a Plexe simulator that is a special C-ACC/platooning extension of Veins, that combines Omnet++ and SUMO, extending it with CAM and DCC functionality to comply with ITS-G5. Our study shows that the communication setup that exploits DCC with more sub-states in Active state (thus, allowing finer granularity in CBR control and allowing slightly higher CBR levels) enhances fuel economy in average with 0.4 L/100 km in a disturbance scenario, indicating that platoon communication setup also plays an important role in fuel consumption. The enhanced fuel efficiency is a result of the platoon’s ability to maintain the required inter-vehicle gap with higher precision under this DCC setup. This comes from the fact that DCC setup with a larger number of "Active" sub-states allows better granularity in controlling CBR, while still keeping congestion level at a required low level. We also suggest an approach of how our results on platoon fuel efficiency can be transformed into potential cost reduction gain. However fuel savings and corresponding cost reduction are highly dependent on the frequency of acceleration/deceleration maneuvers performed by platoon, which requires further extensive study of potential traffic flow parameters for platooning.

3.4 Paper IV

In this paper we propose a simple method that is able to detect certain types of jamming DoS attacks in platooning. We consider platooning with cooperation between the vehicles, which is achieved by the frequent exchange of periodic broadcast messages. To derive our method few assumptions on the operation of the system are taken: first, we assume that the number of vehicles in the platoon is always known to the platoon leader; second, platoon members have a static beaconing generation rate. The proposed algorithm is based on the knowledge of IEEE 802.11p MAC operation. The algorithm is divided into two phases. During the first phase, installation, the detector eavesdrop (via legitimate sniffer installed on the leading vehicle) the sequence of transmitted packets. As soon as it detects a sequence of N successful transmissions (where N is the size of the platoon), it performs classification of the areas in time domain, where collisions are possible and where they can not be observed at any circumstances by the the property of the IEEE 802.11p design. During
the second phase, operational, the detector tracks the information of successful and non-successful transmissions and classify the cause of collision using the classifier obtained in the installation phase to distinguish between normal (legitimate) collisions and packet losses caused by malicious jammer. To verify the performance of the detection algorithm we assumed two types of jamming strategies: random jamming, when the malicious node jams packets randomly with some probability; and ON-OFF jamming, when the jammer corrupts a number of packets in a row with some probability. For the reference platooning scenario under the aforementioned assumptions our algorithm provides in average the probability of detection not lower than 0.9 and no false alarm for any jamming probability. Moreover, the installation delay of the proposed algorithm does not exceed 1 second for the tested setups.
Chapter 4
Conclusion and Future Work

4.1 Conclusions

In this thesis the activities in three main research directions are summarized.

First, we perform an overview of standardization activity focusing on enabling C-ACC/platooning communications. Then, we study the performance of C-ACC/platooning performance enabled by the ITS-G5 protocol stack. We show that communication performance of ETSI CAM may decrease in a C-ACC/platooning scenario due to the phenomenon of CAM synchronization in the time domain. The mechanism of occurrence of the identified phenomenon is explained and its influence on the communication performance is studied under a range of parameters.

Second, we study the influence of different state-of-the-art ITS-G5 communication setups on the fuel efficiency of C-ACC/platooning. We show that different DCC configurations may contribute to different C-ACC/platooning performance in terms of its ability to keep desired inter-vehicle distance and as a consequence to a potential fuel savings.

Third, we propose a simple algorithm to detect jamming DoS attacks in a real-time CSMA/CA-based VANET environment. The algorithm is able to detect certain types of jamming DoS attacks with a delay of just hundreds of milliseconds. For the platooning scenario our method achieves average probability of detection above 0.9 keeping learning phase in scope of a second.

It is worth noting, that the results above are valid for arbitrary CSMA/CA-based VANETs with cooperative awareness provisioning.

4.2 Future Work

We are currently working on the extension of Paper II. In this paper a more extensive study of the identified CAM synchronization phenomenon will be presented. Results will extend the potential negative influence of ETSI EN 302 637-2 CAM generation frequency management on the realistic mobility patterns for both cooperative and semi-autonomous systems. We will consider the
two following scenarios: 1. C-ACC/platooning where coordination is supported by exchanging CAMs, and 2. string of human driven vehicles approaching a traffic light while exchanging CAMs to support cooperative awareness. The CAM performance will be studied using a wide range of parameters. Based on the simulation results recommendations on the parameter’s choice will be given.

We focus on DCC as a crucial mandatory component of ITS-G5 stack, which makes it an objective to evaluate its performance of a great importance. Moreover, so far DCC has been only slightly considered in the literature. In scope of congestion control in ITS-G5 we plan a study where we will evaluate the performance of C-ACC/platooning enabled by ITS-G5 under different ETSI DCC available configurations through a number of realistic simulation experiments. Our preliminary studies show that C-ACC/platooning demonstrates different performance in terms of precision of keeping the desired inter-vehicle distance under different DCC configurations. This should further be thoroughly studied followed by appropriate conclusions on the influence of DCC parameters on cooperative driving applications and proper DCC tuning.

As an extension of Paper IV we are currently working on an algorithm for real-time denial-of-service jamming attacks detection for C-ACC/Platooning applications enabled by the ETSI ITS-G5 standards. The detection algorithm proposed in Paper IV was designed for systems working under several assumptions. Thus, the beaconing was considered to have a static generation frequency. However, ETSI CAMs exploit the dynamic approach, relying on the vehicle’s own kinematics. Also, the detector was designed for systems, where the influence of channel impairments on the packet reception ratio is relatively low, which do not always comply with the wireless channel. The enhanced version of the detection algorithm should cope adequately with aforementioned.
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Appendix A

Paper I
Vehicle-to-vehicle communication in C-ACC/platooning scenarios

Alexey Vinel, Lan Lin, Nikita Lyamin

Vehicle-to-Vehicle Communication in C-ACC/Platooning Scenarios

Alexey Vinel, Lin Lan, and Nikita Lyamin

ABSTRACT

Cooperative adaptive cruise control (C-ACC) and platooning are two emerging automotive intelligent transportation systems (ITS) applications. In this tutorial article we explain their principles, describe related ongoing standardization activities, and conduct performance evaluation of the underlying communication technology.

INTRODUCTION

Sensor-based cruise control (CC) systems are currently deployed worldwide as common driver assistance systems. CC allows a predefined speed to be maintained and thus reduces a driver’s workload in free flowing traffic. Conventional adaptive cruise control (ACC), which is also on the market, is an enhancement of CC. ACC enables a preset distance from the preceding vehicle to be maintained. The measurements of the distance are handled by automotive radar mounted on the front of the vehicle (Fig. 1a). A line of vehicles connected by the ACC system is subject to the adverse effect of shockwaves because information on the acceleration/breaking of the first vehicle propagates along the caravan with significant radar measurement-induced delays [1].

Recent advances in vehicular networking [2] make it possible to further enhance ACC in order to avoid shockwaves propagating along a caravan of vehicles. This is achieved by direct vehicle to vehicle (V2V) wireless connectivity and information exchange with one or more of the preceding vehicles so as to maintain the pre-defined inter-vehicle distances (Fig. 1b). Such a system is referred to as cooperative adaptive cruise control (C-ACC). The information that is transmitted over the wireless connection includes the vehicle’s position, velocity, and acceleration. ACC and C-ACC with automatic longitudinal control only, assume that the driver controls the car using the steering wheel. Thanks to inter-vehicle wireless connectivity, information about the maneuvering of the lead vehicle is available almost instantly to the caravan members.

C-ACC can be further enhanced if automatic lateral control of the vehicle is also provided (Fig. 1c). In such a case, a professional, specially-trained driver manually controls the first vehicle in the caravan, while the others follow it automatically. Such a highly automated system means that drivers revert to manual control in certain situations, although most of the time they are not involved in any driving tasks. Further intelligence, e.g. protocols for joining/leaving the caravan or assisting other vehicles during on-ramp highway merging, can be added to such a system into what results as a platooning application. The differences between the C-ACC and platooning are discussed further in the next section.

Another motivation for C-ACC/platooning is to further reduce the inter-vehicle distances in the caravan, thereby decreasing air drag, which leads to lower fuel consumption [3]. Typically, an interval of 0.5 seconds (12.5 m in 90 km/h) for platoons is considered, while in a typical ACC (no wireless communication involved and based on radar measurements only) the minimum interval is set at 1.6 seconds. The recommended safety interval in Sweden, for example, with no support is set at 3 seconds. Indeed, under Swedish law “the police impose a fine when the safe distance is less than 1 second. If the safe distance is less than 0.5 seconds, the driver’s driving license can be revoked.” Therefore, a re-evaluation to or an amendment of the legal framework is key to the future development and deployment of automated driving systems.

Several projects on vehicle C-ACC/platooning have recently been carried out. These include Connect&Drive [4], Grand Cooperative Driving Challenge (GCDC) [5], and Safe Road Trains for the Environment (SARTRE). The Connect&Drive and the GCDC projects have C-ACC employing longitudinal control, while the SARTRE project has platoons consisting of heavy-duty vehicles and ordinary passenger cars with both automated longitudinal and lateral control. Demonstration of smart platooning functionalities, such as the merging of two platoons, is planned for 2016 within the framework of the GCDC II (i-Game) project.

The rest of this article is organized as follows. In the following section we provide an overview of the relevant standardization activities. The third section briefly discusses V2V communica-
tion patterns enabling C-ACC/platooning. A system model, performance metrics, and simulation results for the platooning scenario are presented next. We then conclude the article with a discussion of plans for future work.

STANDARDIZATION ACTIVITIES

V2V and vehicle to infrastructure (V2I) are also referred to as cooperative ITS (C-ITS). Key stakeholders in North America and the EU have been driving research and development of C-ITS for more than a decade. Standardization is one of the key building blocks of the C-ITS deployment roadmap. In 2014 the European Telecommunication Standard Institute (ETSI) and the European Committee for Standardization (CEN) jointly delivered the first release of C-ITS standards, enabling deployment of a set of day-one applications. The main target applications supported by the release one standard can be summarized as the cooperative awareness application and the road hazard signaling applications. These applications allow any information to be exchanged between vehicles and the C-ITS system, providing the vehicle communication neighbors, providing the vehicle network load in real time and also to implement control mechanism to dynamically measure the application requirements.

In addition, special attention has been paid during the standard specification phase to optimize the network resource usage, given the expected network density level and the amount of data being exchanged between nodes to satisfy the application requirements. For example, ETSI TC ITS operates a decentralized congestion control mechanism to dynamically measure the network load in real time and also to implement functionalities to keep the load below a threshold level. It should be noted that even though ITS-specific technologies standards are made available, the C-ITS does not preclude the use of other technologies, particularly when the penetration rate of the ITS-equipped nodes is low and when the application requirements may be met by other applications (e.g. for nonsafety applications). In fact, legacy communication stacks (e.g. TCP/IPv6 stack) and communication technologies (e.g. cellular network) are also included in the overall ITS communication architecture. Nevertheless, in order to ensure communication interoperability between vehicles from different vendors from the beginning of the deployment, a common agreement among stakeholders is required. The European Car 2 Car Communication Consortium (C2C-CC) is currently developing recommendations based on release one standards, with the aim of specifying a minimum set of standardized features and minimum sets of system performance to be implemented by all major car manufacturers and system providers in the EU and worldwide.

Among the various messages mentioned, CAM is one of the key basic features required for day one deployment. This is a high-frequency (1-10 Hz) periodic heartbeat message, broadcast by every equipped vehicle to its immediate communication neighbors, providing the vehicle is in the traffic flow and the C-ITS system is in operation. CAM includes the following content:

- Highly dynamic vehicle kinematic data such as position, time, heading, speed, acceleration, and status of acceleration control systems.
- Vehicle attributes such as vehicle width, length, vehicle type, vehicle role.
- Vehicle movement data, including vehicle historical path and path prediction data, e.g. yaw rate and curvature.
- Additional information for special vehicle types, e.g. emergency vehicles, buses, road maintenance vehicles, and so on.

In the published standard [7], the CAM generation rate is dynamically adjusted between 1 Hz and 10 Hz according to vehicle speed, movement heading, and changes in acceleration. The generation rate is increased whenever there is an increase in the vehicle movement dynamics, to ensure the movement dynamic is correctly reflected in the message content update rate. During its development phase, CAM and the corresponding protocol have been tested, validated in several ETSI conformance and the interoperability test event ETSI Plugtest, as well as in multiple EU R&D and Field Operational Test Projects (FOT). It was published as a European Norm in late 2014.

European ITS standard organizations are currently preparing for release two of ITS standards. Among many potential fields of stakeholder interest, one is the development of
C-ITS standards for connected automated driving applications and C-ITS-based advanced driver assistance applications. For example, since April 2014, ETSI TC ITS has established three new work units: C-ACC (TR 103 299), Vulnerable Road User safety (TR 103 300), and Platooning (TR 103 301). The focus of these projects is to conduct a pre-standardization study of these three applications. Instead of developing brand new standards from the very beginning, the pre-standardization study provides an overview of the applications, including their functional and operational requirements (e.g., performance requirements, data exchange requirements, communication requirements, and communication security requirements). The requirements analysis is essential for estimating the applicability of existing standards for these applications, as well as any new standard features that are needed (message sets specifications, communication protocol specifications, communication security features, congestion control requirements, etc). The expected outcomes of these projects are the recommended specifications for future standards required for C-ACC, Platooning, and vulnerable road users safety applications.

The initial technical work of the C-ACC and platooning applications in ETSI TC ITS focuses on the development of a high-level definition of C-ACC and platooning applications. This high-level definition is similar to those assumed by us, and can be summarized as follows:

- C-ACC is an embedded in-vehicle system that extends the ACC function so as to further reduce the time gap between the preceding vehicle or preceding traffic. The operation of C-ACC is based on kinematic data directly transmitted from the preceding and/or following vehicles via a V2V communication link. Multiple C-ACC-equipped vehicles may be aligned together to form a convoy (or caravan). Each vehicle is, however, responsible for its own maneuvering. In summary, C-ACC is a distributed automated driving or ADAS system.

- In platooning, a group of vehicles sharing a similar itinerary over a period of time form a vehicle fleet train, coordinated by a platoon leader. With increased levels of automation, the platoon leader may coordinate with platoon members for group maneuvering (platoon joining/leaving/group speed), or even make decisions for members in certain situations. The platoon leader is also in charge of monitoring the driving environment not only for him/herself, but also for the platoon members. Members of the platoon may be responsible for following the vehicle ahead, so in this respect, C-ACC may be considered as one technology for platoon operations.

  - Both longitudinal and lateral control functions may be used in two applications, to further increase operation stability.

  - Different levels of automation should be considered in C-ACC and platooning applications.

Several R&D projects have demonstrated that minor extensions to CAM and DENM may be sufficient to support C-ACC and platooning applications. For a platooning application, new messages/protocols may also be needed to enable platoon group operations such as negotiation for joining/leaving the platoon or merging different platoons. In addition, for new features such as cooperative sensing (exchange of vehicle environment perception with other vehicles), cooperative maneuvering would be helpful in realizing automated driving applications. Such projects would bring important technical inputs for standard development work. For example, in January 2015, a new work item on cooperative sensing (TS 103 324: Cooperative Observation Service) was established by ETSI TC ITS.
with HW/SW solutions that meet certain performance requirements for the processing of CAM messages, including processing at protocol stacks (networking, MAC etc.) and at security. For example, according to TS 101 559–1 (RHS) [8], the end to end latency of CAM should be $u_{\text{max}} = 300$ ms for a road hazard signaling application. For platooning and C-ACC applications, this end to end latency requirement may be further reduced.

**Performance Evaluation**

**System Model**

In the model it is assumed that the platoon has a leading vehicle that is steered by a human and $N - 1$ following automated vehicles moving together along a highway. To enable functioning of the platoon control systems, each vehicle executes the following steps:

- Generate CAMs in accordance with ETSI EN 302 637-2 specification [7] (the generation moment is denoted as $t_0$).
- Generate random transmission delay $\sim \text{uniform}(0, 50$ ms) (processing delay).
- Transmit CAMs on a dedicated channel in accordance with IEEE 802.11p Medium Access Control (MAC) specification [9].

On the receiver side, a random message verification delay $\sim \text{uniform}(50, 100$ ms) is introduced (the moment of time that the verification ends is denoted as $t_f$).

Following our previous work [10, 11], the following assumptions are made in the present study:

- All the vehicles in the platoon are within each other’s communication range. This is a valid assumption for the realistic set-up of a platoon with 20–25 vehicles, when the IEEE 802.11p communication range is in the order of 400–500 m, inter-vehicle distance is 7 m, and truck length is 13 m.
- The kinematic parameters of the leading vehicle are modelled via the constant-acceleration heuristic (CAH) state-of-the-art car-following mobility model [12].
- Random deviations in the velocities of the following vehicles in the caravan are modelled by applying the following approach: we add a random delay $\delta \sim \text{uniform}[0, k\sigma]$ to a CAM generation moment in order to reflect the non-perfect synchronization between their velocities, where $k = 500$ is the maximum delay expressed in $\sigma = \text{aTimeSlot}$ (aTimeSlot is defined in the standard [9]).
- We add independent packet losses to our MAC layer for each pair of nodes (for this work we only need PER values for each ordinary vehicle transmitting to the leader). The Nakagami-m ($m = 1$) propagation model is used.
- The decentralized congestion control (DCC) functionality is disabled.
- Each vehicle is able to update the CAM content for each generated CAM.

**Performance Metrics**

**Data Age:** The data age $u_n$ is a random variable defined as the time elapsed since the last successfully received packet of vehicle $2 \leq n \leq N$ by the leading vehicle. Data age is the difference between $t - t_l$, where $t$ is the current moment of time and $t_l$ is the moment when the last successfully received packet of vehicle $n$ was received by the leading vehicle.

*Note:* data age relates to the leader and is computed for an ordinary vehicle. We assume that the platoon leader determines the inter-distance for all platoon members. Platoon members use automated driving to maintain the distance specified by the leader.

**Cumulative Distribution Function (CDF) of the Data Age:** For a particular vehicle $n$:

$$F_n(t) = \Pr\{u_n \leq t\}$$

We denote the respective empirical CDF (ECDF) of the data age for a particular vehicle $n$ as $F_n^*(t)$.

**Data Age Deadline:** The data age deadline $u_{\text{max}}$ is the maximum acceptable data age of a vehicle from the leader’s perspective.

**Probability to Meet the Deadline:** The probability that data age value will not exceed deadline:

$$U_n^* = \Pr\{u_n \leq u_{\text{max}}\}$$

**Current Standardization**

Let us evaluate if the current CAM generation rules are sufficient to meet the platoon/C-ACC needs.

We chose the parameters sampling period ($\Delta$) and disturbance parameter ($\delta$) so that the CAM generation moments synchronization effect discussed in [11] is eliminated. We fix the mobility pattern to the disturbance scenario presented in [7]. In the scenario in Fig. 2, the leading vehicle decelerates from the desired steady speed ($V_{\text{stb}} = 90$ km/h) to a lower speed ($V_{\text{low}} = 60$ km/h), maintains this speed for some time, and then accelerates back to the initial speed. The disturbance scenario could be regarded as a pattern to describe the appearance of a slow moving vehicle in front of the platoon or a road speed limit. This corresponds to a CAM generation rate change from $1/[4/V_{\text{stb}}] = 6.25$ Hz (generation interval of 160 ms) to $1/[4/V_{\text{low}}] = 4.25$ Hz (generation interval of 240 ms). Addi-
tionally we provide results for the scenario widely used in the literature when CAMs are generated with a fixed frequency of 10 Hz and compare performance of both approaches.

In Fig. 3 ECDF of data age (hereafter, data age ECDF) of each ordinary vehicle in the platoon composed of \( N = 5 \) vehicles is shown. Solid lines show data age ECDF when the platoon maintains \( V_{\text{stb}} \) speed while dashed lines indicate \( V_{\text{low}} \) speed. Since the message-triggering process according to ETSI EN 302 637-2 relies on the current values of kinematic parameters, the data age of each vehicle will proportionally decrease/increase as the respective speed increases/decreases.

Obviously, vehicles located farther from the leader experience higher packet loss due to fading and as a consequence have higher data age. Later in this article we will focus on the data age of the last vehicle \( n = N \) in the platoon.

Figure 4 shows the frequency distribution of data age for the last vehicle in a platoon of \( N = 25 \) vehicles when the platoon maintains \( V_{\text{stb}} \). In our setup the data age for the most distant vehicle may exceed 1 second. The reason for such high values and the form of the distribution is that data age may increase proportionally to the number of subsequently lost CAMs.

Figure 5 illustrates data age ECDF’s for the last vehicle in the platoons of length \( N = 5, 10, 25 \) vehicles. With an increase in platoon size, data age could increase significantly, which could make operation of the control system difficult.

Table 1 shows the probabilities \( U_n^* \) of meeting the deadline \( u_{\text{max}} = 300 \) ms for the last vehicle in a platoon of length \( N = 5, 10, 25 \). Since the CAM generation rate for ETSI EN 302 637-2 is kinematic-dependent, the probability of missing the deadline when the speed is \( V_{\text{low}} \) becomes higher. The situation becomes even more acute if the platoon decelerates to lower speed values. In contrast, \( U_n^* \) for a fixed 10 Hz mechanism is predictable and depends only on the size of the platoon.

Figure 5 shows a comparative data age distribution between when CAMs are triggered in accordance with ETSI EN 302 637-2 (solid lines) and when employing a constant frequency of 10 Hz (dashed lines). It should be noted that when the platoon moves at \( V_{\text{stb}} \) the corresponding generation frequency is about 6.25 Hz (1/[4/\( V_{\text{stb}} \)]). Since we propose a dedicated communication channel for platoon coordination, even for \( N = 25 \) members, 10 Hz will always outperform the ETSI EN 302 637-2 approach (they may perform equally when the platoon’s speed exceeds 1/[4/\( V_{\text{stb}} \)] = 10, \( V_{\text{stb}} = 40 \) m/s = 144 km/h, which is an unrealistic speed pattern for a platooning application). The main conclusion to be drawn is that a 10 Hz CAM rate would be preferable to the current triggering condition, particularly when platoon speed is high. Another conclusion is that although the platoon leader receives CAMs from the platoon members, the current standard CAM rates tend to be insufficient for the leader to maintain the desired 0.5 second distance for safe operation. Therefore, the CAM rate should be further increased.

**Recommendations for Improvement**

- Enable constant CAM generation rates exceeding 10 Hz in a platoon, especially at higher speeds.
- Further reducing the processing delay at the receiving vehicle may be beneficial. In particular, the security-related processing delay has an important impact on data age.

**Future Plans**

In our future work we will:

- Take DCC into account in future simulation studies.
- Improve CAM message content so it can distinguish between platoon and non-platoon members, e.g. group identification.
- Introduce messages and protocols for platoon control in the overall traffic flow, e.g. space reservation for platoon lane change.

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ADDITIONAL READING


### Table 1

<table>
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<th>$U_{stb}$</th>
<th>$U_{low}$</th>
<th>10 Hz</th>
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<td>0.9974</td>
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<td>0.9869</td>
</tr>
<tr>
<td>$N = 25$</td>
<td>0.6182</td>
<td>0.5943</td>
<td>0.8995</td>
</tr>
</tbody>
</table>

BIographies

ALEXEY VINE (M’07, SM’12) received the bachelor’s (Hons.) and masters’ (Hons.) degrees in information systems from Saint-Petersburg State University of Aerospace Instrumentation, Saint Petersburg, Russia, in 2003 and 2005, respectively, and the Ph.D. degrees in technology from the Institute for Information Transmission Problems, Moscow, Russia, in 2007, and the Tampere University of Technology, Tampere, Finland, in 2013. He is currently a professor of data communications at the School of Information Technology, Halmstad University, Halmstad, Sweden. He has been involved in research projects on vehicular networking standards, advanced driver assistance systems, and autonomous driving. He has been an associate editor for the IEEE Communications Letters since 2012.

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NIKITA LYAMIN received a B.S. degree (Hons.) and M.S. degree (Hons.) in 2011 and 2013, respectively, in telecommunications from Siberian State University of Telecommunications and Information Sciences, Novosibirsk, Russia. He is now a Ph.D. student at the School of Information Technology, Halmstad University, Halmstad, Sweden. His current research interest is in the areas of vehicular ad-hoc networks, platooning, and multiple-access protocols.
Appendix B

Paper II
Does ETSI beaconing frequency control provide cooperative awareness?

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2015 IEEE International Conference on Communication Workshop (ICCW)
Does ETSI beaconing frequency control provide cooperative awareness?

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Abstract—Platooning is an emergent vehicular application aiming at increasing road safety, efficiency and driving comfort. The cooperation between the vehicles in a platoon is achieved by the frequent exchange of periodic broadcast Cooperative Awareness Messages (CAMs) also known as beacons. CAM triggering conditions are drafted in the standard ETSI EN 302 637–2 and are based on the dynamics of an originating vehicle. These conditions are checked repeatedly with a certain sampling rate. We have discovered that the improper choice of the sampling rate value may increase the number of collisions between CAMs at the IEEE 802.11p medium access control layer and, therefore, diminish the efficiency of beaconing in a platoon.

Index Terms—VANET, cooperative awareness, beaconing, congestion control, platooning, ETSI.

I. INTRODUCTION

Design of the inter-vehicle communication protocols to support coordinated maneuverings and automated driving is recognized by the vehicular networking community as an emergent research topic [1]. Real-time exchange of kinematic information by all the maneuvering vehicles is crucial for their cooperation [2]. Broadcasting of Cooperative Awareness Messages (CAMs) by every vehicle to their neighbors is studied for multi-channel scenario [3], for the hidden-nodes case [4] and for enabled congestion control approaches [5], to name a few.

Communication support for platooning is currently getting a lot of attention, but the results so far are limited to, e.g., packet loss measurements [6] and a study on the content of the information to be exchanged and its role in the control application [7]. Still, several studies and proposals of how to use IEEE 802.11p in platooning have been reported, e.g., a slotted approach [8], retransmission schemes together with a TDMA approach [9], [10], analysis of the connectivity probability [11], and a study of send rate adaptation, message type prioritization and warning dissemination strategies [12]. However, the recently proposed CAM generation rules are not taken into account in any of the mentioned work.

In comparison to the studies mentioned above, this paper is focused on the ongoing ETSI standardization efforts for CAMs generation rules [13], which have not received an adequate publication activity so far. We focus on the cooperative awareness provisioning for the emergent platooning application [14], where a caravan of semi-autonomous vehicles perform maneuvering together aiming at increased safety and reduced fuel consumption.

The contribution of this paper is twofold:

• a phenomenon of CAM triggering moments synchronization between platoon members is discovered;
• potentials to diminish a negative influence of this phenomenon on the cooperative awareness are discussed.

The manuscript is organized as follows. The assumptions of the system model are outlined in Section II. ETSI CAMs generation rules are summarized in Section III, while in Section IV the identified problem is described. Sections V and VI discuss potential ways to address the identified problem and conclude the paper, respectively.

II. SYSTEM MODEL

We consider a platoon comprised of \( N \) vehicles: a leading human-controlled vehicle and a caravan of automated vehicles moving together along the highway, Fig. 1. To enable functioning of the platooning control systems, each vehicle:

• generates CAMs in accordance to ETSI EN 302 637-2 specification [13];
• transmits CAMs on a dedicated channel in accordance to the IEEE 802.11p Medium Access Control (MAC) specification [15].

![Fig. 1: Reference scenario](image-url)
• All the vehicles in the platoon are in each others communication range. This is a valid assumption for the realistic set-up of a platoon with up to 20–25 vehicles, when the IEEE 802.11p communication range is in the order of 400–500 m, inter-vehicle distance is 5 m and truck length is 15 m (see [16], p. 111).
• All the vehicles in the platoon increase or decrease their speed synchronously. This is a reasonable assumption since the speed deviations within a platoon are targeted to be marginal\(^1\) (see [17], p. 433).
• The kinematic parameters of the leading vehicle are modeled via the Constant-Acceleration Heuristic (CAH) [18] state-of-the-art car-following mobility model\(^2\).

III. ETSI COOPERATIVE AWARENESS BASIC SERVICE
Cooperative Awareness Basic Service [13] sets up the rules for the CAM generation, which are summarized in three items below\(^3\).

Firstly, the generation rate limits for CAMs are defined as follows:
• The CAM generation interval shall not be inferior to \(T_{\text{min}} = T_{\text{GenCamMin}} = 100\) ms. This corresponds to the maximal CAM generation rate of 10 Hz.
• The CAM generation interval shall not be superior to \(T_{\text{max}} = T_{\text{GenCamMax}} = 1000\) ms. This corresponds to the minimal CAM generation rate of 1 Hz.

Secondly, the above conditions for triggering the CAM generation shall be checked by a vehicle repeatedly every \(\Delta = T_{\text{CheckCamGen}}\). We refer to \(1/\Delta\) as the CAM triggering condition sampling rate.

Thirdly, within the specified limits, the CAM generation depends on the dynamics of the originating vehicle. A CAM shall be triggered in one of two cases:
• The time elapsed since the last CAM generation is equal or larger than \(T_{\text{max}}\).
• The time elapsed since the last CAM generation is equal or larger than \(T_{\text{min}}\) and any of the following events has occurred:
  - "Event A": the absolute difference between the current position of the vehicle and its position included in the previous CAM exceeds \(d_{\text{min}}=4\) m;
  - "Event B": the absolute difference between the current speed and the speed included in the previous CAM exceeds \(v_{\text{min}}=0.5\) m/s;
  - "Event C": the absolute difference between the current direction of the vehicle and the direction included in the previous CAM exceeds \(\delta\).\(^4\)

\(^1\)In Subsection V.B we discuss the relaxation of this assumption.
\(^2\)This particular mobility model is chosen for the illustrative purposes only, however, the considerations in the paper are valid for any mobility patterns.
\(^3\)CAM generations are also influenced by the ETSI Decentralized Congestion Control (DCC) [19]. However, throughout of this paper DCC is not considered.
\(^4\)Event C is not considered in the paper, since we assume that the platoon moves along the highway and changes its direction slowly. Nevertheless, all the presented considerations and conclusions are valid also in case Event C might occur.

IV. IDENTIFIED PROBLEM
Throughout this Section we assume that \(\Delta\) is negligibly small, i.e. the CAM generation rules are continuously checked by every vehicle.

A. CAMs Generation Moments: Synchronization
To illustrate the discovered effect of possible CAM generation times synchronization, let us consider two examples.

Example 1: Let the platoon change its velocity, e.g. it temporally slows down due to reduced speed limits in a road construction segment or due to a slow vehicle ahead.

Let us denote the CAM generation moments of the \(i\)-th vehicle as \(V_1, V_2, \ldots, V_N\), Fig. 2. When the platoon moves with a constant speed of 90 km/h, each vehicle triggers a CAM every \(\tau = d_{\text{min}}/v=160\) ms due to the periodic occurrence of Event A.

Due to the deceleration, in a short time period a change of the platoon speed exceeds 0.5 m/s (Event B) and the vehicles with \(t - t_i = T_{\text{min}}\) (i.e. 4, 5 and 6) synchronously trigger their CAMs at time \(t_0\). Other vehicles (i.e. 1, 2, 3, 7 and 8) trigger their CAMs as soon as the time elapsed since their recent CAM generation turns to \(T_{\text{min}}=100\) ms. When the platoon speed stabilizes, the vehicles trigger CAMs with a constant period again (Event A).

The following proposition characterizes the phenomenon described above.

Proposition A. Let a platoon move with a constant speed \(v\) during time interval \([0, t_0]\). If Event B occurs at \(t_0\), then the mean number of CAM generation moments synchronized at \(t_0\) is

\[\rho = \frac{\tau - T_{\text{min}}}{\tau} \times N,\]

where \(\tau = d_{\text{min}}/v\).

Proof: Let the CAM generation moments of all the vehicles be enumerated and denoted as \(T_n, n \geq 1\). The CAM generation moments in the interval \([0, t_0]\) represent the following stochastic process:

• Due to the random and independent occurrence of the first CAM generation moment of each of the \(N\) vehicles, the \(N - 1\) intervals between pairs of subsequent CAMs of any \(N\) consecutive generation moments are exponentially distributed, i.e. \(\forall n : T_{n+k} - T_{n+k-1} \sim \exp(\tau/N), k = 1, N-1\).
• Due to the periodic occurrence of Event A, all the vehicles generate CAMs with period \(\tau\), i.e. \(\forall n : T_{n+N} - T_n = \tau\). Therefore, any time interval of duration \(\tau\), contains exactly \(N\) CAM generation moments (one per vehicle).

All the \(N\) vehicles detect Event B simultaneously at \(t_0\). However, due to the restriction on the value of the minimal possible CAM generation interval \(T_{\text{min}}\), only those vehicles, whose CAM generation moments belong to \([t_0 - \tau, t_0 - T_{\text{min}}]\), are triggered at \(t_0\), Fig. 3. Taking into account the above properties of the considered stochastic process, the mean number of CAM generation moments in \([t_0 - \tau, t_0 - T_{\text{min}}]\) is

\[\frac{\tau - T_{\text{min}}}{\tau} \times N.\]
IEEE ICC 2015 - Workshop on Dependable Vehicular Communications (DVC)

Fig. 2: Example 1 – Synchronization of CAM triggering moments in the platoon

Constant speed \( v \)

Time

Event A

\( V_1 \) \( V_2 \) \( V_3 \) \( V_4 \) \( V_5 \) \( V_6 \) \( V_7 \) \( V_8 \)

\( T_{min} \)

\( T_{min} = \frac{d_{min}}{v} \)

Event B

Speed starts to change

\( V_1 \) \( V_2 \) \( V_3 \) \( V_7 \) \( V_8 \) \( V_1 \) \( V_2 \) \( V_3 \) \( V_4 \), \( V_5 \), \( V_6 \)

Fig. 3: Illustration for the proof of Proposition A

Example 2: Let the platoon slow down and accelerate several times, see Fig. 4.

Fig. 4: Example 2 – Some subsequent maneuvers

Each platoon maneuver influences the CAM triggering process according to the mechanism described in Example 1. More CAMs might become synchronized as long as more maneuvers are performed due to the concurrent occurrence of Event B. For example, in Fig. 5 CAMs from vehicles 7, 8, 9, 10 and 11, 12 become synchronized with the ones from 1, 2, 3, 4, 5, 6 after the 2\(^{nd}\) and the 3\(^{rd}\) maneuvers, respectively.

Notice, that once the synchronization of the CAM triggering times has occurred, further accelerations/decelerations will not lead to desynchronization. Event B occurs simultaneously for all the synchronized vehicles, since their recent CAMs contain the same kinematic information.

B. CAM Transmission Moments: Grouping

Transmission of CAMs generated as discussed above is governed by the IEEE 802.11p MAC protocol, which presumes that CAMs from different vehicles may collide due to their simultaneous transmissions. Synchronization of the CAM generation times does not lead to a guaranteed collision as well as their desynchronized generations do not impose that collisions are impossible [3], [15]. This phenomenon can be characterized using the notions of groups.

Let us consider a platoon moving with a constant speed with all the vehicles periodically triggering CAMs. Let us select a sequence of \( T_i \leq T_{i+1} \leq T_{i+2} \leq \cdots \leq T_{i+N-1} \) CAM generation moments of each vehicle in the platoon such that CAMs from vehicles \( i \) and \( i+N-1 \) cannot collide (formal way to do it is proposed in [16], p. 112).

Algorithm 1 CAMs Grouping Algorithm

1: \( \text{for} \ j \leftarrow 1, N \ \text{do} \)
2: \( L_j \leftarrow 0; \)
3: \( \text{end for} \)
4: \( l \leftarrow i; \ K \leftarrow 1; \)
5: \( \text{while} \ l < i + N - 1 \ \text{do} \)
6: \( \Omega \leftarrow \{l\}; \ m \leftarrow 1; \)
7: \( \text{while} \ T_{i+m} - T_i \leq m \times \left[ AIFS + (W - 1)\sigma \right] + (m - 1) \times T_{CAM} \ \text{do} \)
8: \( \Omega \leftarrow \Omega \cup \{l + m\}; \)
9: \( m \leftarrow m + 1; \)
10: \( \text{end while} \)
11: \( \Phi_K \leftarrow \Omega; \)
12: \( L_m \leftarrow L_m + 1; \ l \leftarrow l + m; \)
13: \( K \leftarrow K + 1; \ m \leftarrow 1; \)
14: \( \text{end while} \)

One can execute Algorithm 1, where \( AIFS \) is the Arbitrary Inter-Frame Space, \( \sigma \) is a \( aSlotTime \), \( W \) is the Contention Window [15] and \( T_{CAM} \) is the CAM transmission time. The outcome of the Algorithm operation is that all \( N \) vehicles are split into \( K \) sets denoted as \( \Phi_k, k = 1 \ldots K \) and further referred to as groups. \( L_m \) is the number of groups consisting
of exactly \( m \) vehicles.

**Proposition B.** The CAMs of vehicles belonging to different groups \( \Phi_k \ (k = 1 \ldots K) \) cannot collide.

*Proof:* From the IEEE 802.11p backoff rules it follows that in the empty system two CAMs can never collide if their generation moments are spread in time for at least \( a + (W - 1) \sigma \), see line 7. When the CAMs are generated during the ongoing transmissions of other vehicles, the backoff counters freeze until the channel becomes idle. Respective maximum possible transmission delays are checked at line 7. Let us consider time intervals, where the speed of the platoon is constant, i.e. before any maneuvers and after each of the four maneuvers (see Fig. 6).

Let us examine how the increase of the sampling interval \( \Delta \) influences CAMs grouping. A reduction of the sampling rate results in the increase of CAM generation moments time diversity (Fig. 8). Moreover, in contrast to the case of \( \Delta \to 0 \), this time diversity may increase as a result of a maneuver for \( \Delta = 500 \) (see \( Q^*(m) \) after the 3rd and the 4th maneuvers). A group might be split when "Event B" occurs between its CAM generation moments.

Let us consider time intervals, where the speed of the platoon is constant, i.e. before any maneuvers and after each of the four maneuvers (see Fig. 6).

**V. POTENTIALS TO SOLVE THE PROBLEM**

A. **Reduced sampling rate**

Let us examine how the increase of the sampling interval \( \Delta \) influences CAMs grouping. A reduction of the sampling rate results in the increase of CAM generation moments time diversity (Fig. 8). Moreover, in contrast to the case of \( \Delta \to 0 \), this time diversity may increase as a result of a maneuver for \( \Delta = 500 \) (see \( Q^*(m) \) after the 3rd and the 4th maneuvers). A group might be split when "Event B" occurs between its CAM generation moments.

B. **Practical considerations**

Although the movements of platoon members are desired to be perfectly synchronized during all the maneuvers, a real system will impose certain restrictions to achieve this goal due to the inter-vehicle communication delays, automated control induced delays, inertness of the braking system and inaccuracies in kinematic parameters measurements.
Fig. 8: Influence of maneuvers on the time diversity of CAM generation moments when $\Delta = 500\sigma$

Let $\delta = \text{uniform}[0, kr]$ be a random delay, which is added to each CAM generation moment when the maneuver is performed, where $k$ is the maximum delay expressed in time slots. $\delta$ aims at modeling the overall inaccuracies between the instance when the CAM would be triggered in the ideally synchronized platoon studied up to now and in the platoon with a non-synchronized movement of members. A random component in CAM triggering moments may diminish the grouping effect (Fig. 9).

To assess the actual impact of the ETSI rules on the CAM successful delivery performance, we examine the cases when the platoon keeps a constant speed (i.e. Event A triggering CAMs) after each maneuver performed (see Fig. 6). From Fig. 10 one can see that the tunings of the parameters discussed above have a crucial impact on the CAM collision probability.

VI. CONCLUSIONS AND FUTURE WORK

Emerging platooning application, where a caravan of heavy-duty vehicles automatically follow a leading one, requires an exchange of updated kinematic information. This is achieved through the triggering of beacons in accordance to the ETSI EN 302 637-2 specification and their transmissions over a dedicated IEEE 802.11p random access channel.

Our study reveals a surprising conclusion: enlarging the sampling rate of the kinematic parameters will not necessarily lead to the improved cooperative awareness, because an increased congestion in the communication channel might decrease the reception rate of beacons.

We believe that our insights should be rapidly delivered to the vehicular communication research and development community and might influence the ongoing ETSI standardization. Our future work will be dedicated to the detailed analysis of the identified problem and will be focused around two major research questions:

- What are the gains and losses in the kinematic data uptodateness with respect to the sampling rate chosen?
- Is it possible to achieve ungrouping of CAM generation moments through the adjustment of the parameters?

ACKNOWLEDGMENT

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REFERENCES


Appendix C

Paper III
Study of the Platooning Fuel Efficiency under ETSI ITS-G5 Communications

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Study of the Platooning Fuel Efficiency under ETSI ITS-G5 Communications

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Abstract—In this paper we evaluate the performance of platoon enabled by contemporary ITS-G5 vehicular communications through the number of simulation experiments. We assess platooning fuel consumption performance under two communication setups and estimate the potential influence of the communication system on the efficiency of the platooning. We also make an attempt to transform our results on platoon fuel-efficiency into potential cost reduction gain. Our study shows that platooning fuel-efficiency may vary depending on the communication setup.

I. INTRODUCTION

Vehicle platooning means a group of vehicle driving closely after each other and being controlled as one unit. It allows many vehicles to accelerate or brake simultaneously, while decreasing the distances between vehicles using vehicle-to-vehicle (V2V) communication. Grouping vehicles into platoons saves space on the highway so that the highway section can accommodate more vehicles. On the other hand, platoon followers experience reduced aerodynamic resistance due to small inter-vehicle distances, which results in fuel saving.

Fuel saving in vehicle platooning, especially for heavy-duty vehicles (HDVs), has been studied extensively by researchers and automotive manufacturers. Vehicle platooning introduces a split-stream effect for the follower vehicle and decreases corresponding air-drag, thus reduces overall restrictive forces. In fact, air-drag constitutes 23% of the total forces acting upon a vehicle at highway speed [1], even modest decrease can have noticeable impact on fuel saving. Previous studies showed that the fuel consumption of HDV platoon follower can achieve 20% saving [2] when it was operating in small inter-vehicle distance. However, this requires robust controller and appropriate communication scheme to guarantee stability and safety. For example, in the case of KONVOI project, it showed no saving during test on public highway since the platoon follower needed to vary its speed to maintain a desired distance to the preceding vehicle [3], which incurred additional fuel consumption.

V2V communications, stability and fuel efficiency in platoon are closely coupled. Proper communication setup can make a platoon follower maintain a desired distance to its predecessor while reducing acceleration and braking frequencies. To enable inter-vehicle communications European Telecommunication Standard Institute (ETSI) delivered the first ITS-G5 release of set of C-ITS standards under European Commission Mandate M/453 [4]. ITS-G5 defines the overall vehicular communication protocol stack [5]. So far there has been no dedicated message type standardized for platooning. However, there is currently pre-standardization activity (ETSI TR 103 301) studying how to apply currently available standards for platooning application [6]. In conformity with aforementioned in this study we implement and apply recently standardized Cooperative Awareness Messages [7] to enable platooning operation. Also according to [8]: Decentralized congestion control (DCC) is a mandatory component of ITS-G5 stations operating in ITS-G5A and ITS-G5B frequency bands to maintain network stability, throughput efficiency and fair resource allocation to ITS-G5 stations.

To the best of our knowledge there are no studies available, that test the fuel efficiency of the platooning under the detailed implementation of the ETSI ITS-G5 communication protocol stack. We compare the potential fuel consumption reduction, when platooning is enabled by two different DCC setups available in ITS-G5. The contribution of the paper is twofold:

• performance of the platoon enabled by the V2V communications in accordance with a complete ETSI ITS-G5 protocol stack is studied;
• case study of fuel savings for ITS-G5 enabled HDV platooning on E4 highway is provided.

The manuscript is organized as follows. In Section II the description of CAM and DCC is summarized. Section III presents the reference platooning fuel consumption models, while Section IV gives specification of the tested reference scenarios. Performance evaluation results are provided in Section V. Finally, Section VI concludes the paper.

II. ITS-G5 COMMUNICATIONS

The coordination between vehicles in the platoon relies on the frequent exchange of broadcast communication messages containing information about vehicle’s position, speed, acceleration and other attributes. The process of broadcast messages’ exchange is usually referred to as beaconing [9]. To support beaconing in the platoon, following [6], we implemented Cooperative Awareness Messages (CAM),
which are part of ETSI ITS-G5 stack [7]. For the sake of simplicity we skip the description of CAM, interested reader may to refer to [10] for detailed explanation.

In order to comply with ITS-G5 requirements we also implemented DCC functionality. DCC operates as gate-keeper at the medium access layer (MAC). The operation of DCC relies on the DCC state-machine 1. In each of the states DCC specifies the restrictions on the vehicle’s transmission behavior. In particular, DCC defines 5 mechanisms to control the access to the communication channel: ”Transmit Power Control” (TPC), ”Transmit Rate Control” (TRC), ”Transmit Datarate Control” (TDC), ”DCC Sensitivity Control” (DSC), ”Transmit Access Control” (TAC). In this study we are focusing on the TRC. TRC defines for each DCC state the minimum allowed time between two consecutive message transmission. In Figure 1 this time is represented in generation frequency of the messages, i.e. 10 Hz means, that vehicle can not generate more than 10 messages per second or in other words, time between two consecutive transmissions is not allowed to be less than $1/10 = 0.1$ s. The transitions between DCC states are performed based on the Channel Busy Ratio (CBR), measured by each vehicles. The detailed DCC operation explanation could be found in [8], [11], [12].

![DCC configurations](image)

To study the influence of the communication setup on the platooning fuel efficiency we implement two different DCC configurations:

- Basic 3-state DCC state-machine, Figure 1.a, described in [8]. Throughout this paper we will refer to this configuration as Communication Setup 1.
- DCC state-machine configuration with set of sub-states in ”Active state”, Figure 1.b, described in [12]. Throughout this paper we will refer to this configuration as Communication Setup 2.

To enable the beaconing in the platoon each vehicle follows the approach below:

- Generates CAM message according to [7];
- The DCC controls the access to the communication channel, according to [8], [12];
- Transmits message on the dedicated ITS-G5 channel according to IEEE 802.11p.

Signal attenuation is modeled using Log-distance path loss model. We also set the sampling rate CAM parameter the value in a way that effect described in [10] is not observed. Other communication parameters are summarized in the Table I.

### III. FUEL CONSUMPTION IN PLATOONING

In order to better understand how communication setup affects the performance of platoon followers, a simplified fuel consumption model is applied to estimate instantaneous fuel usage [13]:

$$f = \frac{1}{H \eta} \left[ (\mu \cos \theta + \sin \theta) M g v + \kappa v^3 + M a v \right] dt$$

where $t_0$ and $t_f$ are the initial and final time instances; $H$ and $\eta$ are energy density and efficiency respectively; $v$ and $a$ are vehicle speed and acceleration; $M$ is the mass of vehicle; $\delta$ indicates if the engine is active:

$$\delta(t) = \begin{cases} 
1 & \text{if } (\mu \cos \theta + \sin \theta) M g v + \kappa v^3 + M a v > 0 \\
0 & \text{otherwise}
\end{cases}$$

the air-drag coefficient $\kappa$ is computed from:

$$\kappa = \frac{1}{2} \rho_A C_D (1 - \phi)$$

where $\phi$ is the air-drag reduction factor. The air-drag reduction $\phi$ is illustrated in Figure 2 or Figure 3, depending on inter-vehicle distance, vehicle type and vehicle position in platoon. The $n^{th}$ ($n \geq 4$) vehicle in car platoon has the same air-drag reduction as $4^{th}$ vehicle, and the $n^{th}$ ($n \geq 3$) vehicle in HDV platoon has the same air-drag reduction as $4^{th}$ vehicle. The detail of parameters for fuel consumption model is presented in Table II.

### TABLE I: Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication parameters</td>
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<tr>
<td>CAM size</td>
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<tr>
<td>$T_c$ power</td>
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<tr>
<td>Bitrate</td>
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<td>Path-loss exponent</td>
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<td>Common parameters</td>
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<td>Size of the platoon (N)</td>
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<tr>
<td>Number of disturbing vehicles</td>
<td>4 vehicles</td>
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<tr>
<td>Inter-vehicle gap</td>
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</tr>
<tr>
<td>Scenario 1</td>
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<tr>
<td>Platoon’s leader speed</td>
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<tr>
<td>Vehicle acceleration capability</td>
<td>2.5 m/s$^2$</td>
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<tr>
<td>Vehicle deceleration capability</td>
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<td>Number of simulation runs</td>
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<tr>
<td>Scenario 2</td>
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<td>Platoon’s leader speed</td>
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<td>Vehicle length</td>
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<tr>
<td>Number of simulation runs</td>
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![Fuel consumption model](image)
TABLE II: Parameters of Fuel Consumption Models [13].

<table>
<thead>
<tr>
<th>Vehicle Parameters</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>$M_{HDV}$</td>
<td>Vehicle Mass of HDV</td>
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<td>kg</td>
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<tr>
<td>$M_{car}$</td>
<td>Vehicle Mass of Car</td>
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<td>kg</td>
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<td>$c_D$</td>
<td>Air-Drag Coefficient</td>
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<td>$A_{a-HDV}$</td>
<td>Front Area of HDV</td>
<td>10.26</td>
<td>$m^2$</td>
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<td>$A_{a-car}$</td>
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<td>2.1</td>
<td>$m^2$</td>
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<td>$\mu_{HDV}$</td>
<td>Rolling Resistant Coefficient for HDV</td>
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<tr>
<td>$\mu_{car}$</td>
<td>Rolling Resistant Coefficient for car</td>
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<td>$\rho_a$</td>
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<td>$g$</td>
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<td>$H$</td>
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<tr>
<td>$\eta$</td>
<td>Energy Efficiency</td>
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</table>

For both scenarios we exploit "disturbance scenario" as speed pattern [6], [16]. Moving along the highway platoon repeatedly meets slower vehicles in front of it and performs appropriate acceleration/deceleration maneuver, see Figure 4. Four additional vehicles are repeatedly added and then removed in front of the platoon during each simulation run. The scenario is equivalent to the road situation when slower vehicle comes to the right-most lane from metering ramp or after the lane changing.

B. Simulation platform

To emulate realistically the operation of the platoon we use novel Plexe simulation platform [17]. Plexe incorporates Omnnet++ for the real-time V2V communications simulation together with SUMO as a realistic traffic simulator. Simulator also contains platoon controller part, which allows to control platoon members based on the input obtained from the communication exchange.

To comply with the ITS-G5 protocol stack [5] we additionally implemented ETSI CAM messages on facilities layer [7] and ETSI DCC functionality [8], [11]. The detailed description of the communication setup is given in Section II. Each vehicle in the platoon utilizes as a control input messages containing kinematic data received from the preceding vehicle and platoon leader, following controller algorithm presented in [18]. Controller implements fixed-spacing policy, which means that inter-vehicle gap between the platoon members is fixed and does not depend on the vehicle’s speed.

The detailed simulation parameters are summarized in Table I.

IV. SIMULATION SETUP

A. Reference scenarios

In this paper we consider two following reference scenarios:

1) Platooning consisting of $N$ passenger cars moving along the road.
2) Platooning consisting of $N$ Heavy Duty Vehicles (HDVs) moving along the road.

V. PERFORMANCE EVALUATION

In this section, the performance of different communication setups is evaluated in terms of fuel economy, which is the relationship between the amount of fuel consumed and the distances traveled by the vehicle. Fuel economy of an automobile is generally expressed as liters per 100 kilometers (L/100km) and used in most European countries. In order to estimate the fuel economy of each vehicle in platoon, experiments are conducted in microscopic simulation environment.
A. Fuel Economy of Platoon in Each Communication Setup

Figure 5 corresponds to the fuel economy of the 15-car platoon. Evidently the platoon leader in two different communication setups has identical fuel economy, due to the same settings and reaction to disturbances. It can be seen that there is only minor difference between the no platooning and platooning cases (for passenger car) in fuel economy, about 0.2–0.44L/100km. And the difference between two platoon communication setup is almost negligible, only 0.01–0.07L/100km. This to some extent indicates that passenger cars usually do not have fuel saving incentive to form platoons, and platooning of cars might probably happen for driving comfort in traffic congestion.

Figure 6 corresponds to the fuel economy of 15-HDV platoon. In the HDV platooning cases, all platoon members, including leader and followers can achieve fuel saving compared with the no platooning case. Communication Setup 1 results in 2.1%–6.4% improvement in fuel economy, and Communication Setup 2 further enhances the improvement to 2.1%–6.8%, indicating that platoon communication setup also plays an important role in fuel consumption. An appropriate communication setup will be able to further improve fuel economy and reduce fuel cost.

The enhanced fuel efficiency in Communication Setup 2 is a result of platoon’s ability to maintain required inter-vehicle gap with higher precision under this scenario comparing...
to Setup 1, see Figure 7. This could be explained by the fact that DCC setup with a larger number of "Active" sub-states allows better granularity in controlling CBR while still keeping congestion level at required low level. Hereby, even though both Communication Setups are defined in ETSI standards and allowed to exploit they may demonstrate sufficiently different performance in the platooning scenario and influence noticeably on the performance of application in terms of stability and fuel efficiency.

### B. Numerical Experiment on European route E4

The European route E4 is the highway backbone of Sweden and used by most of freight transport. It starts from the border between Sweden and Finland, and passes through 22 cities of Sweden with a total length of 1590km. An overview of E4 can be seen in Figure 8.

![Fig. 8: European Route E4](image)

In this subsection, two communication setups are applied on a 15-HDV platoon which starts from Tornio and travels to Helsingborg. It is assumed that there are two on-ramps and off-ramps from/to each of the 22 cities, the speed limit for on-/off-ramp is 60km/h [19]. Since HDV is restricted to drive on the truck lane at the rightmost, the platoon has to decelerate to 60km/h in the ramp area and accelerate to desired speed 90km/h afterwards. Fuel economy can be estimated from the ratio of total fuel consumption to length of E4.

![Fig. 9: Estimated Yearly Saving of HDV Compared with No HDV Platooning Scenario](image)

HDV platooning improves fuel economy, which can be seen in Table III. HDVs consume significantly less fuel when traveling the same distance. The platoon saves 6.44L, or equivalently 17.5% in Communication Setup 1 and 6.48L (17.6%) in Communication Setup 2 respectively for every 100km. In general, an HDV travels over 200,000km per year [20], with average diesel cost 14.4SEK/L. Both HDV platooning in Communication Setup 1 and Communication Setup 2 lead to remarkable amount of saving compared with the no HDV platooning scenario. Table III shows that HDV platooning in Communication Setup 1 and Communication Setup 2 can potentially save 2.78MSEK and 2.8MSEK respectively. According to simulation outcomes presented in Figure 9, 3rd–15th HDV contribute the most significant saving, which is inline with the dramatic air-drag reduction for HDV platoon followers. It is also worth mentioning that HDV platooning in Communication Setup 2 has slightly more saving than Communication Setup 1, which can be explained by the fact that Communication Setup 1 results in smaller fluctuation in the speeds of HDV platoon follower (See Figure 10 and Figure 11) and more stable inter-vehicle distances (See Scenario 2 in Figure 7), therefore reduce acceleration and braking efforts and frequencies.

![Fig. 7: Platoon Inter-vehicle distance](image)
and fuel efficiency of platoon among scenarios. In this manuscript we show, that parameters of communication setup have direct impact on the platoon’s air-drag reduction under disturbance scenario, regardless of the frequency they appear.

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Appendix D

Paper IV
Real-Time Detection of Denial-of-Service Attacks in IEEE 802.11 p Vehicular Networks

Nikita Lyamin, Alexey Vinel, Magnus Jonsson

Real-Time Detection of Denial-of-Service Attacks in IEEE 802.11p Vehicular Networks

Nikita Lyamin, Alexey Vinel, Magnus Jonsson, and Jonathan Loo

Abstract—A method for real-time detection of Denial-of-Service (DoS) attacks in IEEE 802.11p vehicular ad-hoc networks (VANETs) is proposed. The study is focused on the "jamming" of periodic position messages (beacons) exchanged by vehicles in a platoon. Probabilities of attack detection and false alarm are estimated for two different attacker models.

Index Terms—IEEE 802.11p, VANET, DoS attack, jamming, platooning.

I. INTRODUCTION

IEEE 802.11p is an international standard for short-range inter-vehicle communication in the 5.9 GHz frequency band. Vehicular ad-hoc networks (VANETs) comprised of the IEEE 802.11p-enabled vehicles aim at increasing road safety, efficiency and driving comfort and are currently a subject of an intensive research. Platooning is an example of such an application based on vehicle-to-vehicle communication.

In a platoon the leading vehicle (normally a truck) is driven by the human, while the following vehicles either automatically maintain the velocity of the leading one, but their direction is still controlled by the driver (e.g. Connect & Drive project [4] and Grand Cooperative Driving Challenge – GCDC [5]), or follow the leading one in a fully automatic manner (e.g. Safe Road Trains for the Environment project – SARTRE [6]).

The cooperation between the vehicles in the platoon is achieved by the frequent exchange of periodic broadcast messages carrying information on vehicle position and velocity, which we refer to as beacons, in the dedicated channel [9].

Since the IEEE 802.11p medium access control (MAC) protocol specifies random access, during its normal operation the beacons can be lost either due to the wireless channel impairments or due to collisions (i.e. overlapping transmissions of beacons from several vehicles). The probability of collisions can be reduced by the proper choice of the MAC protocol parameters [10]. However, the beacons can also be intentionally corrupted by the malicious node in case of a jamming Denial of Service (DoS) attack [11], [12]. In the latter case the safety of the platoon can be jeopardized especially seriously since the vehicles will not be able to update the information about each other within the delay requirements imposed by the automotive control systems. Therefore, the real-time detection of jammers in IEEE 802.11p VANETs is an important practical problem, which motivates our study.

Real-time detection of DoS attacks in IEEE 802.11 networks have been studied in [13], where the proposed detector observes the events happening in the wireless channel and probabilistically computes how "explainable" occurring of each particular collision is. The method in [13] targets the basic mode of IEEE 802.11 with an arbitrary unicast traffic, which is retransmitted according to the binary exponential backoff algorithm. The method to detect the jammers in VANETs with unicast traffic, which is based on linear regression, is proposed in [14]. However, very limited performance evaluation results are reported in [14], e.g. no results on the detection time are given.

In comparison to the above studies, we consider the beacons, which are transmitted regularly in IEEE 802.11p broadcast mode without retransmissions, making it possible to propose an alternative jamming detector. To the best of our knowledge no literature has considered the problem of jamming DoS attacks detection in VANET platoons so far.

The contribution of this paper is twofold:

- a simple real-time detector of jamming DoS attacks in VANET platoons is proposed;
- the detector is validated in terms of detection and false alarm probabilities within the limited time for two types of jamming attacks.

We emphasize that in this paper we do not consider MAC layer misbehavior, when some nodes violate IEEE 802.11 rules and choose a small backoff counter to get the channel access more frequently than other nodes, and therefore, degrade their performance. The real-time detection of such cases has been studied recently, e.g. in [15] and [16].

The manuscript is organized as follows. In Section II we describe the system model. Section III presents the proposed DoS detection method. Performance evaluation results are provided in Section IV. Finally, Section V concludes the paper.
II. System Model

The following assumptions on the system operation are adopted in our study:

1) The platoon is comprised of $N$ vehicles, which are all in each others communication range. We assume a practically feasible case with the following reference values of the parameters: IEEE 802.11p communication range $\approx 400-500$ meters, inter-vehicle distances in the platoon $\approx 5$ meters, truck length $\approx 15$ meters, this assumption holds for platoons with $N \leq 25$. The current value of $N$ is known to the vehicles since joining and leaving of the platoon involves some negotiation protocol [6].

2) The time between the generation of two subsequent beacons, which is chosen by a vehicle, is fixed and denoted as $T$ and referred to as beaconing period. According to [7] the possible range for $T$ is $0.1–1$ second and varies accordingly to the current rapidity of its kinematic information change. Therefore, the assumption roughly holds for the platoon keeping constant velocity on a highway.

3) Each generated beacon is broadcasted into the channel according to the IEEE 802.11p MAC rules. The random backoff counter value is chosen uniformly from the interval $[0, W - 1]$, where $W$ is the minimal Contention Window (CW). The counter is decremented by one after each slot of length $\sigma$ when no activity is sensed in the channel. In case transmission is detected, the vehicle has to ensure that the channel becomes idle for the Arbitrary InterFrame Space (AIFS) before further decreasing the backoff counter$^3$. The transmission is performed, when the counter turns to zero$^4$. The beacons are neither acknowledged by the recipients nor retransmitted. The beacon transmission time is $\tau = T_h + L/R$, where $T_h$ is the header transmission time, $L$ is the beacon payload size and $R$ is the channel rate.

4) The communication channel is assumed to be error-prone with independent losses of beacons and fixed packet error rate (PER). As it follows from the practical measurements reported in [17], when the platoon length does not exceed 400 meters, PER is lower than 1%, given the line-of-sight condition between the antennas of vehicles holds (this can be achieved by placing them, e.g. at the outdoor rear-view mirrors). Apart from the noise, collisions with beacons from any of the $N - 1$ remaining vehicles are also possible.

Two attacker models are assumed [13]:

- "Random jamming". Each packet transmitted in the channel is corrupted independently with probability $p$.
- "ON-OFF jamming". In the OFF state no packets are jammed, while in the ON state $K$ subsequent beacons are destroyed with probability one. Then the attacker switches to the OFF state. The OFF–ON transitions occur at the moments of beacon transmission start with probability $p$.

III. Simple Jamming Detection Method

A. Preliminaries

Let us assume that there is a node (detector), which continuously listens to the channel, where the exchange of beacons between the vehicles in the platoon occurs. Practically the detector can be envisioned as a sniffer mounted on the leading vehicle.

The operation of the proposed jamming detector comprises two phases: installation phase and normal operation.

B. Installation phase

The objective of the installation phase is to divide all the vehicles in the platoon into groups in a way that the beacons from different groups never collide with each other. For this reason the detector tries to obtain some estimates for the beacons generation moments of all the vehicles in the platoon. The actual transmissions may occur at a later moments due to the random backoff delays.

The detector listens to the channel until it has received the sequence of $N + 1$ successfully transmitted beacons in a row$^5$. The sequence of time intervals between these transmissions is denoted as $(t_1, t_2, \ldots, t_N)$, where $t_i$ is the duration between the end of transmission of the $i$-th beacon and start of the transmission of the $(i + 1)$-th one, see Fig. 2.

**Proposition 1.** Beacons from nodes $i$ and $i + 1$ never collide if both the following conditions hold:

$$\tau + AIFS > (W - 1)\sigma,$$

where $\tau$ is the time needed to receive such a sequence is studied later in the paper.

$^3$If the jammer receives the preamble of a packet and starts to corrupt only its payload, then Extended InterFrame Space (EIFS) should be used instead of AIFS [2]. In this paper we assume that the packet is completely destroyed by the attacker.

$^4$In the IEEE 802.11p if the channel was sensed as idle for the AIFS time prior to the packet generation it is allowed to transmit it immediately without entering the backoff process. Throughout of this paper we ignore this option to avoid persistent collisions at each beaconing period in case two (or more) beacons are generated at a nearby time instances.
\[ t_i > AIFS + (W - 1)\sigma. \] (2)

**Proof:** Let \( x \) be the moment of time when the transmission of node \( i \) has finished. From (1) it follows that independently of its backoff counter choice, node \( i \) could not start its transmission later than \( x + AIFS \). Analogously from (2) it follows that node \( i + 1 \) could not start its transmission earlier than \( x + AIFS \). ■

In the following we assume that system parameters are chosen in a way that (1) is satisfied (see Section IV) and we adopt the notation \( S = AIFS + (W - 1)\sigma \).

**Proposition 2.** Let \( t_m = \max_{1 \leq i \leq N} t_i \), then nodes \( m \) and \( m + 1 \) never collide if \( \frac{T}{\tau} > \tau + S \).

**Proof:** The minimal possible value of \( t_m \) is achieved when the transmissions of all the \( N \) vehicles are uniformly spread in time within the beaconing period \( T \), i.e. the difference between their transmission times is \( T/N \). Taking this into account, it is easy to see that inequality (2) for \( t_m \) holds. ■

Applying Proposition 2 the detector operation is divided into independent detection periods of duration \( T \). We define that the first detection period begins \( \sigma(W - 1) \) prior to the transmission start of the \( m \)-th beacon, see Fig. 3.

Let \( \bar{t} = (t_{m+1}, t_{m+2}, \ldots, t_N, t_1, t_2, \ldots, t_m) \). For easiness of notation let us renumber the components of this vector as \( \bar{t} = (t_1^*, t_2^*, \ldots, t_N^*) \), where \( t_j^* \) is the duration between the end of transmission of the \( j \)-th beacon and start of the transmission of the \( (j + 1) \)-th one.

Applying Proposition 1 it is possible to divide all the vehicles into groups in a way that beacons from different groups never collide. For this reason vector \( \bar{t} \) should be analyzed:

- If for some vehicle \( j \): \( t_j^* \leq S \) and \( t_j^* > S \), then the beacon of this vehicle never collide with other beacons.
- Analogously if there is a group of \( K > 1 \) vehicles \( j_1, j_2, \ldots, j_K \) such as \( t_{j_k}^* \leq S \) holds for all \( k : 1 \leq k \leq (K - 1) \), but \( t_{j_{K-1}}^* > S \) and \( t_{j_K}^* > S \), then the beacon of these \( K \) vehicles can collide with each other, but not with the beacons of the other \( N - K \) vehicles.

Therefore, the outcome of the installation phase is the sets \( \Omega_i \) of vehicle identifiers such as beacons from different sets never collide with each other, which is obtained by analyzing the transmission in the first detection period. By the end of the first detection period the detector switches to normal operation.

**C. Normal operation of the detector**

Normal operation is organized in detection periods of length \( T \). The detector listens to the channel and records the identifiers of the vehicles for which beacons have been successfully received. The decision is made by the end of each detection period as follows:

- "Alarm": if there is at least one group among \( \Omega_i \), where exactly one beacon has not been received.
- "No alarm": otherwise.

The underlying idea of such an approach is simple: in case of a beacon loss there should exist at least two nodes involved in the collision within the same group.

**IV. PERFORMANCE EVALUATION**

**A. Preliminaries**

We study an IEEE 802.11p system with \( N \approx 25 \) vehicles and \( T \approx 0.1 \) s with the following parameter values (see [2], best effort MAC access category): \( AIFS = 110 \) \( \mu s \), \( W = 16 \), \( L = 400 \) bytes, \( R = 3 \) Mbit/s, \( \sigma = 13 \) \( \mu s \), \( T_b = 52 \) \( \mu s \).

It is easy to check that for the above parameters, the condition (1) holds. Simulations demonstrate that the installation phase time, i.e. the time from the moment when the detector is turned on until the end of the first detection period, does not exceed 150 ms for the error-free channel and 200 ms for \( PER = 0.01 \), see Fig. 4.

Under the given set of assumptions and based on the rules of detector operation, the probability of false alarm, i.e. the probability that the alarm is triggered although no beacons have been jammed in the detection period, is zero for error-free channel and does not exceed 2% for \( PER = 0.01 \) (0.1 \( \leq p \leq 0.5 \)).

In the following subsections we study the probability of attack detection \( P_{\text{detection}} \), i.e. the probability that the alarm is triggered, given that at least one successfully transmitted beacon is jammed in the detection period.

**B. Random jamming case**

For the random jamming case, the relation between the probability of attack detection and the jamming probability is depicted in Fig. 5. We average the detection probability for different initial mutual offsets of beacon generation moments. For any \( p \) value the averaged \( P_{\text{detection}} \) exceeds 0.996 for error-free case and 0.993 for \( PER = 0.01 \). Taking into account that one detection period is \( T = 0.1 \) s, in most cases the attack is detected with probability close to one within a few hundred milliseconds.

The minimal value of \( P_{\text{detection}} \) is observed when two beacons in average are jammed during the detection period, i.e. when \( pN \approx 2 \), since the probability that these two beacons belong to the same group and, therefore, the attack is not detected, is high.

The operation of the system for the error-free case can be analytically modeled using the following approximate approach.

Let us assume that the detection period is divided into \( M \) slots, such that \( M = \frac{T}{AIFS} \). If \( i \) vehicles choose the same slot for the transmission (each with probability \( 1/M \)), then they form one group. Due to time diversity provided by the backoff mechanism, transmissions of the group take \( i \) slots.
probability is depicted in Fig. 6.

\[ P_{\text{detection}}(n, p) = \sum_{j=2}^{\infty} \binom{n}{j} p^j (1-p)^{N-j}. \]  

Finally, taking into account the detector operation rules, which cannot detect the cases when more than one beacon is jammed in a group, we obtain:

\[ P_{\text{detection}} \approx 1 - \sum_{n=2}^{N} P_n Q(n, p). \]  

C. ON-OFF jamming case

For the ON-OFF jamming case \((K = 2)\), the relation between the probability of attack detection and the jamming probability is depicted in Fig. 6.

In contrary to the random jamming, \(P_{\text{detection}}\) in this case is an increasing function of the jamming probability. Small \(p\) values correspond to the case when exactly two subsequent (and therefore highly probable – belonging to one group), beacons are jammed, which is not detected. With the increase of \(p\), more pairs of beacons are likely to be jammed, i.e. it is more probable, that a group of exactly one beacon is involved and, consequently, the attack is detected. Further increase of the \(K\) value also increases \(P_{\text{detection}}\).

V. CONCLUSION AND FUTURE WORK

We have proposed a simple algorithm for real-time detection of jamming attacks against beaconing in 802.11p vehicular networks. For the reference platooning scenario under the simplified assumptions our algorithm provides in average the probability of detection not lower than 0.9 and no false alarm for any jamming probability.

Our ongoing work is focused on relaxing the assumptions of the presented model (especially about the fixed beaconing period) and correspondingly enhancing the detector for realistic scenarios.

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