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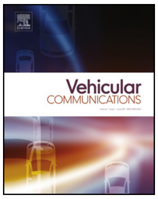

A survey on vehicular communication for cooperative truck platooning application

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ABSTRACT

Platooning is an application where a group of vehicles move one after each other in close proximity, acting jointly as a single physical system. The scope of platooning is to improve safety, reduce fuel consumption, and increase road use efficiency. Even if conceived several decades ago as a concept, based on the new progress in automation and vehicular networking platooning has attracted particular attention in the latest years and is expected to become of common implementation in the next future, at least for trucks.

The platoon system is the result of a combination of multiple disciplines, from transportation, to automation, to electronics, to telecommunications. In this survey, we consider the platooning, and more specifically the platooning of trucks, from the point of view of wireless communications. Wireless communications are indeed a key element, since they allow the information to propagate within the convoy with an almost negligible delay and really making all vehicles acting as one. Scope of this paper is to present a comprehensive survey on connected vehicles for the platooning application, starting with an overview of the projects that are driving the development of this technology, followed by a brief overview of the current and upcoming vehicular networking architecture and standards, by a review of the main open issues related to wireless communications applied to platooning, and a discussion of security threats and privacy concerns. The survey will conclude with a discussion of the main areas that we consider still open and that can drive future research directions.

1. Introduction

Compared to the huge increase in the number of vehicles on the road, the overall improvement of the transportation systems is very slow. This is causing traffic conditions and safety to be daily challenges in our cities and highways. Thanks to significant recent advances in computation, communication, and control technologies, connected and autonomous vehicles are slowly becoming a reality and promise to give answers to such unsolved problems. Yet, for a number of reasons, time will be needed before a high penetration is reached and the benefits visible on a large scale.

Among the several applications that have been imagined and experimented in the last decades, platooning is surely one of those attracting highest attention, also because of its peculiarity to be implementable without the need to reach a large number of vehicles [1]. Platoon, in fact, is simply one or a group of vehicles (following vehicle (FVs)) that follow a leading vehicle (LV), as depicted in Fig. 1. Platooning supports the capabilities of the driver by reacting more quickly, more accurately, and more reliably, compared to what a driver normally does. This directly impacts on security, but at the same time allows reducing the inter-vehicle distance, which in turn improves road efficiency and fuel consumption.

The initial automated platooning targeted convoys of, or at least including, passenger cars, such as in the PATH project [2] and in the SARTRE project [3]. However, a much greater effort from both industry and academia research has later been put on heavy vehicles, which are the main subject of this survey. The main reasons behind that, clearly detailed in [4], include:

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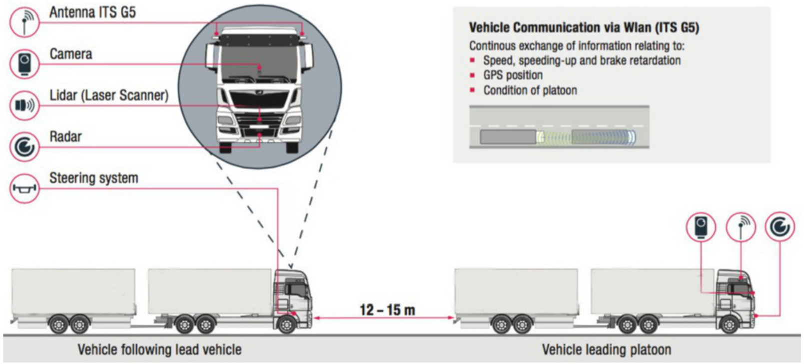

Fig. 1. Platooning and the technologies.

1. Energy saving efficiency is much larger for trucks, and investments on the automated driving units by freight operators can be quickly returned by energy saving;
2. Automated driving will decrease driver's workload, which is an aspect of particular importance for truck drivers who usually drive for longer distances;
3. Safety improvement is of particular significance when it focuses on heavy vehicles, since accidents caused by trucks along expressways have large influence, with more serious consequences both in terms of damages and impact on traffic;
4. As the truck drivers are professional, it will be easy for them to handle the automated driving system;
5. Due to the long common route among passenger cars, these types of cars are more suitable for platooning.

Targeting trucks, special remark goes to fuel consumption and the consequent pollution, which are indeed among the main reasons why platooning is raising so much attention. This becomes clear when we note that 5% of global carbon production is done by heavy vehicles [5], and that a significant reduction can be achieved thanks to platooning. For example, in [6], Bonnet and Fritz have shown a fuel reduction of more than 20% for FVs trucks and even about 5% for LV. These results were achieved at a modest speed of 80 km/h and a relatively relaxed distance of 10 m between vehicles. Thus, an even higher impact is expected in some cases.

The reference to fuel consumption already allowed to intuit that in platooning the inter-vehicle distance is a crucial point, eventually subject of a trade-off: a smaller distance among vehicles leads to better use of road capacity and reduced drag (reduced fuel consumption); on the other hand, reducing the distance among cars increases safety concerns, which must be challenged by fast and accurate communication and control. In the end, the achievable gain is inversely related to the distance that can be maintained, and therefore to the ability of technologies to make a given gap, as short as possible, to be safe enough [7].

The consideration motivating this survey is that very short gaps and thus significant advantages can be obtained only with the adoption of advanced wireless systems. As represented in Fig. 2, during manual driving, safe following distances between trucks are maximized to give enough time for driver perception, reaction, and brake lag whenever there is an obstacle ahead. In recent years, trucks are increasingly being equipped with world-class sensors, such as radar, lidar and ultrasonics sensors, which mitigate collisions, removing driver perception and reaction; however there is still a delay before the rear truck detects the front one slowing down and brakes. It is to be noted that in the case of platoons with multiple trucks, such delay is detrimentally propagated back and thus its effect magnified at the last vehicle. With wireless communications potentially connecting all trucks with a latency that reduces impressively with the technology evolution, the vehicles will ultimately be able to act as they were one, with just a few meters of gap.

1.1. Existing surveys

Although this domain is almost 45 years old, as far as we know and discussed in this section, as reported in Table 1 there are several surveys on platooning but neither of them strictly addresses recent developments on wireless communications for platooning [8–11,7,12–17].

Going through the list in Table 1 in chronological order, the authors of [8] have presented one of the first surveys, reviewing the published platooning papers between 1994 and 2010. The paper briefly explains what platooning is and describes its evolution. The authors organized the main part of the paper into three sections: inter-vehicle communication, control strategies, and string stability. Santana et al. highlighted in [9] some of the important issues and challenges for the platooning application, such as communication, control, and even security, without specifically focusing on wireless communications. An update of the literature on platooning with details on wireless communications is then provided in [10], where the authors present a survey on cyber-physical issues in platoon system. Their concerns include clustering, cooperative adaptive cruise control (CACC), and communications, for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Still, much work has been done after [10] was published.

Later, [11,7,12] again focus on platooning, but not addressing wireless communications in particular. Specifically, Tsugawa et al. [11] review the papers and the projects that pay attention to fuel consumption in platoon system from mid-1990s to 2013, including PATH, KONVOI, Energy ITS, etc. Axelsson in [7] provides the definition of safety and what is needed to achieve acceptable level of safety in platoon system. In [7], the authors considered the current status of safety in platoon system. Then, they have analysed various aspect of the platoon system including business ecosystem safety analysis methods, variability in vehicles, and human factor issues. In [12], have presented truck platooning issues and related solutions and approaches.

Artificial intelligence (AI)-based algorithms applied to the vehicle-to-anything (V2X) paradigm have been presented in [13]. The authors have shown that these approaches can perform better performance compared to the traditional approaches. Although relevant also for platooning, that use case is not explicitly addressed by the survey.

Then all the surveys in [14–17] specifically focus on platooning but do not consider or consider only partially the aspects related to wireless Communications. In [14], Park et al. provide a brief discussion on wireless communications for platooning that provide an interesting overview but do not enter in the details of the

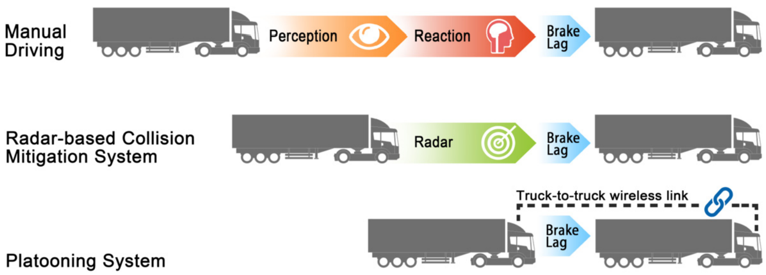

Fig. 2. Safety gap in platooning and other approaches.

Table 1
Comparison with existing surveys on platooning.

Year	Paper	Focus on platooning	Topic(s) of the survey	Enhancements in our paper
2011	[8]	✓	Inter-vehicle communication, control strategies, and string stability	Enhanced list of papers since 2010 to date
2015	[9]	✓	Highlighted some of the important issues and challenges for the platooning application, such as communication, control, and even security	In-depth discussion of challenges for wireless communication protocols such as IEEE 802.11p, cellular network, visible light communication focusing specifically on MAC layer and detailed discussion of security and privacy issues
2016	[10]	✓	Discuss the fundamental issues, including vehicle platooning/clustering, CACC, and platoon-based vehicular communications, both including V2V and V2I communications. Give an overview of simulation tools, which are commonly used for vehicular environment	Enhanced technologies covered with adding cellular and visible light communications and enhanced list of papers since 2015
2016	[11]	✓	Show a history of important national and international projects, which investigated the impact of platooning on fuel efficiency from mid-1990s to 2013	Enhanced list of projects since 2013 to date
2017	[7]	✓	Investigate the current status of safety analysis for platooning, including identification of hazards and failures, and improvement of safety	Coverage of wireless communication technologies for implementing platooning application
2018	[12]	✓	Classifying the different planning problems in truck platooning, reviewing the papers related to this issue, and presenting future research directions	Coverage of wireless communication technologies for implementing platooning application
2019	[13]		Presenting AI-driven algorithms for V2X applications and showing improved performance over traditional algorithm	Addressing of communication, security and privacy for platooning application in detail
2020	[14]	✓	Presenting approaches to utilize the bandwidth and considerations in inter-vehicle communication to support platooning	Comprehensive analysis of all aspects of platooning communication
2020	[15]	✓	Overview of state of the art papers with respect to platooning objectives such as: Energy Efficiency, Safety, Traffic Flow & Road Capacity, Velocity, Time, User Comfort, Destination & Distance, Balance of Individual Objectives, Cost Balancing	Presenting platooning technical issues and their solutions in communication and security
2021	[16]	✓	Introducing the main issues of autonomous vehicles coordination and different approaches to deal them	Analysing important issues in platooning such as: communication, security and privacy
2021	[17]	✓	Presenting vulnerabilities of the V2V communications, with detection mechanisms and proactive defenses	Addressing main issues in platooning such as communications, networking, privacy and security

technological issues. Sturm et al. [15] has categorized the existing surveys according to their purpose. These categories include: Energy Efficiency, Safety, Traffic Flow & Road Capacity, Velocity, Time, User Comfort, Destination & Distance, Balance of Individual Objectives, and Cost Balancing. The various coordination problems for autonomous vehicles have been presented in [16]. The researchers have tried to present the main solutions that can be analysed for each type of platooning. In [17], the authors have specifically presented security vulnerabilities and related defense mechanisms for platooning.

As summarized in Table 1, to date a few surveys have been conducted that focus on wireless communications in platooning, and the few are not recent and thus do not cover the latest literature on the topic. Therefore, this is the first article that offers an up to date review of new communication technologies for platooning. As an added value, we discuss security and privacy issues and challenges that has not been strictly considered before in any survey for platooning application. Table 2 shows a summary of main acronymns and their definitions used throughout this paper.

1.2. Scope and organization

In this paper, we have focused on wireless communications for truck platooning, and related technology and challenges. In particular:

1. We briefly summarize in Section 2 the key points of previous platooning projects that were carried out in the US, Europe and Asia to show what they covered and excluded.
2. Then, we quickly discuss the requirements for platooning application on the vehicular networking architecture in Section 3.
3. In Section 4 we recap the available wireless communication standards, regulations and architectures in the US and Europe and show what other alternatives are available and being discussed in addition to these standards.
4. We then provide in Section 5 an insight of the main aspects at the medium access control (MAC) layer, given the relevance of this layer to avoid message losses due to concurrent access to the medium by platoon members.

Table 2
Main acronyms and their definitions.

Acronyms	Definition	Acronyms	Definition
ACC	adaptive cruise control	BSM	basic safety messages
BSS	basic service set	C2C-CC	Car-2-Car Communication Consortium
CACC	cooperative adaptive cruise control	CAM	cooperative awareness messages
CC	cruise control	CAV	connected and automated vehicle
CCH	control channel	CEN	European Committee for Standardization
C-ITS	cooperative-intelligent transport systems	CSMA/CA	carrier sense multiple access with collision avoidance
C-V2X	cellular-vehicle-to-anything	D2D	device-to-device
DCC	decentralized congestion control	DENM	decentralized environmental notification messages
DIS	driver information system	DSRC	dedicated short-range communications
EC	European commission	EDCA	enhanced distributed coordination access
ETSI	European Telecommunications Standards Institute	eMBMS	evolved multimedia broadcast multicast services
EV	electric vehicle	FV	following vehicle
GNSS	global navigation satellite system	GPS	global positioning system
IR	infrared	IST	information society technologies
ITS	intelligent transport systems	LOS	line-of-sight
LTE	long term evolution	LV	leading vehicle
MAC	medium access control	NLOS	non-line-of-sight
OFDM	orthogonal frequency division multiplexing	OFDMA	orthogonal frequency division multiple access
PSP	platoon service provider	RSU	road side unit
SAE	Society of Automotive Engineers	SCH	service channel
SDO	standardization development organization	SDN	software-defined network
STDMA	self-organizing time division multiple access	TDMA	time division multiple access
V2I	vehicle-to-infrastructure	V2V	vehicle-to-vehicle
V2X	vehicle-to-anything	VANET	vehicular ad-hoc network
VLC	visible light communications	WAVE	wireless access for vehicular environments

5. Additionally, in Section 6 we cover the main issues related to security and privacy, which are very important aspects in the platoon system.
6. Finally, some open research challenges related to wireless communications for platooning are discussed in Section 7.

2. History of truck platooning

There are different stories about when the idea of platooning started. Apparently, Norman Bel Geddes suggested the idea of automatic truck for the first time in 1939. Some tens of years later, ARAMIS (1972-73) was the first European industry project which implemented the concept with 5 small transit vehicles, and later, again in Europe, platooning was one of the use cases of Prometheus (1987-1995), a project making car and truck makers cooperating towards the idea of automated vehicles.

In the last decades, several other projects were carried out in the United States, Europe and Asia to improve the platooning technology, among which the main ones are hereafter reviewed.

2.1. CHAUFFEUR

The CHAUFFEUR project [18] was started in 1996 and was one of the initial efforts in Europe to offer truck platooning and driver assistant functionalities by European Commission (EC) information society technologies (IST), including Germany, Italy, France and the UK. Three applications were considered in this project: 1) two truck platooning, where only the LV needs an active driver; 2) platoon of more than two trucks, again with an active driver only in the LV; and 3) fully automated truck platoon. All system input and output, as well as communication protocols and messages have been defined in detail. A radio communication system was used to ensure reliable and efficient data and information exchange between trucks, with the antennas mounted on rear view mirrors. Two key parameters were identified: the sampling frequency of the signal to be transmitted by trucks and the time delay between the data acquisition on the first truck and the availability of the signal in the vehicle control system of following trucks. Communications were based on three data flows: 1) from the LV to all the FVs; 2) from all the FVs to the LV; and 3) from each vehicle to its successor. Two different types of messages were identified: a forward-message and a backward-message. The forward-message contains data from the LV and from the vehicle that precedes. The backward-message starts containing data of the last vehicle and then the others in the chain add their own information.

Fig. 3. PATH Program Eight-Car Fully-Automated Platoon Demonstration [20].

2.1.1. California PATH

The California PATH program [19,20] was started in 1986, as the first research program in North America on intelligent transport systems (ITS) and as a collaboration between the California Department of Transportation (Caltrans) and the University of California's Institute of Transportation Studies. The objective was to twist information technology (IT) and transportation systems to significantly increase the capacity of the highway infrastructure. Initial experiments were performed in 1992 with a platoon of four cars, using automated longitudinal control. Other experiments of platooning include the National Automated Highway System Consortium demonstration of eight fully automated cars in 1997, shown in Fig. 3, automated merging of passenger cars in 2000, and automated platoon of transit buses and tractor-trailer trucks in 2003, shown in Fig. 4.

Fig. 4. PATH Program Two-Truck Platoon [20].

The PATH project was based on three fundamental assumptions: 1) automated and non-automated vehicles must be physically separated to avoid interventions; 2) automated vehicles should be fully automated, with the driver out of the control loop; and 3) the automated vehicles must be able to communicate with each other and the roadway infrastructure, rather than operating autonomously. Steven Shladover summarized key advances in knowledge resulting from PATH program in [19]. The results show that platooning could increase the capacity of highways by a factor of two to three for passenger cars (in platoons of up to ten vehicles) or a factor of 2 for trucks (in platoons of up to three trucks). The PATH project also showed that platooning of American-style tractor trailer can save 10 to 15% of the fuel consumption for the leading truck and 5 to 10% for the following truck at highway speed.

The PATH project is still operational and currently runs three-truck platoons moving at 14 feet intervals [2].

2.1.2. KONVOI

The KONVOI project [21] started in 2005 and ended after 5 years. The project was funded by German's Federal Ministry of Economics and Technology with the main objective to develop and evaluate truck platooning. As shown in Fig. 5, the project scenario consisted of up to four trucks, which were operated at a speed between 60 and 80 km/h and a distance of 10 meters. Within KONVOI, there is a central server with a data mining algorithm for determining the order of vehicles in each platoon, which merely uses the information of the global positioning system (GPS). The truck driver plans his route, selects economic platoon participants as well as initializes and confirms the platoon maneuvers in order to build and dissolve the platoon, with the help of a driver information system (DIS). In [21], different sources of errors are mentioned, including the uncertainty of the GPS signal and calculations for the interpolation and extrapolation. However, the authors believe that an upper-bound can be calculated for them. In addition, an algorithm is proposed to find the order of platoon members based on several information, such as loading weight, engine power, etc; however, it is not mentioned who performs this process and what is the impact of re-ordering on non-platoon members.

2.1.3. Energy ITS

The Energy-ITS project [4,22,23] was a 5 years national project that started in 2008 in Japan, aiming at energy saving and global warming prevention with ITS technologies. Energy-ITS focused on a 3 vehicles platoon driving at a constant velocity of 80 km/h with gaps of 10 m and 4 m (the trucks have a bumper at the rear for passive safety and the length is 0.7 m. Thus, the aerodynamic gap is 4.7 m), and empty load. Each truck was equipped with 2 machine vision units for the lateral control, one attached at the front and the other at the rear, as shown in Fig. 6.

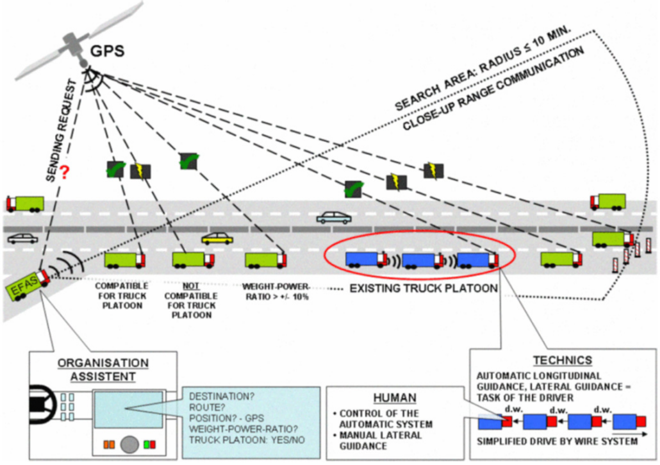

Fig. 5. KONVOI project [21].

To improve robustness, infrared (IR) was used together with DSRC. They were attached with the IR units at the bumpers in order to prevent the influence of a sunbeam. The experiments included a passenger car, which was not automated, one automated light truck, and 3 automated heavy trucks. The automated trucks had 3 driving states, including manual, semi-automated (only longitudinal control using adaptive cruise control (ACC)), and fully automated (both lateral and longitudinal control); the driver was responsible to change the state. The project included the following 5 scenarios: platoon formation, passenger car driving at 60 km/h in front of the platoon, passenger car trying to get into the gap between trucks, platoon lane changing, and platoon LV braking (the lead truck manually operates the brake). The results showed that the energy consumption can be improved by about 14% when the gap is 4.7 m, as reported in Fig. 7. A CO_2 reduction of 2.1% and 4.8% was derived with a gap of 10 m and 4 m, respectively (assuming a penetration rate of 40%). It was also concluded that the longest platoon can be of 4 trucks, since longer convoys might cause difficulties to the other vehicles sharing the road. In addition, the Energy-ITS project depicted a road-map for the service introduction, including the definition of 3 types of truck platooning: 1) near future platooning, based on ACC and with each truck needing a driver; 2) mid future platooning, based on CACC and still with the necessity to have a driver in each truck; and 3) far future platooning, which is controlled by CACC driving in a dedicated lane and with only one driver in the leading truck. A major open issue highlighted by Energy-ITS was when and where platoon should be formed and split.

2.1.4. SARTRE

European Commission, Ricardo UK and Volvo have cooperated in SARTRE project (2010-2012) [3,24–26].

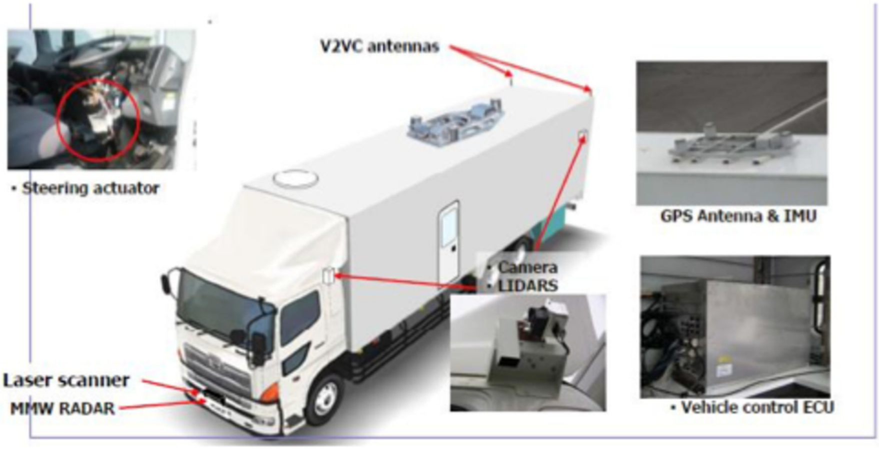

Fig. 6. Configuration of the automated truck in Energy ITS project [21].

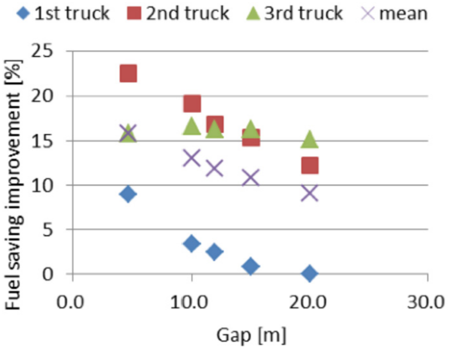

Fig. 7. Effect of gap on the fuel saving improvement in Energy ITS project [21].

Experiments were performed with a platoon of 5 cars, including two trucks and three passenger cars, as shown in Fig. 8.

Some of the assumptions defined by the project are as follows (not all of these assumptions were then implemented in the demonstrator) [3]:

- No changes to road infrastructure are required (differently from the PATH project, which assumed dedicated lanes);
- A minimal platoon is one LV and one FV;
- A platoon has a maximum size; if a vehicle wants to join after the platoon reaches its maximum size, join will not be allowed;
- Dynamically varying size of gaps between vehicles in a platoon is allowed, i.e., there is no requirement for maintaining a fixed distance;
- A heavy duty vehicle is not allowed to follow a passenger car;
- If required response time is shorter than what is achievable by a human, then autonomous driving handles the situation.

In SARTRE, several important aspects of platooning have been investigated, including the proper gap size for joining and leaving, the time needed for creating, joining or leaving a platoon, string stability, the influence on the traffic flow (e.g., at highway entrances and exits) and fuel consumption.

SARTRE included the following use cases: 1) platoon formation; 2) platoon dissolution; 3) platoon joining from rear, side and front; 4) platoon leaving from side and front; and 5) platoon maintenance. The simulation results showed that all considered leaving and joining use cases are technically feasible and the duration vary from 22 to 75 seconds [24].

V2V communications were based on the IEEE 802.11p standard using the 5.9 GHz frequency band. SARTRE involved automated control in longitudinal as well as lateral positions (lateral positions were used for the first time in platooning experiments). Two antennas were installed on the LV, including one on the cabin and one at the rear of the container. In the FV, one antenna was placed on the roof. During the experiments, the distance between the vehicles was varied between 20 and 170 meters. The experiments showed that the performance of the V2V is sensibly affected by line-of-sight (LOS) conditions and the placement of the antenna is a key factor. The rear placement displayed superior results, especially for distances above 70 meters.

The SARTRE project also measured the fuel consumption for each vehicle while they drive in a platoon and compared it with their individual consumption. The results, reported in Fig. 9, show that there is an important decrease in fuel consumption when inter-vehicle distances are shorter. For example, the following truck saw the highest fuel savings of 16 percent at a gap of 5 meters. When the gap was increased to 15 meters, it still observed fuel savings, but just over 8 percent. The fuel savings of the first of the following vehicles ranged from nearly 12 percent at a 7 meters gap to just over 4 percent at a 15-meter gap.

An extended version of the ITS-G5 V2V communication was used for intra-platoon communication. Since ITS-G5 is not designed for platooning, additional information was added to the standard CAM and DENM messages and proposed to ETSI to be included in the new standards [29]. This extra information includes platoon ID, position in the platoon, presence of an intruder, speed of intruder, distance to intruder, and intended speed and retardation. The project also proposed to the standardization that the control channel (CCH) is not enough to send all platooning information and it can be used only to send general information; in particular, controlling and directing information should be sent on an specific service channel (SCH). Moreover, it was also identified that the default frequency for broadcasting CAMs, i.e., 10 Hz, is not enough and it needs to be increased to 20 Hz to guarantee an acceptable level of safety.

In addition to the mentioned projects, which are concluded, the following are presently running worldwide.

2.1.5. CONCORDA

The CONCORDA project started beginning of 2018 as partnership between several members of the European Automotive Telecom Alliance (EATA) from Germany, the Netherlands, Spain, France, Belgium. CONCORDA aims at enhancing and upgrading the environment for existing pilot projects for three main use cases: automated highway chauffeur, truck platooning and automated collision avoidance functionalities.

Fig. 8. SARTRE project, two trucks and three passenger cars following leading trucks [27].

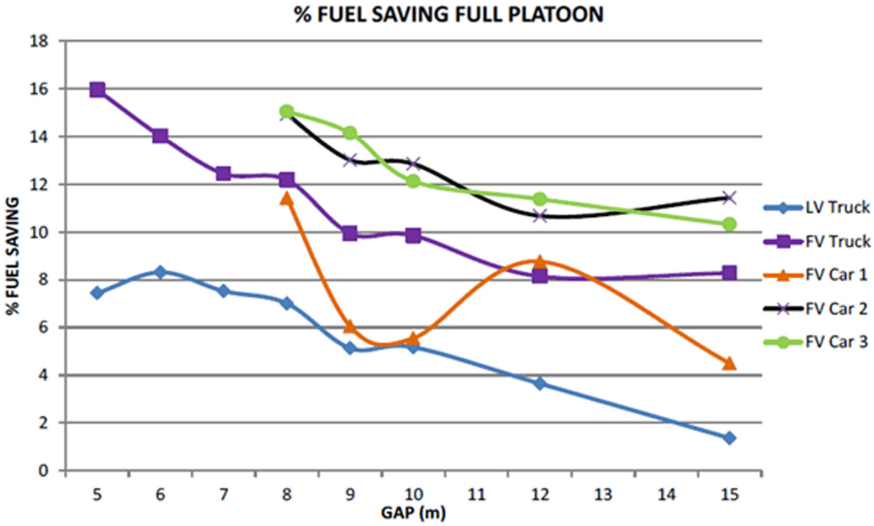

Fig. 9. Fuel savings of each vehicle in the platoon at varying gaps [28].

More specifically, the project seeks to identify the potential of hybrid, safe and secure communications and digital infrastructures, as well as tackling challenges in these fields. The main driver is that with connectivity technologies developing so rapidly, it becomes increasingly important to test the several communication technologies available, such as ETSI ITS-G5, cellular based 3G/LTE, pre-fifth generation (5G) long term evolution (LTE)-V2V and multi-access edge computing (MEC).

2.1.6. Sweden4platooning

The Sweden4Platooning project is a national funded project started beginning of 2017, including the truck manufacturers Volvo and Scania and the haulage company DB Schenker. The main project objectives are to demonstrate feasibility of CACC on public roads and to verify platooning with automated longitudinal and lateral control at test sites.

2.1.7. ENSEMBLE

The Enabling SafE Multi-Brand pLatooning for Europe (ENSEMBLE) project started in 2018 within the framework of Horizon2020. It is a research project between vehicle manufacturers, suppliers, associations and policy makers, aiming at making platooning multi-brand, interoperable, safe, based on real-life conditions and embedded in today logistics flow.

In addition to the publicly funded R&D projects that were mentioned, there are also several commercial development projects going on in Europe, the US and Asia. Among these activities, we can mention Peloton Technology as an example, which is a company developing platooning as a product for the market.

Table 3 shows a summary of the main platooning projects concluded in the last twenty years, with the most relevant characteristics.

Table 3
Comparison of the main concluded projects on platooning.

Projects	Funding	Duration	Objectives	Control	Communication Technologies	Scenarios	Results
CHAUFFEUR	USA	1996-2004	To demonstrate the feasibility of a three-truck platoon operating in real world environments.	Long only	V2V communications system at 5.8 GHz	1) Two truck platooning, where only the first truck needs an active driver; 2) platoon of more than two trucks, again with an active driver only in the first vehicle (feasibility study); and 3) fully automated truck platoon (feasibility study).	The CHAUFFEUR II project has proven the technical and operational feasibility of CHAUFFEUR assistant and platooning. Five prototype vehicles have been constructed, that successfully performed the operations defined at the beginning of the project.
PATH	USA	2000-2011	Increase of the capacity of the highway infrastructure.	Lat + Long	DSRC/IEEE 802.11	1) Platoon of four cars using automated longitudinal control in 1992; 2) eight fully automated cars in 1997; 3) automated merging of passenger cars in 2000; 4) automated platoon of transit buses and tractor-trailer trucks in 2003.	The results show that platooning could increase the capacity of highways by a factor of two to three for passenger cars (in platoons of up to ten vehicles) or a factor of 2 for trucks (in platoons of up to three trucks). The PATH project also showed that platooning of American-style tractor trailer can save 10 to 15% of the fuel consumption for the leading truck and 5 to 10% for the following truck at highway speed. p
KONVOI	Germany	2005-2009	To investigate the benefits and deployment issues associated with truck platooning in mixed traffic on German highways.	Lat + Long	3G, ITS-G5	Up to four trucks, which are operated at a speed between 60 and 80 km/h and a distance of 10 meters.	Although previous projects showed that smaller inter-vehicle distances between vehicles leads to more significant fuel savings, this requires a robust controller to guarantee stability. Otherwise, the followers need to accelerate and brake in order to maintain a safe distance to the vehicle ahead, which causes additional fuel costs. The KONVOI project showed fuel saving on the test sites but no fuel savings during the test on public highway [30].
Energy-ITS	Japan	2008-2013	Energy saving and global warming prevention	Lat + Long	DSRC/IEEE802.11p	The experiments included 5 vehicles, a non-automated passenger car, one automated light truck, and 3 automated heavy trucks. Platoon vehicles drove at a constant velocity of 80 km/h, the gap was of 10 m and 4 m. The project included 5 different scenarios: platoon formation, passenger car driving at 60 km/h in front of the platoon, passenger car trying to get into the gap between trucks, platoon lane changing, platoon leader braking.	The energy consumption could be improved by about 14% when the gap was 4.7 m. The CO_2 emissions could be reduced by 2.1% and 4.8% when the gap was 10 m, and 4 m, respectively (assuming a penetration rate of 40%). They also concluded that the platoon cannot be longer than 4 trucks.
SARTRE	EU	2009-2013	To develop and integrate solutions that allow vehicles to drive in platoons. The other objective of the system are Reduction in fuel consumption (potentially up to 20%), improvement in safety (10% reduction in fatalities) and increasing driver convenience (autonomous systems for following vehicles).	Lat + Long	ITS-G5	Platoon of 5 cars, including two trucks and three passenger cars. SARTRE included the following use cases: 1) platoon formation; 2) platoon dissolution; 3) platoon joining from rear, side and front; 4) platoon leaving from side and front; and (5) platoon maintenance.	The results show that there is an important decrease in fuel consumption when platooning at shorter distances. The experiments also showed that the performance of the V2V is affected by line of sight conditions and that the placement of the antenna is a key factor. The rear placement displayed superior results, especially for distances above 70 meters.

Table 3 (*continued*)

Projects	Funding	Duration	Objectives	Control	Communication Technologies	Scenarios	Results
GCDC	EU	2010-2016	To accelerate real-life implementation and interoperability of cooperative automated driving by both development and demonstration.	Long	ITS-G5	1) Merging on highway (“zipping”) and 2) Cooperative intersection	Several different interaction protocols have been designed and implemented to coordinate different maneuvers for each of the scenarios. The project concluded that interaction protocols should be designed for robustness against “failing” cooperation partners, localization still is a main challenge (even though the accuracy requirements are not that high), and a common automation framework is lacking.
CAMPANION	EU	2013-2016	Creation, coordination, and operation for platooning application	Lat + Long	3G, LTE, ITS-G5	The designed system by COMPANION included both off- and on-board parts. The off-board part calculates the optimal route for different trucks by using transport assignment that is entered to the system by the transport dispatcher at a carrier company. The platooning plan is sent to the vehicle before the trip via the cellular network (3G or LTE). An extended version of the ITS-G5 V2V communication was used for intra-platoon communication.	Additional information have been added to the standard CAM and DENM messages, including platoon ID, position in the platoon, speed of intruder, distance to intruder, intruder exist, and intended speed and retardation. Controlling and directing information were sent on an specific SCH channel. Moreover, the CAM broadcasting frequency increased to 20 Hz in order to guarantee an acceptable level of safety.
ENSEMBLE	EU	2018-2021	Interoperable platooning, Safe platooning Real-life platooning and Embedded platooning	Lat + Long	3G, LTE, ITS-G5	(1) Platooning as a support function, (2) Platooning as an autonomous function	It is the explicit aim of this project to take important steps of technological research before full deployment of multi-brand truck platooning. ENSEMBLE wants to communicate the economic, societal and environmental impact of decisions surrounding platoon forming and dissolving. ENSEMBLE also strives to modernize the transport system by finding an optimal balance between fuel consumption, emission level, travel times and impact on highway traffic flow, resulting in reduced impacts on climate change, air pollution, noise, health and accidents.

3. Backgrounds and assumptions

A platoon is a complex physical system. Drivers must act cooperatively to control and manage the platoon, including formation, merging, splitting, maintenance, etc. Many new technologies have been developed to be used for platooning application. For instance, the distance between adjacent vehicles and autonomously maintain the speed and/or distance is detected by ACC system using the sensors. Moreover, platoon can be equipped with modern wireless communication technologies, which provides more information about the surrounding environment beyond what can be detected by sensors installed in modern vehicles. Such a complex system includes computing, communication, and control technologies. It seems that in order to meet the current needs in the field of platooning, the compatibility of this technology with 5G and 6G technologies should be considered. It also seems that the adaptation of this technology to electronic vehicles should be considered. In this section, we will present some background information and assumptions for platoon application which needs to be considered for designing the communication system.

3.1. Infrastructure requirements and challenges

Apart from how a platoon is built, in the literature it has been evaluated the possibility of using a dedicated platoon lane or the alternative of driving in normal lanes and it has been analyzed the advantages and disadvantages of each possibility. The feasibility study from Texas A&M Transportation Institute presented in [31] reports that the implementation of special lanes where truck platooning would be permitted has been considered in several countries, including the US and Japan. These roadways could be normal dedicated lanes for truck platoons at night on intercity divided rural highways or could be managed lanes at night or off-peak in urban areas.

Dedicated lanes has the advantage to: 1) separate traffic; 2) make better utilization road; and 3) take advantage of similar operational capabilities of trucks in separated traffic. However: 1) it reduces the available capacity of road and flexibility of non-platooned vehicles; 2) it requires special incident management; and 3) it causes public opinion problems whenever the truck-only lane is unused and the others are congested.

3.2. Urban platooning and platoon of electric vehicles

The majority of papers that have been written so far is focusing on platooning for highway areas. Nonetheless, recently platooning has been demonstrated as an option for optimizing also urban traffic [32]. Authors in [32] investigate the effects of platooning on average idling time around signalized intersections. Speed optimization is proposed as function to minimize the average idling time and number of stops. This scheme relies on V2V and V2I communication capabilities so that vehicles could receive signal timing and queue information from the traffic light. Vehicles can decide in a decentralized manner whether to be part of the platoon or not when they are approaching an intersection. The simulation results show that the platoon using the proposed scheme grant shorter average idling time and lower number of stops. In addition, it is shown that this method can achieve the minimum average idling time at an activation distance of 700 meters. Urban platooning is very different compared to other developments focusing on highways: while platoon members on highways share the same route for many kilometers, vehicles on urban areas only share the same route for a very limited time, for instance, passing a few intersections before separating again. The EU H2020 project MAVEN (Managing Automated Vehicles Enhances Network) [33] is developing infrastructure-assisted traffic management solutions for cooperative automated vehicles at signalized cooperative intersections for improving urban efficiency and safety. One of the use cases for MAVEN is urban platooning. In [34], authors describe the functional and communication requirements, and a designed dedicated communication system, which in turn is compliant to the standard ETSI ITS architecture and supports exchange of V2X messages over the ETSI ITS-G5 technology.

Bashiri et al. [35] presents a rule based algorithm for realizing platooning at traffic lights to increase the throughput and to reduce the shock wave effect at intersections. Each traffic light is connected to a dedicated road side unit (RSU) which disseminates information, including the current and next signal states as well as the remaining duration of the state. The proposed algorithm focuses on mixed traffic, in which not all vehicles are necessarily equipped with V2X technologies.

Two different policies has been proposed by Bashiri et al. [36,37]. In [36], they introduced two stop-sign based policies for autonomous intersection management for platoons. These policies outperform regular stop-sign policy both in terms of average delay per vehicle and variance in delay. In [38], the authors introduce a reservation-based policy based on the cost functions proposed in [36] to achieve optimal schedules for platooning. All possible schedules to pick the best that minimizes a cost function is searched by a greedy algorithm based on a trade-off between total delay and variance in delay.

Moreover, with increasing the number of electric vehicles (EVs), it becomes increasingly relevant, especially in urban areas, the concept of platoon of EVs (a.k.a. e-platoon), which also allows EVs to recharge their battery on the fly. In an e-platoon, EVs can share energy with each other and recharge from an electric source carried by a truck. Vehicles need to be equipped with required connectors, either wired or wireless, to transport energy from the truck to e-platoon EVs and between EVs [39]. The platooning in smart cities have some benefits, such as efficient roads usage, time-saving through route optimization, and traffic minimization in peak times. In [40] a traffic management solution for combining platooning on highways and urban areas has been presented. Also, the differences between these two type of platooning has been analysed.

[41–43] presented a strategy for the formation of urban platoons. The results showed that driving in a platoon in urban environments Significantly reduced fuel saving and travel time. It also improved the level of safety.

4. Vehicular networking standards and architecture

A number of standardization development organizations (SDOs) have indeed participated in the last decade to the development of standards for vehicular communications. The International Organization for Standardization (ISO) at international level, the Institute of Electrical and Electronics Engineers (IEEE) and the Society of Automotive Engineers (SAE) in North America, the European Telecommunications Standards Institute (ETSI) and the European Committee for Standardization (CEN) in Europe, and the association of Radio Industries and Businesses (ARIB) in Japan. More recently, also the third generation partnership project (3GPP) for what concerns cellular systems. The different architectures that have been proposed based on such standards are reported in Fig. 10.

Currently, the reference technology for short range vehicular communications, which also appears ready to be applied to platoons, is IEEE 802.11p [44] with the related protocol pillars. IEEE 802.11p is a WiFi-based standard describing the physical (PHY) and MAC layer protocols as part of suits that have been separately defined in the US and Europe, as hereafter better detailed. Even if it is worth to acknowledge that new technologies have been also introduced as alternatives by the 3GPP under the name of sidelink LTE-V2X (since 2017) and sidelink 5G-V2X (since 2020) [45], still the evidence of their maturity and applicability to platooning is

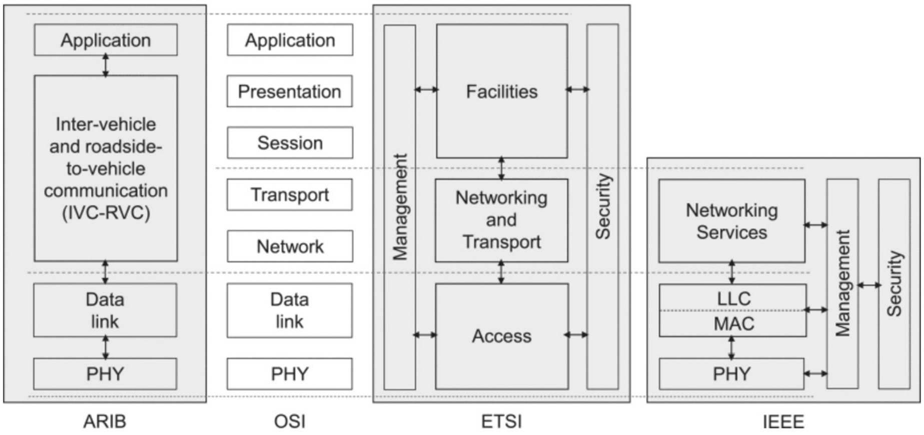

Fig. 10. Proposed vehicular network architectures.

debated. Therefore, more attention has been given in the literature related platooning to IEEE 802.11p and, as a consequence, more emphasis is hereafter given to such technology.

To support the requirements of different vehicular applications, each vehicle must be aware of the position, status and intention of its surrounding vehicles through message broadcasting. ETSI defines two types of messages: periodic Cooperative Awareness Messages (CAM) [46], and event-triggered Decentralized Environmental Notification Messages (DENM) [47]. CAMs include information such as geographical location, speed, and acceleration, and are only sent to a close neighborhood, as the validity of the information they contain is very limited in time. A large variety of C-ITS based safety applications are built upon the periodic exchange of CAMs, and their timely and reliable transmission is vital as a vehicle that continuously fails to deliver its beacon becomes invisible to its neighbors, which may result in potentially hazardous situations. Based on American standardization, CAMs are periodically generated, while ETSI recently decided upon a set of kinematic CAM triggering rules that trigger beacons when needed rather than keeping it strictly periodic. On the other hand, DENMs are only generated when an event of common interest occurs, and it is spread within an area of interest for the duration of the event.

After providing an introduction to the American and European protocol stacks, with particular attention to IEEE 802.11p, we focus our survey on the latest research efforts and state-of-the-art technology for PHY and MAC layers.

4.1. C-ITS standardization in the US and Europe

Standardization of cooperative-ITS (C-ITS) officially started with the allocation of the 5.9 GHz frequency band in the US, which was granted in 1999. Since then, in the US and Europe specifications have been developed and different standards are designed based on it.

In the US, the main SDOs are IEEE and SAE, which have concurred in the definition of the set of protocols normally referred as short-range communications (DSRC). Specifically, IEEE 802.11 wireless LAN working group, through the amendment 802.11p, and the 1609 working group, through a number of specifications still under development, brought to the protocol suite widely known as vehicular environments (WAVE), covering all aspects from the PHY to the transport layer and also including security aspects. In addition to IEEE 802.11p, which is now part of IEEE 802.11-2020 [48], a new version is also under development under the name IEEE 802.11bd [49], promising in 2022 a retro-compatible solution which doubles the range and the peak throughput compared to the current one. Above the LLC sublayer, the DSRC protocol stack is split into two branches. The first uses the WAVE Short Message Protocol (WSMP) defined in IEEE 1609.3 [50], which is optimized for the non-routed data exchanges that are common to vehicular networks, e.g., V2V safety messages. The second uses traditional internet protocols, principally IPv6, UDP, and TCP. In general, a service can choose to run over WSMP or IPv6, depending on its requirements. IEEE 1609.3 also defines the WAVE Service Advertisement (WSA). IEEE 1609 suite also provides security services like message authentication and encryption protocols, which are standardized in IEEE 1609.2 [51]. Above WAVE, SAE has produced the SAE J2735 application layer standard [52], which is a message set dictionary that defines the format of various application layer messages in both abstract syntax notation one (ASN.1) and extensible markup language (XML) formats, and is currently developing the J2945 standard to specify the minimum DSRC performance requirements (e.g., message transmission rate). Fig. 11 represents the DSRC protocol stack in the US.

Regarding frequency allocation, in the US the FCC allocated in the mentioned 1999 total 75 MHz of spectrum in the range 5.850-5.925 GHz (known as the 5.9 GHz band) for short range vehicular communications [55,56]. The spectrum, as conceived in the following years, is shown in Fig. 13. Each channel is further classified as either a CCH or a SCH. Channel 178, in the middle of the seven 10 MHz channels, is the CCH. The other six 10 MHz channels are classified as SCHs. One channel (i.e., 172) is reserved for safety-related basic safety messages (BSM), containing the location and speed of the vehicles. It is however to say that this allocation, which is a consequence of several years of discussions and experiments, have been questioned by FCC itself in the late 2020. Due to the limited usage shown in twenty years, in fact, the lowest frequencies are being opened to other uses and all the planning is thus under debate.

In Europe, active SDOs are ETSI and CEN, and their work is known as part of C-ITS. In particular, ETSI has focused on specifications for the communication system and V2V applications, while CEN has mainly produced standards for V2I applications. In Europe, IEEE 802.11p has become the basis of ETSI ITS-G5, which is now part of several tens of standards concurring to the C-ITS. A minor part of such standards is outlined in Fig. 12. As a complement to the efforts made by ETSI and CEN, contributions have been also provided by several other organizations, including the Car-2-Car Communication Consortium (C2C-CC) [57] (an industry driven group of automobile manufacturers, suppliers, and research bodies) and ERTICO (a partnership between more than a hundred European public and private stakeholders). Fig. 12 shows the protocol stack for C-ITS in Europe and the corresponding standards for different layers.

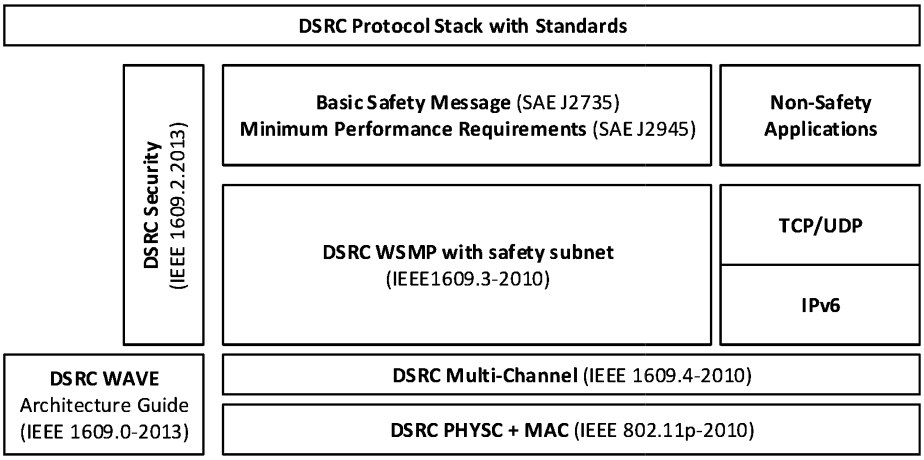

Fig. 11. DSRC Protocol stack for C-ITS in the US [53].

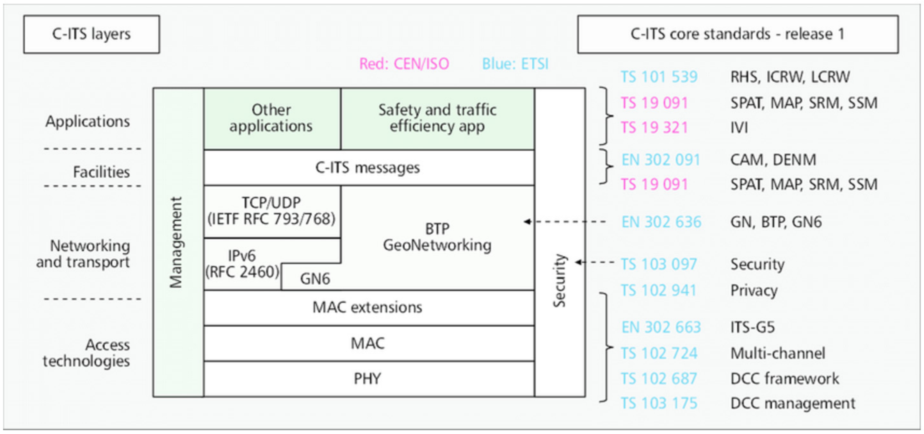

Fig. 12. Protocol stack (Release 1 core standards) for C-ITS in Europe [54].

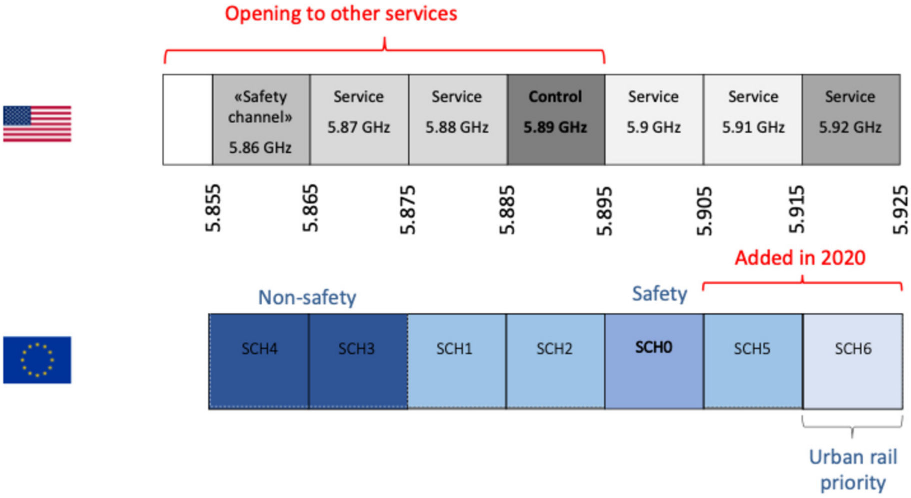

Fig. 13. Frequency allocation for road safety and traffic efficiency in the 5.9 GHz band. American and European frequency allocation for road safety and traffic efficiency in the 5.9 GHz band.

In Europe, a similar band has been reserved for the purpose around 5.9 GHz, starting from 2009. As shown in Fig. 13, in Europe 30 MHz (from 5.875 to 5.905) were initially planned for safety applications and 20 MHz (from 5.855 to 5.875) to non-safety applications. In 2020, additional 20 MHz have been also added from 5.905 to 5.925 (the upper 10 MHz shared with urban rail systems).

4.2. IEEE 802.11p/ITS-G5 Access Layer

As already stated, IEEE 802.11p, now part of IEEE 802.11-2020 [48], amended the IEEE 802.11 standard for the specific case of V2X communications. Like all 802.11 parts, it defines the protocols at the PHY and MAC layers. In Europe, it has been adopted under the name ITS-G5 [58], and we here generally use IEEE 802.11p to identify both of them.

At the PHY layer, IEEE 802.11p is very similar to IEEE 802.11a [59], including the use of orthogonal frequency division multiplexing (OFDM) and its configuration (same sub-carriers, same eight modulation and coding schemes (MCSs), and so on). The main difference is that the bandwidth used for each channel is 10 MHz, which corresponds to half of the bandwidth used in IEEE 802.11a.

At the MAC layer, IEEE 802.11p is based on collision avoidance (CSMA/CA), which applies a listen-before-talk approach and back-off mechanisms to allow uncoordinated access and minimize collisions. It also takes advantage of the service priority schemes provided by IEEE 802.11e through the enhanced distributed coordination access (EDCA). Some modifications have been also added to cope with the quickly varying scenario, such as: 1) the inhibition of the request-to-send (RTS)/clear-to-send (CTS) aided four ways handshake; and 2) a fast ad-hoc connection allowed by the so-called “outside the context of a basic service set (BSS)” mode, which bypass the long authentication procedures of the other versions. In most of the cases, transmissions are in broadcast and thus the acknowledgment is not returned and the exponential backoff is not applied. In addition, for what concerns the US, the IEEE 1609.4 contributes to MAC level operations by managing channel coordination and supporting MAC service data unit delivery.

Under heavily loaded channel conditions, packets might still collide or faced to high volume of delay, which might be critical for the correct functioning of platooning [60–63]. Also to say that, differently from other applications that rely on transmission of messages every 100 ms or more, the platooning application requires continuous messages sent at a rate higher than 10 Hz [29].

4.3. Cellular networks

Given the concrete business opportunities that are coming around connected and autonomous vehicles, in the last years the cellular ecosystem has oriented much activities to the standardization and development of what they call cellular-V2X (C-V2X), which had the first milestone in 2016 with the definition of LTE-V2X inside 3GPP Release 14 [64–67]. Such standard introduces modifications to improve the legacy long-range downlink/uplink for V2X and also introduces the new sidelink for direct communications among vehicles and road-side devices. Thus, both classical long-range and the recent short-range cellular technologies come as candidates to contribute or even enable the platooning application. Additionally, Releases 15 and 16 followed this initial standardization, with the latter adding the new sidelink 5G-V2X, based on New Radio and promising to address the needs advanced applications including platooning.

Due to the industrial interest in the implementation of platooning, several studies have indeed proposed to use cellular technologies to implement the required communications. Even before the device-to-device (D2D) communications were defined in 3GPP Release 12, LTE-based solutions were proposed, alluding to the advantages of a centralized architecture [68]. Although this characteristic has many advantages, in this case compared to an ad-hoc network with IEEE 802.11p, a centralized architecture has difficulties to ensure low latency requirements for the safe operation of the platoon. Even so, Mazzola et al. propose at [68] to use LTE and focuses its study on evaluating the system performance in the case of disturbances. Simulation results show an increased impact on packet losses when the delay of the communications increases and the paper concludes that localization uncertainties have the most significant impact on the system performance because of their direct influence on the inter-vehicle distance calculation. [69] presents an analysis of the capacity of the LTE network to support the platooning application by evaluating the message rates that the network can support under different traffic and road characteristics such as progress, number of vehicles per platoon, speed and number of lanes. The results obtained in this article indicate that current LTE deployments can comfortably support message rates and reliability that are adequate for an effective platoon. However, this paper does not assess the presence of other types of traffic, such as infotainment.

Since 3GPP Release 12 defined D2D communications, which allow sending information to other users without going through the infrastructure, academia and industry began to seriously believe in cellular technologies as a competitor to the IEEE 802.11p technology. In this way, in [70,71] the authors take advantage of the benefits offered by D2D communications, and propose an underlay radio resource management strategy. This implies the capability of reusing radio resources among platoon-members thanks to spatial diversity and the low transmitting power due to small inter-vehicle distances. In [71], they also leverage the ability of the eNodeB to allocate resources more efficiently thanks to its global knowledge of the network. In addition, to reduce control overhead they propose that the platoon-leader is responsible for requesting radio resources for all platoon-members. On top of that, to reduce even more the overhead of the per-transmission time interval (TTI) scheduling, due to the periodic traffic pattern of cooperative awareness messages (CAMs), semi-persistent scheduling (SPS) is assumed. However, this centralized proposal finds many difficulties for managing the cell handover for platoons.

[72,73] also suggest an underlaying resource allocation approach, but in this case for a multi-platooning scenario. Then, the transmission delay of intra-platoon and inter-platoon communications is reduced by using evolved multimedia broadcast multicast services (eMBMS) communications and a subchannel allocation and power control schemes are proposed for minimizing the number of radio resources needed. Although numerical results show that the proposed approach outperforms the candidate scheme in terms of transmission delay, the fact that resource allocation is made by eNodeB, as in [70], creates difficulties of management in some scenarios and problems for guaranteeing maximum communication delays required by platooning application. In order to improve the efficiency and stability of vehicle platooning with limited spectrum resources, Wang et al. [74] propose a platoon leader evaluation-based two-stage platoon formation algorithm in which a time division-based intra-platoon resource allocation for D2D communications is defined. Numerical results show that this proposal improves spectrum resource utilization, the stability of platoons and meets LV’s and FVs’ service needs.

Nevertheless, promising results from research on the applicability of LTE-D2D for vehicular communications led to the definition of LTE-V2X in 3GPP Release 14 and its evolution in 3GPP Release 15 as part of 5G. In [75] the 3GPP LTE-V2X standardization process is surveyed and an overview of the relevant 5G building blocks in the context of vehicular communication is provided in [76]. The promising characteristics of 5G with its ability to offer highly reliable and ultra low latency data delivery, which are critical requirements in platooning, has received even more the attention of academia and industry [77–82]. In addition, platooning appears in Release 15 as one of the safety use cases that will resolve C-V2X.

However, the most of studies found about 5G platooning are focused in finding out the limitation of ITS-G5 and LTE-V2X for platooning development that 5G could solve [77–79]. In particular, in [77] a control algorithm is proposed that allows a platoon-member to follow the platoon-leader without using any kind of sensors. This control algorithm is evaluated in a real environment using C-V2X and ITS-G5. Results of this test lead the authors to conclude that the mean communication latency for 5G is 50% smaller than that of ITS-G5 and that it is seen a relatively large standard deviation for latency in case of ITS-G5. These conclusions imply that 5G provides better performance to the platooning. The issue of these results is that the test has been carried out with only two vehicles, thus their wider validity needs to be verified. In [78], the suitability of ITS-G5 is analyzed for platooning applications, using metrics as end-to-end delay, packet delivery ratio (PDR) and update delay (UD). This evaluation concludes that using ITS-G5 the performance of CAM transmissions is not reliable enough to enable efficient, safe, and stable platooning, so they propose 5G technology as an alternative because of its ultra-low latency and ultra-high reliability. Similarly, [79] introduces a demo with the objective to find limitations to the functioning of the platooning using ITS-G5 and LTE-V2X, in order to demonstrate the need of 5G for this use case. However, in this demo the authors do not really find any limitation of ITS-G5 nor LTE-V2X for a normal functioning of a platoon. Therefore, it is foreseen that these limitations could appear for extreme situations, such as following an emergency braking in which minimum delays like those offered by 5G are needed. In [81], the use of IEEE 802.11p and LTE-V2V for platooning is compared. The results, obtained via simulations, demonstrate that the latter is a better choice for this advanced application, especially if radio resource allocation is coordinated by the infrastructure. The comparison of C-V2X and IEEE 802.11p for truck platooning made in [83] and [84]. [83] concludes that due to centralized radio resource scheduling for the side-link, C-V2X Mode 3 offers better performance in areas where there is cellular coverage. The researchers also conclude that C-V2X Mode 4 could provide better results than IEEE 802.11p thanks to SPS resource scheduling for periodic traffic. However, they highlight that resource re-selection triggers must be carefully avoid persistent collisions. [85] proposes a platoon-based scheduling scheme to increase the reliability of intra-platoon V2V communication. In this scheme, instead of letting each vehicle perform spectrum sensing and resource selection individually, the LV performs the scheduler functions for all FV. The paper compares both schemes and results show that the number of successful transmissions received by platoon based scheduling scheme is higher than that provided by the distributed scheduling in LTE-V2X sidelink.

An aspirational example of what future personal mobility might look like, where platoons are daily used, is proposed in [86]. This paper also provides a qualitative gap analysis of the capability of existing technologies and concluded that only 5G V2X will support the stringent requirements of some use cases that cannot be supported by any currently available technology.

Other communication alternatives to solve reliability problems of V2V communications have been proposed. As communication reliability has even more relevant in platoon scenario, in [87] a dynamic spectrum management mechanism in V2V communications for platooning purposes is proposed. The proposal is based on maintaining only the necessary information in the ITS channel and moving the rest of the data to an alternative channel that is selected from the available set of spectrum whitespaces.

In [82] the potential of C-V2X technology to match the latency and reliability demands of platooning application is evaluated implementing two types of dynamic scheduling for CAM transmissions within platoons: sequential mode and simultaneous mode with spatial frequency reuse.

4.4. Visible Light Communications (VLC)

In the last years, visible light communications (VLC) has gained increasing attention for vehicular networking as an alternative or to integrate communications in the radio spectrum [88,89]. VLC exploits the light emitting diodes (LEDs) that are used for illumination to carry data, by modulating the lights quickly enough to be imperceptible to the human eye. Using a separate and basically unused spectrum, VLC can take advantage of large bandwidth and low interference, at limited costs. In [90], preliminary experiments on real vehicles moving at 25 km/h are shown to guarantee 10 Mb/s throughput at a distance up to 25 m.

Although the capabilities of VLC have been largely proven, such technology has not found real application yet, mainly due to the strict need of direct LOS between transmitting LED and receiving device (normally a photodiode or a camera) and the range limited to few tens of meters in normal light conditions. Such drawbacks, however, might not be so critical in the platooning scenario, where each vehicle is inherently close and in LOS to the front and rear vehicles. For these reasons, VLC has been increasingly studied for platooning applications.

In an early work, Fernandes et al. [91] propose to add IR communication to cope with the unreliability of IEEE 802.11p. Although not using the visible spectrum, similarities are evident. In their solution, IR is used to carry the time-stringent data within the platoon, leaving IEEE 802.11p for less urgent exchanges or communications with external nodes.

A novel class of VLC receivers has been introduced in [92] for vehicular communications. The SNR-adaptive VLC receiver evaluates the SNR of the received signal using a simple technique, and based on the result it selects the optimal signal processing scheme to be used [92]. The use of VLC for platooning is then proposed in [93], where the feasibility is demonstrated through link level simulations. In [94], the same authors propose a trajectory compensation control at each vehicle of the platoon to cope with possible LOS loss due to sharp curves. In [95], Abualhoul et al. investigate the accuracy of VLC for ranging purposes, showing less than 10 cm resolution within 25 m.

First indoor experiments with platooning in mind are presented in [96]. The authors, have used commercial off-the-shelf headlights and taillights, measure 100 kb/s at 10 m distance (compatible with platooning) with less than 10^{-6} error rate, and also shown that it is achievable for any reasonable angle between preceding and following vehicles. [97] shows that interference on a curved road from transmissions on neighboring lanes or of following vehicles is significant. To deal with this issue, Adaptive Front-Lighting System (AFS) has been employed. It reduces the effect of interference on beacon dissemination by steering the transmission specifically to the intended recipient.

A specific aspect that makes VLC an attractive option is also the high security level that is inherent in the almost reserved channels. For this reason, in [98] and [99] the authors propose to use both VLC and IEEE 802.11p for information exchange inside the platoon, highlighting radio frequency (RF) jamming as the main threat. In addition to jamming, also fake maneuver attack is pointed out as a possible danger by Ucar et al. in [100], where the use of VLC is shown to reduce, but not cancel the risks. For this reason, in [101] the same authors propose the addition of an IR link to share a secret key to be used on encrypted data.

Other works consider VLC integrated with other technologies. Simulations of IEEE 802.11p coupled with VLC are performed in [102], where the latter is used for information from the vehicle just in front and the former for that from the LV. It is shown that, although a slightly higher delay in VLC would make the information from the front vehicle arriving a little later, the reduced load of RF channel would imply a significant improvement in the updates from the leader. In [103–105], combining of VLC and IEEE 802.11p is addressed. IEEE 802.11p has been used to disseminate the messages and VLC has exploited multi-hop. In [103], a multi-platoon scenario is considered and it is proposed to silence the RF interface upon detection of a congestion on the channel. Results show an improvement of both latency and reliability, although it is noted that frequent network disconnections are an open issue. In [104], particular attention is posed on security, showing that

Table 4
Description of the characteristics of radio interfaces currently being considered for platooning.

Radio Technologies	Pros	Cons
IEEE 802.11p	1. No need for network infrastructure 2. Low latency 3. Fully distributed and uncoordinated access	1. Hidden node problem 2. Limited transmission data rate
Cellular V2X	1. High density support 2. Ultra-high availability 3. Ultra-low latency 4. Continuous technology evolution	1. New technology 2. Less validated
Visible Light	1. Unlicensed spectrum and unrestricted very large (400 THz wide) 2. Low interference 3. Limited costs 4. High security level	1. Strict need of direct LOS 2. Limited range of few tens of meters in normal light conditions

the use of VLC for key exchange and backup during various kinds of attacks can protect the platoon and avoid speed reductions or inter-vehicle gap increase. In [105], the authors compare different cases for the dissemination of the messages: VLC only, IEEE 802.11p only, VLC at all vehicles with a copy through IEEE 802.11p at the LV, and both technologies in parallel. The results show that VLC is effective in all configurations to improve reliability, as long as multi-hop forwarding of messages from the LV is existed. In [106], VLC is instead coupled with laser-based perception, used for ranging.

Even if results are promising and the technology appears mature enough, at the best of the authors' knowledge there are however still no on-field implementations demonstrating platooning with VLC.

4.5. Some conclusions about radio technologies

The performance of the radio links available to offer V2X links in vehicular environments, including platooning applications, has been evaluated in a multitude of works. Thus, Tahir and Marcos [107] make a comparative analysis between IEEE 802.11p, LTE and 5G in different scenarios. Works such as Wu et al. [108], Eckermann et al. [109], or Wang et al. [110] provide recent evaluations of C-V2X communications in different scenarios and applications.

In the case of Segata et al. [111] the performance of C-V2X for platooning applications is evaluated, while Ucar et al., propose and evaluate a hybrid communications protocol using both IEEE 802.11p and VLC. Similar approach to the one proposed by Boukhalfa et al. [112] where they conclude that the VLC modems can be used in addition to the radio links. In that case, they have obtained and increase of the probability of successful during transmission. Similar conclusion obtained by Lobato et al. [113] in their work, in which they conclude that VLC appears as an interesting alternative to solve the congestion problem of the channel caused by the number of nodes that transmit at the same time using DSCR inside the platooning.

Finally, the exhaustive work carried out by Boubakri and Mettali [114] analyze the use of these three technologies, DSRC, C-V2X and VLC, in an intra-platooning scenario. In their conclusions, it is highlighted that a communication technique that ensures real-time sharing of data between vehicles, low latency and a high rate of transmitted packets is needed in the scope of a platooning. However, despite his extensive work dedicated exclusively to analyzing results obtained by using these three technologies in a platooning, a single conclusion cannot be obtained about which technology is ideal, since its choice depends on multiple factors (Table 4).

5. Platoon-specific communication issues

Specific methods have been proposed by the research community to improve communication issues of IEEE 802.11p for platooning application. One of the parameters often used in the literature to compare different techniques is reliability. Thus, in [91], the authors suggest two different technologies: IEEE 802.11p and IR to improve reliability. Bohm et al. in [61] and [115] have considered different MAC layer priority classes to avoid overloading the medium in existing both beacons and event-driven messages. In [116–118], the authors have considered age based re-transmission of received messages into the reserved service channel to improve reliability. Segata et al. [119] have used slotted scheduling and a transmit power control to improve the reliability. MAC protocols for VANETs often ignore the Network connectivity. Differently, authors in [120] have presented connectivity and reliability sensitive protocol. They have also considered some issues like distance between the RSUs and the congestion control.

Other parameters commonly evaluated in the literature are channel availability and string stability. The authors in [121] have presented a token-based MAC protocol to overcome the competitive channel access, age-based transmission and damage caused by vehicle joining and leaving the platoon. In [122] the authors have analyzed the use of a distributed consensus algorithm to improve stability in the platoon while maneuvers are performed and the topology of the platoon changes. Joining cars to platoons has been considered in [123]. The assignment decision will be different based on the features of individual cars (e.g., max. acceleration or speed) and the driver's preferences (e.g., min/max. traveling speed, preference on travel time vs. fuel consumption). The researchers in [124] have shown the channel busy ratio for vehicles in a platoon can be reduced to less then half by using directional communication. The authors also have shown that the leading vehicle in the platoon has the greatest advantages. [125] presents an approach to consider network and control perspective. The authors shown safety bounds on the inter-vehicle distance depending on vehicle dynamics and packet losses caused by network issues. The mentioned bounds are respected with a large margin due to the robustness of the algorithm to packet losses.

Of all different and original techniques proposed in the literature to improve Platoon-Specific Communication Issues, the most relevant ones are new MAC solutions, beaconing methods, antenna placements and multi-hop transmissions. The following table summarises the pros and cons of these techniques, which will be discussed in depth below (Table 5).

5.1. New MAC solutions

Many survey papers in the literature have been written to summarize and categorize available MAC protocols for (VANET). Most of them divide MAC protocols into two groups: contention-free and contention-based protocols. Booysena et al. in [126] provide an overview of V2V MAC protocols and highlight some challenges that still need to be addressed in future work. The authors mention that contention-free protocols can satisfy QoS requirements for safety

Table 5
Techniques for improving Platoon-Specific Communication Issues.

Improvement techniques	Pros	Cons
New MAC solutions – contention-free	Satisfy QoS requirements for safety critical applications	Need a high level of coordination
New MAC solutions – contention-based	Not suitable to exchange messages for safety applications	Very efficient for not safety applications
New MAC solutions – Hybrid MAC	Enhence network performance to satisfy QoS requirements for safety critical applications	Add overhead of coordination and transmission delay compared with contention-based solutions
Beaconing methods	Reduce channel congestión in high density scenarios	Add overhead of coordination or complexity to the system
Antenna placements – on the top	Easier place to install	Lower performance because of geometry of trucks
Antenna placements – on the side	Reduce NLOS situations	Need of having two antennas
Antenna placements – on the rear	Better performance	Not practical for container trucks
Multi-hop transmissions	Reach shadowed areas	Add overhead of coordination and transmission delay

critical applications, but they need a high level of coordination due to high level of mobility in VANETs, whereas contention-based protocols are not suitable to exchange messages for safety applications due to their unbounded delay and low performance in high dense networks. Hadded et al. in [127] survey (TDMA)-based MAC protocols. They explain the benefits of TDMA for VANETs and divide TDMA solutions into three categories: TDMA MAC protocols in a fully distributed VANET, TDMA MAC protocols in a clustered-based topology, and TDMA MAC protocols in centralized topology.

Starting from the dualism of contention-free and contention-based MAC, Mohamed Zain et al. in [128] focus on a new group of MAC protocols, which is denoted hybrid MAC. A hybrid MAC protocol benefits from both contention-based and contention-free MAC protocols to enhance the network performance in VANET. In this direction, a few proposals add (OFDMA) to IEEE 802.11p: in [129], OFDMA is used to create four orthogonal subchannels then accessed with CSMA/CA, whereas in [130], a contention-based period is assumed to perform allocation request and confirmation, followed by a time interval where transmissions are carried out without interference.

Below, we provide an overview of MAC protocols, which are enhanced or designed especially for platooning application. We also classify these MAC protocols into three different groups, including IEEE 802.11p-based, TDMA-based, and token-based MAC protocols.

In the work proposed by Hadded et al. at [127], reliability, access time, and channel utilization have been considered in TDMA-based schemes. The authors in [131] have presented five TDMA-based MAC protocols to improve platooning reliability based on the priority. This improves the reactivity to, e.g., velocity changes.

However, TDMA-based methods typically are not very dynamic when it comes to changing the beacon period or scheduling re-transmissions and they require slot synchronization. However, other works as [132–134] have shown that considerable overhead should be tolerate to make the TDMA-based methods dynamic. Similarly, retransmissions usually require extra overhead for control data and scheduling, and also a centralized control unit to determine if retransmissions are needed, and when.

To improve concurrent collaborative, Aslam et al. in [135] have used reconfigurable and adaptive-TDMA (RA-TDMA) which proposed an overlay TDMA protocol on top of IEEE 802.11p. By this approach they have reduced the overhead of synchronization. The authors in [136,137] presented decentralized TDMA-based MAC to improve the scalability and predictability. Based on the reduction of channel delay, STDMA is alternative of the CSMA/CA in real-time applications. As it is described at [138], STDMA also can be combined by CSMA/CA for considering the performance measure distance between nodes.

In [139] the authors have implemented the token ring above of IEEE 802.11 to improve the bandwidth usages and delay. In [140], the authors present an approach to deal with the fast topology changes. In [141], the authors have shown that in a fully connected network, the vehicle do not have to update the information of their neighbor in a token-based approach. In [142], an approach is presented to deal with the centralized and synchronization overhead token based solutions.

In [143,37] a platoon adapted and token-based MAC method is proposed. This method transmit beacons in case of the required time constraints. They have improved the reliability and also concurrently enabling efficient usage of event-driven messages. They also increase the reliability by using the circulated token-base protocol.

5.2. Beaconing methods

As it has been already discussed, vehicles are able to create and maintain a platoon by disseminating periodic beacons, known as BSMs in US and CAMs in Europe. Beacons are awareness based message and report information about vehicles' status such as position, speed, and acceleration. If high density scenarios are considered, the transmission channel can be congested, causing what is known as the broadcast storm problem [144]. This can result in heavy packet losses with a big impact on the stability of the platoon. To reduce channel congestion, algorithms to adapt the beaconing frequency, such as transmit rate control (TRC), can be applied in a platoon scenario. In [119], instead of using a fixed interval value of 10 Hz as often done, this algorithm is adopted to modify the time interval between consecutive beacons according to the measured channel occupation. In [145], beacon transmission rate is dynamically adapted and updates are reported only when it is needed, using what the authors define as jerk beaconing. Comparing this approach against beacons sent with a constant frequency of 10 Hz, it offers better performance in terms of both safety and resource saving. To mitigate the problems of radio signal shadowing dynamics and massive broadcasting, an adaptive beaconing solution is also proposed in [146], defined as dynamic beaconing (DynB). Through the experimentation and simulations carried out, authors show that this method allows to increase beacons transmission rate with a very low transmission delay and to react very quickly to overload situations. In [147], it is proposed the adaptive beacons and event-based safety messages dissemination scheme (ABSD), which consists on different periodical control messages generated by the platoon control mechanism to be deployed in a scenario shared by a platoon and individual vehicles.

5.3. Antenna-placement

One of the main problems in the design of a platoon is the antenna placement, due to its implications in the communications performance. Works presented at [148] and [25] focus on practical issues and their impact on platooning performance. In [148], the impact of packet loss on the performance of platooning simulated scenario with a platoon of ten vehicles located in a straight single lane road 5000 meters long is evaluated, while in [25] antenna placement and its impact on the packet error rate by real-world experiments in the framework of SARTRE project is evaluated.

As it is described in [149] and [150], non-line-of-sight (NLOS) conditions have a great impact on the channel reliability and in platooning they easily occur due to different sizes of vehicles and environmental conditions. It must be also considered that size and geometry of trucks is also a problem when it is compared to the wavelength of a signal at a carrier frequency of 5.9 GHz, resulting in shadowed regions [151].

The alternatives for mounting the antennas are in principle three: on the top of the vehicle, on the sides, and on the rear. All of them appear to have advantages and drawbacks, although the last one is hardly viable for the reasons explained later.

In [25], two antennas are placed on the LV, one on the top of the cabin roof and the second one placed at the far rear on top of its trailer. Results show that the rear antenna provides better performance, obtaining 96,3% of successful round trip messages. In addition, the difference of satisfactory messages increases considerably for larger distances between the LV and the FV, reaching 151% at more than 100 m with respect to the antenna located on top of the cabin. However, as anticipated, placing the antenna on the rear does not appear practical: in real implementations, in fact, the containers are often replaced and are normally independent from the trucks.

In [151] and [152], two antennas are placed on the left and right rear-view mirrors of the truck, with the aim to evaluate communication on both sides of the truck. The same approach is adopted in [153], where two antennas are mounted on each side of the truck, located near the back panel of the trailer. Both in [152] and [153], results of the tests demonstrate that delivery ratio can be greatly improved by using the two side antennas alternately. This is particularly relevant when the truck makes a turn: if the tractor and the trailer are not align with each other, in fact, one of the antennas is obstructed by the trailer during the communication towards the vehicles behind [153].

5.4. Multi-hop transmissions

One of the basis of platooning performance is the capacity of each vehicle to receive information about position, speed, and acceleration from the other participants within a specific deadline. In a scenario like the platoon, multi-hop transmissions can help to reach shadowed areas where receivers are out-of-range from the original sender.

Larsson et al. propose in [151,154] a reachability matrix algorithm that decreases the ratio of missing a time limit of 0.2 seconds from 18% to 11%, while increasing the message intensity by only 21%. In [155], the authors propose an approach to improve the reliability of event-driven messages within a fixed deadline. They also have considered various metrics in their approach such as: reduce error at receiver.

Authors in [156,157] have carried out different simulations, considering several platoon scenarios. The one proposed in [156] is based on two types of beacon scheduling algorithms, one for V2V that uses decentralized beacon scheduling, and the other for V2I based on RSU-assisted centralized beacon scheduling algorithm. In [157] the goal is to maintain a constant space of one meter between all the vehicles within the platoon, achieving negligible spacing errors. The deployed communication architecture uses time division multiple access with the token passing, transmitting each vehicle its data at each token cycle, in its respective time slot.

Rehman et al. propose in [158] the bi-directional stable communication (BDSC) relay nodes selection scheme designed to improve packet delivery and delay for multi-hop broadcasting protocols.

To achieve it, BDSC estimates the link quality between the message source and a set of potential relay nodes, considering also the distance between the nodes involved in the retransmission.

The approach considered in [159] is based on the reduction of end-to-end communication delay over densely populated networks, selecting relays falling furthest in distance from the source. It defines a set of potential relay nodes, that are the only ones that can become the next hop relays.

The work presented at [160] proposes a scheme which is used to regulate the formations of moving vehicles so that they are aggregated into properly synthesized platoons. The goal of these platoons is to reduced on-ramp waiting times, and assuring the timely delivery of high priority safety messages. In this scenario and to provide access to the media, it is proposed an optimized platoon-wise spatial-TDMA scheduling scheme, limiting its operation to involve only vehicles that are members of the same platoon. That is, authors propose a platoon-based reuse-M TDMA protocol, where M is the spatial reuse factor. According with the obtained results, the best value of M is in the range of 3-6.

The authors in [161] have presented an approach for optimizing the one-hop delay of inter-platoon. This approach has adjusted the minimum contention window size of each backbone vehicle.

6. Security and privacy issues in truck platooning

Both security and privacy are key aspects of vehicular networks. Altered information exchanges can have disruptive effects; in the worst cases, hijacked vehicles could even become weapons in the wrong hands [162]. At the same time most people do not want third parties to have full knowledge of their movements and habits [163]. Indeed, as clearly discussed for example in [164], there is an inherent conflict between the need of information integrity and redundancy and the willingness to protect the privacy of drivers and passengers. The design of any vehicular protocol and application should thus pay particular attention to the concurrent and sometimes opposing needs for confidentiality, integrity of information, service availability, trustability and revocability, non repudiation and respect for privacy.

All these aspects apply and in some cases amplify in truck platooning applications. For example, attacks are harder to be detected when they come from inside the string, i.e., from vehicles that are already part of a trusted group, and privacy is more difficult to guarantee to the participants, since its respect might compromise the correct operations of the platoon.

6.1. Classifying the threats

Many threats have been observed in vehicular networks and truck platoons, with several specific examples listed for example in [165] and [17]. In [166,167], the main security threats for strings of vehicles are grouped into three categories, which also apply to the analysis of security in truck platoons: 1) those related to the modification of the information exchanged among vehicles (denoted as application layer in [166]), which can be in turn from outside the convoy or from inside, and in the latter case towards heading or following trucks; 2) those causing simple or distributed denial of service (DOS/DDOS) of the wireless communications technologies (network layer in [166]); and 3) those acting on the software or hardware of the truck (system level in [166]).

The first category aims at causing one or more vehicles involved in a platoon to have a wrong view of the convoy and take wrong decisions as a consequence. The attacks can be performed from a vehicle that is external to the platoon, or can be implemented from a truck that is itself member of the platoon; in the latter case, depending on the control flows, the attack can be restricted to the followers or also involve the heading trucks. Examples are spoofing, where the attacker impersonates another vehicle, and Sybil attack, where the node injects data in the network related to fake nodes. Thanks to GPS-aided synchronization and certificates, many of these threats are normally considered as solved, especially the replay attack and in most cases spoofing from outside the platoon [167]. However, when such countermeasures do not apply properly, anomaly detection is often the only solution, which hardly gives 100% guarantees [166]. Thus, they still remain a major issue, especially when data injection is produced by an insider.

The second group has the objective to force the convoy to downgrade to ACC, thus acting on service availability and canceling the benefits on fuel consumption and traffic efficiency. These threats can be for example based on radio jamming or through MAC protocol violation. In some cases, it has been shown that a temporary maintenance of the platoon is also possible if the attack has a limited duration [167], but the downgrade to ACC is anyway an effective last resort, assuming the attack is detected in time. Clearly, a DOS/DDOS attack is especially relevant for platoons of trucks, where the downgrade may imply a significant cost increase or even the interruption of the service if the following trucks are fully or highly automated.

The last family of threats is tampering of hardware or software, including intrudes in the internal network or actions causing misbehaving sensors to origin false information. In such case, the analysis of data from different sources (e.g., speed from GPS and meters on wheels) can help to detect and solve anomalies and higher costs could be payed to equip the trucks with tamper-proof components.

6.2. Impact of cyber attacks

Mainly addressing the first two categories, some studies have been conducted recently on the impact that attacks could have in a platoon. Before entering in the details of the various studies it is worth mentioning that some of the attacks might have a different impact depending on the control strategy applied to the members of the platoon.[1] Indeed, in [167] it is for example shown that the effects of various manipulations (jamming or data injection) strictly depend on the implemented controller and that none of those tested shows full immunity to such attacks. Hereafter, the focus is anyway on wireless-aided cooperative strings of vehicles and therefore the attention is mostly on communication reliability and string stability and the specific control strategy that is addressed is indicated only when relevant.

In [166], simulations focusing on message falsification are shown to significantly influence the string stability, especially when dealing with data on acceleration. An instability can thus be caused, which then magnifies and eventually brings to an accident. In addition, it is shown in [166] that a downgrade to ACC due to radio jamming can cause almost double the inter-vehicle gap in the platoon, with remarkable reduction of its efficiency. Jamming is also addressed in [169], where the authors point it out as a significant threat with the support of experimental results, and in [170], where it is concluded that the highest impact is obtained when the attacker acts near the second vehicle of the platoon and that more damage is caused if the leader is decelerating. In [171], the authors consider a replay attack where the controls from the LV are repeated after few seconds, demonstrating that this can cause an FV to significantly deviate (tens to hundreds of meters) from the planned trajectory. In [172], it is shown that a Sybil attack with multiple fake nodes can cause high speed accidents with the injection of sudden and opposed (false) variations of the acceleration. It is also demonstrated that even when smooth variations are falsified, which are very difficult to detect, still accidents can be provoked. [172] focuses on joint Sybil-falsification attacks from a vehicle outside the platoon, with several different scenarios. Also in [172], the attacker acts either with aggressive injections of false information as well as slower but less detectable ones. In addition, it either transmits data directly or through the hijacking of a third party vehicle. Results show that all scenarios can lead to a collision that do not involve the attacker. In the worst case, the objective is accomplished in less than 3 seconds.

Although not in the main focus of the paper, it appears useful to mention that there are also a few works discussing security issues from a control perspective. In [173], the focus is on the energy waste that a malicious vehicle inside a platoon can cause by simply moving with a specific acceleration-deceleration pattern. It is shown that 20% to 300% increase of consumption is possible with limited effort. In [174] and [175], it is demonstrated that a vehicle placed at any position, acting against the governing control laws or even altering them just slightly, can destabilize the full string and also induce serious accidents.

6.3. Detection and solutions

Due to the expected wide diffusion of connected vehicles and the high impact of possible attacks, increasing activity is being devoted to the detection and solution of specific threats [165] or to systematic approaches to predict, mitigate and test the vulnerabilities [176]. As an extremely relevant use-case, particular attention has been posed to platooning. Hereafter, the proposals dealing with DOS/DDOS are first reviewed, followed by the other attacks caused from outside the platoon and finally from inside.

Detecting DOS/DDOS: A few works focus on the prompt detection of denial of service attacks. For example, in [177] the authors address the case where jamming is performed on a portion of DSRC messages and propose a method to detect the attack by analyzing the estimated losses. As already discussed in previous section, some papers [178,179,98,99,101,102,104] propose to contrast such threats with the use of communication technologies that inherently guarantee more immunity to jamming, such as IR or VLC. Similarly, adaptive beamforming is used in [180] as a countermeasure when an anomalous increase of the interference is detected. In all these cases, since the communication is restricted to a short distance and a limited angle between transmitter and receiver, it is harder to an external node to intrude into the channel.

Other attacks from outsiders: The use of IR or VLC can also strengthen the immunity to falsifications from external sources, which are anyway normally tackled with the use of certificates. In [181], VLC is combined with IEEE 802.11p and used for secret key establishment and periodic update to ensure the participation of only the target vehicle in communication. In [182], the authors focus on distributed deception attacks to the platoon, which is an attack where the information collected by the sensors is falsified to give a wrong description of the positions and surrounding objects, and use distributed Kalman filter incorporated with a modified generalized likelihood ratio (GLR) to estimate and detect the attack. A proposal to enhance the protection from external attacks is provided in [183], where a new group cryptography solution is detailed and shown to be secure and efficient. Still looking at the protection against attacks from outside, in [184] the authors propose a novel architecture to be applied to clusters of vehicles, with one of them elected as secure gateway and private addresses within the group. This solution takes advantage of the software-defined network (SDN) technology and finds natural application to platooning. Protection at the application layer is investigated in [185], with the proposal of a complete solution concurrently grant-

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[1] Deepening the control models is outside the scope of the present survey and the interested reader can refer for example to [168,10].

ing secure message exchange, entity authentication, authorization and privacy. Specifically focused on authentication is instead the proposal discussed in [186], which is a protocol based on a Game-Theoretic approach with a token passed among members. The authors demonstrate that vehicles are successfully motivated to follow the protocol. Further work on authentication is performed in [187], where a key management scheme is proposed to deal with dynamic platoons where vehicles joint and leave the convoy based on their independent routes.

Attacks from insiders: As already stated, more critical is anyway to find solutions when the threat comes from an insider. In [188], the issue of detecting misbehavior from a member of the platoon is addressed. The main outputs are that receiving information from all members seems more important than checking consistency of received claims and that verifying the identity of vehicles in front or behind appears less determinant than expected; it is also clarified that the study does not take into account the actual danger related to the specific cases and thus insights are required. To counteract message modifications from an insider, Petrillo et al. propose in [189,190] to exploit a collaboration based control that lets participants to detect and discard misleading information and preserve the stability of the string, without the need to downgrade to ACC. In [190], in particular, they analytically prove the stability of the decentralized control in the presence of time-varying communication delays and cyber threats by exploiting the Lyapunov–Krasovskii approach. A specific focus to the detection of reply attacks is proposed in [191], where a decentralized diagnosis algorithm is proposed. In [192], DeBruhl et al. propose to perform an anomaly detection based on the comparison of the behavior of the preceding vehicle with what is expected by the information received from all nodes of the platoon. If the vehicle ahead is not driving as expected, a malfunctioning or attack is supposed and the driving mode downgrades to ACC. The authors notice that the proposed solution cannot be applied if the misbehaving vehicle is the leader. The detection of an attack is also proposed in [193] based on the information collected by the other members about their positions and what returned by the sensors. More in particular, each truck calculates the similarities between the sensing data shared by the other vehicles and the received messages and evaluates the consistency with the implemented operations in order to individuate possible misbehavior. Abnormal behavior detection is also investigated in [194], based on a novel statistical learning technique. The authors demonstrate through simulations that shared speed value among platoon members would be sufficient to detect an attacking vehicle, even if it corresponds to the LV. Indeed, it is clear that when the misbehaving vehicle is the LV this represents a higher threat; starting from this consideration, both [195] and [196] propose solutions to improve the trustworthiness of the leading vehicle, based on the blockchain and a service query scheme, respectively. In [197], Asplund lists a number of possible attacks performed by a single hacker through information manipulation and argues that they can be effectively counteracted by equipping platoon nodes with the addition of: 1) mechanisms that verify the identity of the neighbors (e.g., checking the license plates); 2) that overhear and check the communications between the other vehicles; and 3) that are able to detect Sybil attacks. The authors do not discuss specific implementations of these features and highlight that the case where colluding nodes cooperate in the attack remains an open problem. Finally, in [198] an attack from inside is faced without focusing on communications. The proposed solution is that each vehicle implements a filter able to detect an attack and, in case, acts modifying the adhered control law. The results show that the proposal can protect against most of collisions or at least reduce the deriving damage.

Besides the much work done to date, several issues appear however still under-investigated. For example, it is noted in [166] that the compromise between the need for timely information and respect of privacy is particularly challenging in the platooning application and that such an issue still requires more effort. In [167], van der Heijden et al. warn that the Sybil attack, especially if a node owns multiple certificates to simulate more than one vehicle, is still an open issue. It also seems necessary to work to improve the immunity of the control algorithms themselves against malfunctioning or attacks. Other relevant under-studied problems are the presence of multiple colluding attackers [197] or the detection of leader misbehavior and consequent countermeasures [192]. Finally, most works focus on the behavior of a formed platoon and the attacks carried out during maneuvers are rarely addressed.

7. Conclusions and open research issues

Cooperative truck platooning appears as one of the first applications where vehicular communications can really make the difference without requiring large deployments and huge investments. Trucks exchanging information in real time can move together in a coordinated manner, saving fuel, improving traffic efficiency, and increasing safety.

However, the requirements to be fulfilled are very stringent: vehicles are expected to transmit more than 20 updates per second, with a coverage that increases of approximately 20/30 m per each involved truck (truck plus inter-truck gap), and with minimum errors and latency. Platoons will be limited in size, but 15 vehicles as a maximum is supposed in [3], which would mean more than 300 packets per second transmitted by the convoy and 300/500 m of distance from the LV to the last FV.

For these reasons, even if experiments are being carried out in several projects worldwide and commercial availability is expected soon, a number of problems remain to be solved. Focusing on wireless communications, among such open issues, we can remark the limits posed by what is presently the main technology for vehicular communications, i.e., IEEE 802.11p/ITS-G5, the need to consider multiple technologies and, thus, manage the coexistence and interaction of various radio interfaces, and the concern for risks in terms of security and privacy. Hereafter, a brief discussion of each of these topics is provided to remark open issues and give guidance for future research on platooning.

7.1. New communication technologies for platooning

Currently, the de-facto standard for short-range vehicular communications is IEEE 802.11p and related protocols, including the European ITS-G5. IEEE 802.11p is a mature technology, widely tested with even thousands of vehicles moving in any kind of scenario. However, the relatively old PHY specifications and the collision based CSMA/CA medium access give questionable guarantees in terms of range, reliability, and latency. This becomes more evident with the increasing penetration of technology on board and the consequent increase in levels of congestion and interference in the channels.

For this reason, other options are being studied, from the use of already deployed cellular communications to the standard but not yet diffused VLC, to fully new proposals.

Regarding cellular technologies, the classic long range connection has been discussed as a possible solution, due to its widespread diffusion and high performance. Indeed, in principle the currently running LTE-Advanced guarantees limited latency and high throughput, without the risk of uncontrolled interference and channel congestions. Although still under-investigated in the context of platooning, the advantages appear to further improve with the coming 5G, thanks to even more capacity, even lower latency, and high processing capabilities enabled by new technologies such as MEC. However, using long range connections inherently lacks of low scalability and, more importantly, cannot guarantee uninterrupted operations in all scenarios and under any conditions.

Still within the cellular ecosystem, recently 3GPP has added short-range direct communications (starting with LTE-V2X and later adding 5G-V2X) that aims at overcoming the mentioned limitations. This technology is presented as a strong competitor to IEEE 802.11p, as it uses the same chipset as the long-range and promises to ensure high spatial reuse and the ability to work without connection to an eNodeB. However, the superiority of LTE-V2X with respect to ITS-G5 is still under debate, whereas 5G-V2X is still to be investigated. Moreover, the concerns about issues under channel congestion and the ability to meet the high requirements in terms of coverage, error rate and latency for LTE-V2V and 5G-V2X still hold. In addition, a few on field experiments have been carried out to date and none of them involving large number of vehicles nor platooning as a specific application.

Other technologies have been also considered for intra-platooning communications, among which is worth to mention VLC. Exploiting the LEDs already present on trucks, VLC can be implemented with limited costs and with possibly very high bandwidth. Even the main drawbacks of VLC, which are its inherit high directivity and reduced range, come in platooning as possible advantages, able to avoid any risk of channel congestion and improving security against external eavesdroppers. For this application, actually the main issues are that multi-hop is required among trucks that are not just in front one of the other and the impossibility to use VLC during all joining and leaving operations.

Another option that have been evaluated for both V2V and V2N communications is mmWave. The great potential of this technology is the large bandwidth it provides. However, due to the difficult propagation characteristics at high frequencies and the dynamic topology of vehicular environments, the stability of communications is limited. This makes mmWave unsuitable for V2V safety applications just like VLC. However, thanks to its beamforming gain, its spatial isolation and its potential of PHY-layer security/privacy, it has great potential as an intra-platoon additional technology and, more in general, for other V2V applications such as video streaming and, of course, for new autonomous and cooperative driving services. In order to improve communication reliability, new alternatives such as considering very directional transmissions and frequent alignment operations and increasing the density of the infrastructure are being evaluated.

Due to the increase of data transmission over wireless networks, specially in VANETs networks where infotainment services could demand a high throughput downlink, other gaps of the spectrum can be used to provide vehicle communications. It is the case of TV white space (TVWS) band, where thanks to the switch from analog to digital format, some frequency channels have been released for cognitive access in many countries. Then as it is introduced at [199], a portion of data traffic from the DSRC band could be offload to the TVWS band. This traffic movement could arise interference problems as it is analyzed by Fadda et al. [200,201]. During their experiments, they observed that the effect of the 802.11p adjacent interference changes with its configuration. Then a 5 MHz bandwidth signal disturbs less compared to a 10 MHz bandwidth signal both for the multiple frequency and single frequency network configuration. The obtained conclusion was that higher modulation schemes with high data rates are more robust to DVB-T2 interference. In the meanwhile, [202] bases their experiments in the goal of limit the emissions to reduce the aggregate-interference when TVWS is shared by different technologies. In others tests, as the one carried out in [203], dynamic TVWS spectrum access is experimented guaranteeing a quality of service according with the requirements of VANETs. Proposed new resource/channel allocation method is based on an algorithm which implements the matching between vehicles/requests and available channels keeping the throughput of the whole system and the QoS of vehicles/requests. In the related work [204] it is presented a geolocation database assisted vehicular data piping framework for dynamic DSRC/TVWS spectrum sharing. Altintas and Ihara [205,206] demonstrate in their works that TVWS can be used to provide multi-Hop V2V communications at field test and indoor simulation setup.

7.2. Coexistence of communication technologies

Most of the mentioned challenges can be in principle overcome using more than one technology at the same time, also known as hybrid communications. First of all, even if long-range cellular can be hardly thought as an enabler of intra-platoon communications for the reasons above, it appears almost mandatory in order to allow control and management by platoon service providers (PSPs) from remote. In addition, it can be exploited for joining and leaving operations, when the trucks are not yet or not still near to each other. Any other short-range technology would be instead used for the information exchange within the platoon.

The use of more than one technology can be also exploited to improve the quality of service. For example, two short-range solutions like LTE-V2V and IEEE 802.11p could be imagined at the same time to have higher reliability if the channels are uncorrelated, or an alternate use could reduce channel congestion and the consequent issues. Another approach that has been proposed is the use of directive communications for the nearest trucks and longer range ones for the other links, e.g., coupling VLC with IEEE 802.11p.

In all these cases, the attention moves to the challenges related to coexistence. If two radios are used, for example, interference must be kept sufficiently low. If long and short-range cellular links are concurrently activated, resource management becomes an issue, especially if the same bandwidth is exploited for both.

With hybrid communications, a crucial role is also played by an optimized, efficient, and reliable management of the multiple media. To this aim, appropriate multi-technology operation services must be designed and implemented to collect run-time information and act opportunistically.

Due to important role of platooning in efficiency of traffic and avoidance of congestion by using reinforcement learning method to train, the vehicle will not blindly explore everywhere, but will find the fastest route to reach the target state. By this approach the vehicle encounters the similar situations again, it will quickly select and reduce the calculation. The calculation task and sensing the data of vehicle can be uploaded to MEC server through RSU to reduce the delay. In this way, the efficiency of traffic can be improved, and finally realize the sustainable development of urban traffic [207].

7.3. Security and privacy

Another aspect of clear relevance and particular importance for the platooning application is security. Not so much as a risk of information theft from competitors or third parties, which has anyway always a not negligible role, rather for the possibility that external users take partial or full control of what can become a severe threat for people safety. It has been already proved that if a truck starts working under altered control laws, it can cause string instability and even heavy damages. Experiments showed that an attack can be indeed destructive in just a few seconds.

Among the possible attacks, those altering the exchanged information are those expected to cause the heaviest damages. Both if the data related to a node of the platoon is modified or a fake node is introduced by a malicious node, trucks might not be able to correctly follow the control laws and accidents can be eventually caused. Most of these threats are considered solvable with certificates as long as coming by actors outside the convoy, but remain challenging if they start from some hacked or malfunctioning participant. Further techniques to detect and manage these attacks are still required.

Less dangerous in principle, but still opening risks and damaging the involved companies, are all actions that aim at a denial of service. If communications are impaired, a safe solution is always to downgrade to ACC and only rely on sensors. However, on the one hand, the event must be detected promptly and the downgrade carried out immediately, and on the other this solution implies loosing all the advantages gained with platooning.

In large part open for proposals is also the exploitation of multiple technologies to improve the security of the system. First ideas have supposed the use of directive communications to check, validate, and thus protect, the exchanges done with other technologies. For example, directive antennas or VLC could be used to check the consistency with the broadcast position or to privately share keys without the risk of eavesdropping.

At the same time and in some sense against the need of a high level of security is the request for a sufficient level of privacy. Indeed, preserving privacy beyond a certain level appears impossible, since nodes in a platoon must be able to cooperate. In addition, any attempt to anonymize data comes up against the fact that devices are mounted on large trucks, easily identifiable and easily traceable.

Declaration of competing interest

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