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Enhancements of V2X Communication in Support of Cooperative Autonomous Driving

Laurens Hobert, Andreas Festag, Ignacio Llatser, Luciano Altomare, Filippo Visintainer, and Andras Kovacs

Laurens Hobert is with Hitachi Europe.

Andreas Festag and Ignacio Llatser are with Technische Universität Dresden.

Luciano Altomare and Filippo Visintainer are with Centro Ricerche Fiat.

Andras Kovacs is with Broadbit.

[1] http://www.gcdc.net/i-game

[2] http://www.adaptive-ip.eu

[3] http://www.companion-project.eu

Abstract

Two emerging technologies in the automotive domain are autonomous vehicles and V2X communication. Even though these technologies are usually considered separately, their combination enables two key cooperative features: sensing and maneuvering. Cooperative sensing allows vehicles to exchange information gathered from local sensors. Cooperative maneuvering permits inter-vehicle coordination of maneuvers. These features enable the creation of cooperative autonomous vehicles, which may greatly improve traffic safety, efficiency, and driver comfort. The first generation V2X communication systems with the corresponding standards, such as Release 1 from ETSI, have been designed mainly for driver warning applications in the context of road safety and traffic efficiency, and do not target use cases for autonomous driving. This article presents the design of core functionalities for cooperative autonomous driving and addresses the required evolution of communication standards in order to support a selected number of autonomous driving use cases. The article describes the targeted use cases, identifies their communication requirements, and analyzes the current V2X communication standards from ETSI for missing features. The result is a set of specifications for the amendment and extension of the standards in support of cooperative autonomous driving.

Introduction

In the last years, there has been tremendous interest in the development of vehicles capable of driving autonomously, from both the research community and industry. Autonomous vehicles promise highly increased traffic safety and fuel efficiency, better use of the infrastructure, and the liberation of drivers to perform other tasks. For these reasons, autonomous driving may create a paradigm shift in the way people and goods are transported.

Most autonomous vehicles currently in development are based on a perception subsystem consisting of onboard sensors, which build a map of the vehicle's environment, and a control subsystem that governs the longitudinal and lateral motion of the vehicle [1–3]. Even though this approach has already been demonstrated in field tests, it presents some drawbacks: first, the limited perception range of onboard sensors only allows for detecting adjacent vehicles; and second, the vehicles are unable to cooperate in order to efficiently perform maneuvers with a high complexity.

These limitations may be overcome by means of vehicle-to-vehicle/infrastructure (V2X) communication, which enables two key features in autonomous vehicles: *cooperative sensing* increases the sensing range by means of the mutual exchange of sensed data, and *cooperative maneuvering* enables a group of autonomous vehicles to drive coordinatedly according to a common centralized or decentralized decision-making strategy. The integration of onboard sensors and V2X communication also results in a solution that is more cost-effective than an approach based on high-quality sensors only.

The application of V2X communication to autonomous driving has been a research topic for many years, such as in the pioneering implementations of the PROMETHEUS initiative in Europe and the PATH Automated Highway System in the United States. More recently, several research activities [4, 5] and successful field trials of V2X communication for safety and traffic efficiency [6] have triggered manifold ongoing activities to bring V2X communication for autonomous driving closer to reality. Cooperative autonomous driving is currently being further developed by the European R&D projects AutoNet2030 [7], i-GAME,[1] AdaptIVe,[2] and COMPANION.[3]

We regard V2X communication in support of autonomous driving as a natural evolution of the communication system for cooperative vehicles. The latter, here referred to as first generation V2X communication systems (1G-V2X), has been designed to provide driver assistance, which corresponds to level 1 in the definition of automation levels in SAE J3016 [8]. Higher levels of automation introduce new requirements that are not covered by 1G-V2X; therefore, the definition of new or enhanced messages, communication protocols, and their standardization is needed for cooperative autonomous driving.

The next section outlines some important use cases of autonomous driving where V2X communication plays a key role. The main V2X requirements for the implementation of the considered use cases are then identified, and an overview of the state-of-the-art V2X standards in Europe is given following that. Based on the presented requirements and standards, the message extensions required to support autonomous driving use cases are then explained. Finally, we conclude the article.

Autonomous Driving Use Cases

Use cases for autonomous driving can be grouped in three categories: close-distance, urban, and freeway use cases. Whereas close-distance use cases typically cover autonomous vehicles with the lowest operating velocities — an example is a vehicle able to park autonomously — urban and freeway use cases focus on common traffic situations. The latter two categories have the highest potential to improve traffic safety and efficiency. For this reason, we present the following four urban and freeway use cases for autonomous driving:

Convoy Driving

One of the autonomous driving applications that has gained strong attention from research and industry in recent decades is platooning. In a platoon, vehicles in the same lane are grouped together in a stable formation with small inter-vehicle distances to increase road capacity, driver safety, and comfort. A platoon typically consists of one master, usually the leading vehicle, and multiple following vehicles.

However, a platoon is not the only approach to group vehicles on freeways. In a multi-lane convoy use case, as studied in the AutoNet2030 project, a master, centralized controller, or supervisor does not exist. Instead, the vehicle control, in both lateral and longitudinal directions, is distributed over all members of the convoy (Fig. 1). The result of this approach is that vehicle disturbances, such as a braking vehicle, affect all members of the convoy to a greater or lesser extent, resulting in a stable formation.

In order to maintain small inter-vehicle distances, convoy members rely on the high-frequency exchange of up-to-date and high-quality vehicle dynamics data among vehicles in the convoy. The convoy control algorithm presented in [9] requires just the vehicle dynamics information of neighbor vehicles, instead of the information of all convoy members. As such, the algorithm scales well to large convoys and converges easily to a desired formation when vehicles join and leave the convoy.

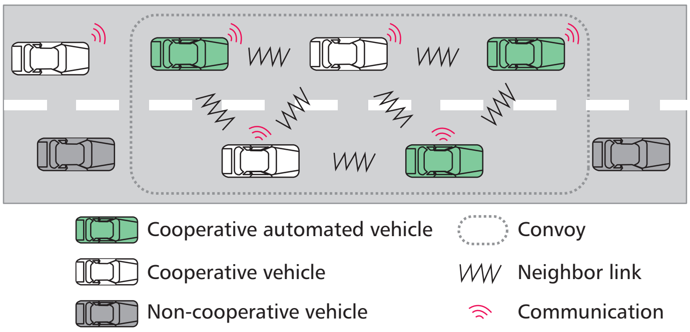

Figure 1. Exchange of vehicle dynamics data for multi-lane convoy driving.

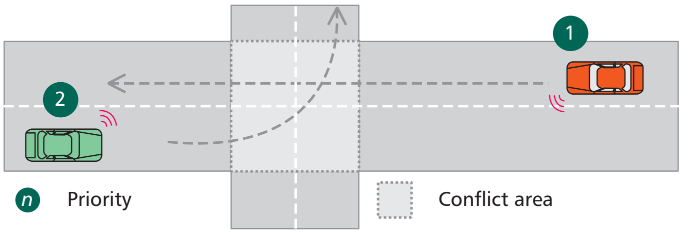

Figure 2. Priority-based coordination of incoming vehicles at an intersection with V2X communication.

Cooperative Lane Change

In the cooperative lane change use cases, cooperative vehicles (both autonomous and manually driven) collaborate to perform a lane change of one or a group of cooperative vehicles (e.g., a convoy) in a safe and efficient manner. Unlike in a traditional lane change situation, cooperative vehicles share their planned trajectories in order to negotiate and align their maneuvers.

The cooperative lane change may be aided by a roadside unit, which supports the communication among the interacting vehicles. However, when this infrastructure is not available, vehicles are forced to coordinate the lane change in an ad hoc fashion.

Cooperative Intersection Management

A cooperative intersection allows cooperative vehicles to traverse an intersection without the need for traffic lights [10]. This scenario requires a coordination mechanism in case their planned trajectories overlap.

A possible solution is shown in Fig. 2, where a roadside unit coordinates the traffic flow through the intersection by assigning relative priorities to incoming vehicles in real time. Then vehicles are able to cross the intersection efficiently following the order of their assigned priority.

Cooperative Sensing

All of the above presented use cases, as well as autonomous driving in general, depend on an adequate and reliable perception of the vehicle surroundings in order to navigate through traffic and ensure safety with a high level of automation. Broken sensors, blind spots, and low level of trust in sensor data may degrade the perfor-

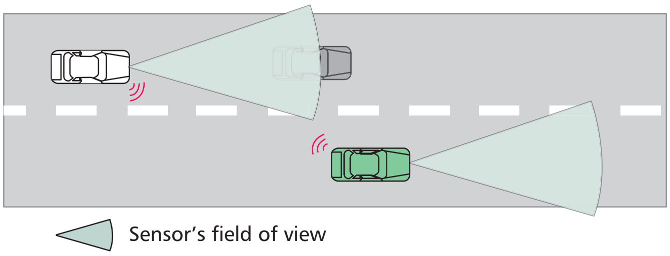

Figure 3. Exchange of detected objects for cooperative sensing.

mance or even disable automated functions of the vehicle.

In the cooperative sensing use case, shown in Fig. 3, neighbor vehicles share information gathered from local perception sensors in order to improve the quality and reliability of individual detections.

COMMUNICATION REQUIREMENTS

1G-V2X mainly addresses road safety and traffic efficiency for manually driven vehicles. Typical applications include obstacle warning, road works information, in-vehicle signage, traffic light phase assistance, and others [6]. The use cases for autonomous driving presented above demand new requirements. New *functional requirements* are below.

Additional Vehicle Status Data: In 1G-V2X, every vehicle broadcasts periodic safety messages to inform neighbors of its position, speed, heading, and other parameters. Autonomous vehicles need to include additional data in the periodic messages for the convoy driving and cooperative lane change use cases, such as their predicted path over the next few seconds.

Convoy Management: In 1G-V2X, a vehicle communicates with vehicles and roadside stations in its neighborhood, or located in a specific geographical region, also called a relevance area for safety information. Opposed to this "open group" concept without an explicit membership, a convoy represents a "closed group" where a vehicle needs to become a group member to participate. In order to create and maintain convoys, as well as to coordinate decentralized maneuvering negotiations, new fault-tolerant mechanisms for group management are needed.

Maneuver Negotiation: In autonomous driving, vehicles may actively need to reserve road space for lane change maneuvers. Unlike the distribution of periodic or event-driven safety messages for 1G-V2X, a reservation requires a negotiation among the involved vehicles to request and acknowledge the maneuver. This exchange enables optimal and safe trajectories for the cooperative vehicles and minimizes their collision risk.

Intersection Management: 1G-V2X is limited to the periodic broadcast of static and dynamic information of intersections, that is, to the distribution of the intersection topology and traffic light information, enabling use cases such as green light optimal speed advisory. It also allows requesting and changing the status of traffic light control systems for priority control and preemption of road traffic. With autonomous driving, communication for intersection management is extended to allow for more detailed information of the intersection geometry and to assign priorities to incoming vehicles, potentially displacing traffic lights.

Cooperative Sensing: Communication allows the exchange of locally acquired sensor data from the radar, camera, and other sensors. The captured data from the local sensors is aggregated into a list of detected objects along the road, such as obstacles, vehicles, and pedestrians, that can be exchanged with neighboring vehicles. Cooperative sensing increases the sensors' field of view to the V2X communication range and enables cooperative perception among vehicles. In 1G-V2X, the aggregation level of sensor data is much higher, and messages only carry a coarse event classifier and relevance area. Instead, the cooperative sensing use case requires the exchange of highly detailed information about the detected objects.

In addition to the functional requirements, specific qualitative *performance requirements* for cooperative autonomous driving include the following.

High Message Rate: In 1G-V2X, vehicles periodically broadcast safety messages with an interval between 100 ms and 1 s, where the rate within these limits is controlled by the dynamics of the generating vehicle and the load on the wireless channel. In contrast, the small inter-vehicle distance among autonomous vehicles requires the use of a high and fixed broadcast frequency with a timeliness guarantee on the information that autonomous vehicles possess about their neighbors. These requirements demand that autonomous vehicles have a complete and up-to-date environmental model, which allows them to coordinate maneuvers in a safe manner.

Data Load Control: The small inter-vehicle distance and corresponding high vehicle density lead to a higher data load in the network. This is even amplified by the high message rate and by additional data load for the exchange of control messages. In order to control the amount of data traffic in the network, efficient utilization of the available frequency spectrum, effective prioritization of messages by the decentralized congestion control (DCC) function, and strict control of the forwarding operations are required.

Low End-to-End Latency: The end-to-end latency is mainly composed of the delay to gather data from local sensors, the processing delay in the protocol stack, and the transmission delay over the wireless link. The end-to-end delay also includes the delay induced by the security mechanisms (generation and verification of signature and certificate, respectively) and by queuing delays in the DCC function. In 1G-V2X, the latency requirements for critical road safety applications are set to 300 ms (ETSI TS 102 539-1). In autonomous driving use cases such as convoy driving, the latency requirement is more stringent due to the smaller inter-vehicle distance between vehicles and also to ensure the string stability of large convoys.

Highly Reliable Packet Delivery: The requirement for reliable exchange of information is more critical than in 1G-V2X, since a lost or erroneous message might cause a malfunction of the vehicle control algorithms and create a safety risk.

Both functional and performance requirements impose demanding challenges on the V2X communication system. This article proposes enhancements of 1G-V2X to meet some of these challenges.

Current Standards for V2X Communication

The R&D efforts on V2X communication over the last years were accompanied by standardization efforts in the European Committee for Standardization (CEN), European Telecommunications Standards Institute (ETSI), IEEE, and International Standards Organization (ISO) in the context of cooperative intelligent transport systems (C-ITS). These activities have led to a consistent set of standards in Europe [11] and the United States [12]. We summarize the core standards for the European Release 1 defined by ETSI, which builds the basis for extensions for communication support toward autonomous vehicles, presented later in this article.[4]

The bottom layer of the reference model in Fig. 4 comprises access technologies: for V2X communication, ITS-G5[5] [EN 302 663] is the most relevant access technology in the context of this work. It has similar features as IEEE 802.11a (e.g., orthogonal frequency-division multiplexing, OFDM), but operates in the 5.9 GHz frequency band, enables a basic ad hoc mode, and disables management procedures. The medium access scheme relies on the well-known enhanced distributed channel access (EDCA) from IEEE 802.11 with carrier sense multiple access with collision avoidance (CSMA/CA) and quality of service (QoS) support. At the ITS network and transport layer, the GeoNetworking protocol (EN 302 636-4) provides single-hop and multihop packet delivery in an ad hoc network of vehicles and roadside stations. Specifically, it utilizes geographical positions carried in the packet headers for geographical addressing and forwarding of packets on the fly. On top of GeoNetworking, the Basic Transport Protocol, BTP (EN 302 636-5-1) provides a UDP-like connectionless transport protocol service.

Facilities layer standards specify application-supporting functionality: the cooperative awareness message (CAM) standard (EN 302 637-2) conveys critical vehicle state information in support of safety and traffic efficiency applications, with which receiving vehicles can track other vehicles' positions and movements. While the CAM is a periodic message sent over a single wireless hop, the decentralized environmental notification message (DENM) standard (EN 302 637-3) specifies a protocol for dissemination of event-driven safety information in a geographical region, typically via multiple wireless hops. Facility-layer messages for vehicle-to-infrastructure communication are specified in TS 103 301, including for transmission of static information about intersection topologies (MAP) and dynamic information for traffic lights. The standards

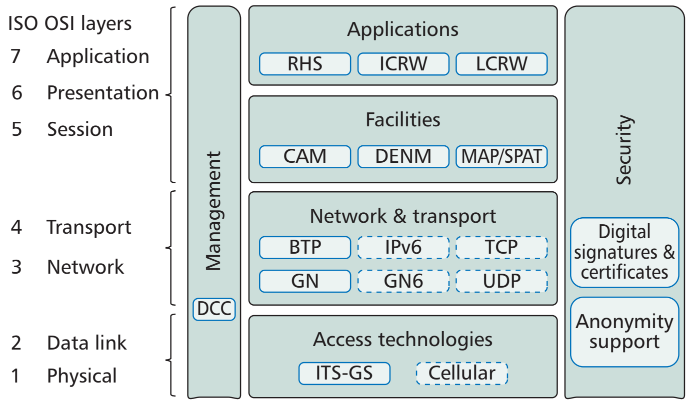

Figure 4. Reference model for 1G-V2X (functional components surrounded by solid lines are within the scope of this article).

at the application layer specify requirements for road hazard signaling (RHS), intersection collision risk warning (ICRW), and longitudinal collision risk warning (LCRW) (TS 101 539-1,-2,-3). RHS comprises use cases for initial deployment, including emergency vehicle approaching, hazardous location warning, and emergency electronic brake lights. ICRW and LCRW address potential vehicle collisions at intersections and rear-end/head-on collisions. Standards at the security block enable cryptographic protection by digital signatures and certificates (TS 103 097); changing pseudonyms for support of anonymity impedes tracking. Finally, management standards mainly cover support for decentralized data congestion control (TS 103 175).

Message Extensions for Cooperative Autonomous Driving

The specification of the European 1G-V2X system and its corresponding standards have been driven by application requirements of RHS, ICRW, and LCRW. Cooperative autonomous driving creates additional communication requirements as described above and justifies a new generation of V2X communication. Compared to 1G-V2X, the new generation still relies on ITS-G5 but modifies the upper protocol layers. We extend and amend the facilities layer to satisfy the functional and performance requirements, in particular the CAM standard (ETSI EN 302 637-2), and we introduce new facilities layer components as shown in Fig. 5. The figure also illustrates enhanced networking and transport protocols; we have already shown that the GeoNetworking protocol can be adapted to meet the network requirements for platooning use cases [13]. Also, we introduce a modification of BTP called Reliable BTP (RBTP). However, here the focus is on facility layer components, indicated by solid boxes in Fig. 5.

The vehicle state information conveyed in a CAM (ETSI EN 302 637-2) is insufficient for the convoy and cooperative intersection use

[4] Available at http://etsi.org/standards

[5] ITS-G5 can be regarded as the European variant of the former "p"-amendment to IEEE 802.11, which has been integrated into IEEE 802.11-2012.

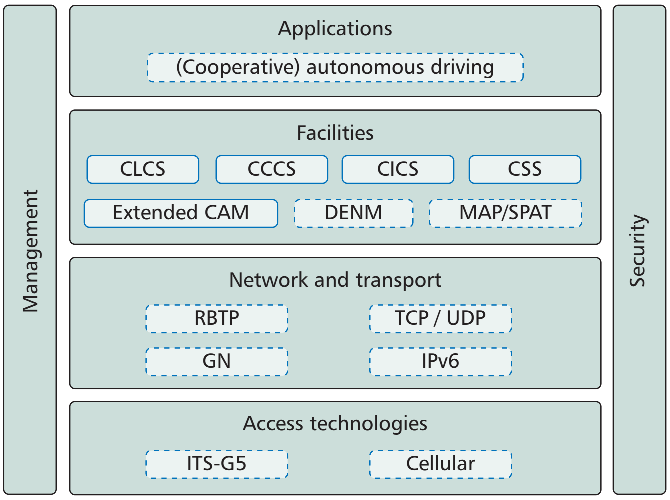

Figure 5. V2X communication architecture considered in the AutoNet2030 project.

cases. For planning maneuvers and avoiding safety-critical situations, both use cases require the exchange of periodic control-related data between neighbor vehicles, such as their predicted trajectory. This trajectory is calculated by the autonomous vehicle and cannot be measured with external sensors. Additionally, driving in a convoy requires the exchange of additional information, such as the distance to the preceding and following vehicles, target speed and acceleration, and convoy identifier.

In order to satisfy these data requirements, we propose to extend the CAM standard with additional *high* and *low* frequency containers that carry the control data specific to cooperative autonomous vehicles. The high frequency container includes only the minimum set of highly dynamic vehicle attributes for convoy driving to limit the total CAM size, including speed, heading, acceleration, and others. The low frequency container contains the less critical vehicle control data mentioned above.

In addition, two operating modes are introduced: *normal* mode and *high awareness* mode. In normal mode, CAMs are broadcast with variable frequency according to the standardized triggering conditions (i.e., between 1 and 10 Hz) depending on the vehicle dynamics. The high awareness mode augments the normal mode and increases the transmission frequency to a fixed value of 10 Hz. The newly introduced containers are only generated in high awareness mode and transmitted to single-hop neighbor vehicles using ITS-G5 on a separate service channel to relieve the heavily used control channel.

Convoy Control Communication Service

The *convoy control communication service* (CCCS) supports the exchange of information messages among cooperative vehicles in the convoy driving use case and satisfies the functional requirement for convoy management. The transmission frequency of convoy messages is dynamically adjusted depending on the convoy properties and traffic conditions. The messages exchanged among convoy vehicles via the CCCS enable each vehicle to maintain a local graph, whose nodes are the convoy members; the edges represent the dependence of the vehicle dynamics. A decentralized vehicle control algorithm performs the cooperative maneuvering, adjusting the vehicle lateral and longitudinal dynamics to keep a balanced formation and performing lane changes as required [9].

The message types offered by the CCCS to convoy members are the following.

Join/leave convoy: A join request is a single-hop broadcast message sent by an approaching vehicle, which detects a convoy and requests to become a convoy member. Similarly, a convoy vehicle that decides to abandon it (e.g., when it reaches its destination) will broadcast a leave request to inform its neighbors of its intention.

Lane change: A lane change message allows convoy vehicles to change their lane within the convoy. The message is broadcast by a convoy vehicle to inform its neighbors of a planned lane change. This way, the convoy members in the destination lane will adjust their positions to make space for the incoming vehicle.

Modify local graph: As a result of a lane change or a new vehicle entering the convoy, a vehicle may update its local graph. In this case, the new graph is broadcast to its neighbors by means of a modify local graph message. The neighbor vehicles then modify their own local graphs accordingly, thereby ensuring the consistency of the graphs among all the convoy members.

Cooperative Lane Change Service

The *cooperative lane change service* (CLCS) enables the communication for the cooperative lane change use case. CLCS supports maneuver negotiations among vehicles not belonging to the same convoy and relative space reservation by dedicated messages. The cooperative lane change is divided into three phases.

Search Phase: The planned lane change of a subject vehicle is announced in this phase, in search of a peer vehicle to start the lane change negotiation. This phase is optional and only executed when the subject vehicle has insufficient awareness of the traffic situation, and is unable to select the appropriate peer in advance. The planned lane change is described in a *lane change request* (LCR) message and is broadcast multihop around the lane change area. Any vehicle receiving the LCR will decide, based on its own planned trajectory, whether it is a suitable peer and will respond with a *lane change response*, which is unicast multihop to the subject vehicle. The subject vehicle eventually selects the most appropriate peer vehicle and informs all vehicles around the lane change area, including the selected peer vehicle, about this decision by broadcasting periodically an updated LCR message until the cooperative lane change has finished.

Preparation Phase: The selected peer vehicle opens the requested headway distance, and both vehicles adjust to the agreed speed and time of arrival. Once prepared, the peer vehicle informs the subject vehicle with a *lane change prepared* message that the next phase can start.

Execution Phase: The lane change maneuver is executed in this phase without communication support of the CLCS component. The maneuver safety is ensured by the autonomous vehicles, based on received CAMs and local sensor information.

During all cooperative lane change phases, unexpected events may occur, which require to abort the lane change. In this case, a dedicated *lane change abort* (LCA) message is exchanged between the subject and peer vehicle. The CLCS component uses a retransmission and acknowledgment mechanism in order to improve the reliable delivery of LCA messages.

COOPERATIVE INTERSECTION CONTROL SERVICE

The *cooperative intersection control service* (CICS) supports the traversing of an intersection by cooperative autonomous vehicles, that is, *intersection management* as the functional requirement. In order to allow for a collision-free and deadlock-free intersection crossing, a roadside unit acts as intersection controller to coordinate the maneuvers of the vehicles approaching the intersection [10]. The intersection controller sends on-demand messages to incoming vehicles in order to assign them priorities based on information about their current status and desired trajectories; these regulate the order in which they are allowed to cross the intersection.

The message types offered by CICS are below.

Intersection Entry Request: This unicast message is sent by approaching vehicles, which detect the presence of the intersection controller. In the intersection entry request, the vehicle specifies its desired entry and exit lanes, the predicted time to enter the intersection, and information about the vehicle dynamics.

Intersection Entry Cancellation: With this message, a vehicle is able to inform the intersection controller that it wants to cancel a previous intersection entry request, for instance, in order to send a new entry request with different parameters.

Intersection Entry Status: The calculated relative priorities by the intersection controller are broadcast to all cooperative vehicles near the intersection. With this information, the vehicles are able to maneuver cooperatively and traverse the intersection safely.

It is worth noting that CICS also supports non-cooperative vehicles crossing the intersection. Two cases can be considered: first, if a non-cooperative vehicle is driving on its own, the intersection controller communicates the assigned priority by means of traffic lights; second, if the non-cooperative vehicle belongs to a platoon led by a cooperative vehicle, all the platoon vehicles will cross the intersection according to the priority assigned to the platoon leader.

COOPERATIVE SENSING SERVICE

The *cooperative sensing service* (CSS) enables the sharing of detected objects, including vehicles, pedestrians, cyclists, and so on, by means of *cooperative sensing messages* (CSMs) and enables the cooperative sensing use case.

A CSM can describe up to 16 detected objects in terms of their main attributes, including position, heading, speed, acceleration, and respective confidence level. Compared to raw sensor data, such as video frames of a camera or point cloud of a lidar, object attributes are less sensor-dependent and result overall in smaller messages being transmitted.

The tendency in the design of future autonomous vehicles is to combine the data of multiple sensors in order to create more concise detections and improve the overall detection accuracy compared to individual detections. The CSS component can interface with such a sensor fusion process in two ways: as a consumer and as a producer of perception data. As a consumer, the CSS constructs new CSMs with the sensor fusion output. As a producer, the CSS component can provide the content of received CSMs and act as a virtual sensor.

The nature of many perception sensors is to measure and provide relative object attributes, such as the distance or relative speed of a detected vehicle. Even though these values are appropriate for the control of an autonomous vehicle, relative object attributes are not suitable for inter-vehicle sharing. For this reason, the CSM only contains absolute object attributes.

The CSS component constructs CSMs at a rate of 1 Hz and disseminates the message over a single wireless hop to the neighbor vehicles. In order to deal with a higher data load, CSMs are transmitted on the service channel (e.g., SCH1) rather than on the control channel on which packets are typically transmitted in 1G-V2X.

CONCLUSION

Autonomous driving is regarded as a major innovative step that has the potential to fundamentally transform the mobility of people and goods. Today, most developments target standalone autonomous vehicles, which are capable of sensing the surroundings and control the vehicle based on this perception, with limited or no driver intervention. The inherent drawback of this solution is the lack of coordination among vehicles and the limited range of sensors, which results in suboptimal performance. Vehicle-to-vehicle/infrastructure communication (V2X) overcomes these drawbacks by increasing the planning horizon of autonomous vehicles and enabling two key features for autonomous driving: *cooperative maneuvering* and *cooperative sensing*.

In this article, we have presented four use cases for cooperative autonomous driving, and analyzed their requirements for safe and efficient operation. Compared to the first generation of V2X communication systems (1G-V2X) and its corresponding Release 1 of communication standards, cooperative autonomous driving requires adaptations and extensions. We have presented an evolution of the V2X communication system as standardized by ETSI. In particular, we have shown how the CAM standard as the V2X core facility can be extended, and we have introduced new facilities layer components.

The proposed V2X communication system for cooperative autonomous driving uses an enhanced ITS-G5-based protocol stack. This

Vehicle-to-vehicle/infrastructure communication (V2X) increases the planning horizon of autonomous vehicles and enables two key features for autonomous driving: cooperative maneuvering and cooperative sensing.

AutoNet2030 in particular will focus on the analysis of quantitative performance requirements using simulations and demonstration of AutoNet2030 concepts in a prototypical implementation. All in all, these developments will demonstrate the level of automation that can be achieved by V2X communication toward the vision of fully automated driving.

approach allows a gradual deployment of the next generation of V2X communication for cooperative autonomous driving relying on 1G-V2X. While the introduction of 1G-V2X is expected in the next few years, AutoNet2030 and other projects contribute to the development of concepts, protocols, prototype implementations, evaluation, and standards for the next generation of V2X communication systems. AutoNet2030 in particular will focus on the analysis of quantitative performance requirements using simulations and demonstration of AutoNet2030 concepts in a prototypical implementation. All in all, these developments will demonstrate the level of automation that can be achieved by V2X communication toward the vision of fully automated driving.

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BIOGRAPHIES

LAURENS HOBERT has been a development engineer since 2010 for the Automotive and Industry Laboratory of Hitachi Europe, Sophia Antipolis, France. He received his Diploma (M.Sc.) in telematics from the University of Twente in 2012. His research interests include intelligent transport systems, wireless communication, automated driving, and software prototyping. He has been involved in various European projects, including CoVeL, DRIVE-C2X, eCo-FEV, and AutoNet2030, and actively contributes to standardization in ETSI Technical Committee ITS and the CAR-2-CAR Communication Consortium.

ANDREAS FESTAG is research group leader and lecturer at the Technical University Dresden, Vodafone Chair Mobile Communication Systems. He received a diploma degree (1996) and Ph.D. (2003) in electrical engineering from the Technical University of Berlin. His research is concerned with 5G cellular systems and vehicular communication. He actively contributes to the CAR-2-CAR Communication Consortium and ETSI Technical Committee ITS.

IGNACIO LLATSER received a double degree in telecommunication engineering and computer science (2008), a Master's degree (2011), and a Ph.D. degree (2014) from the Technical University of Catalonia, Barcelona, Spain. He is currently a postdoctoral researcher at the Technical University of Dresden, Germany, in the framework of the FP7 project AutoNet2030. His research interests lie in the fields of nanoscale communication networks, vehicular networks, and autonomous driving.

LUCIANO ALTOMARE is a researcher and developer at Centro Ricerche Fiat, FCA company, since 2007. He received a Master's degree (2006) in physics from the University of Bologna, Italy. Currently his research activity is mainly focused on vehicle-to-vehicle applications and prototype integration.

FILIPPO VISINTAINER graduated in physics and is a senior researcher of Centro Ricerche FIAT, Trento Branch, part of FCA Vehicle Research and Innovation, where he has been working since 2001. Within the European Framework Programmes he has been Project Manager within several projects on intelligent mobility, preventive safety, e-Inclusion, and vehicular communication, including DRIVE C2X, TEAM IP, AutoNet2030, and AdaptIVe. Lately he has been leading an innovation project of his company on connected vehicle services.

ANDRAS KOVACS has been working in the field of ITS for 10 years. His background is in telecommunication networks research. He has contributed to the work of the Car-2-Car Communication Consortium in the past, and currently participates in the work of ETSI ITS. His research interests relate to geonetworking, ITS applications, and their testing aspects. He is currently the director of R&D at BroadBit and the technology manager of AutoNet2030.