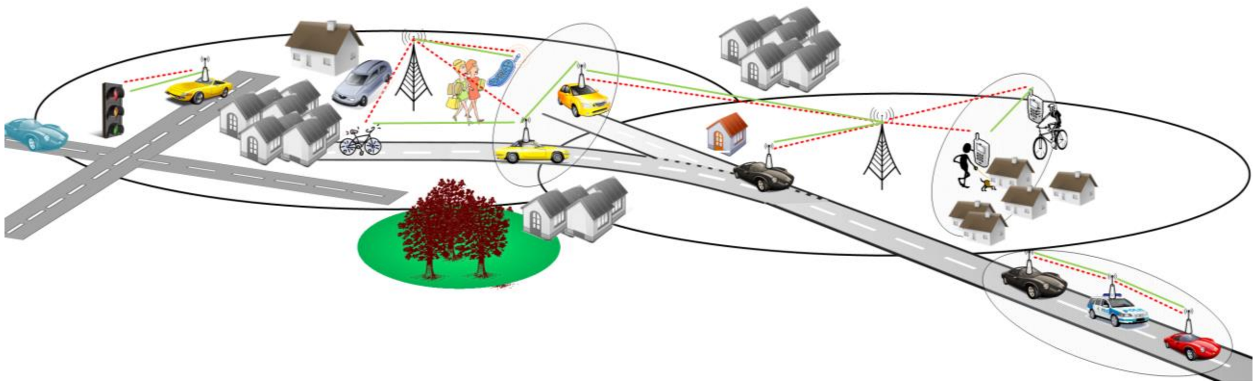
5G Automotive Vision



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Executive Summary

The automotive industry is currently undergoing key technological transformations, as more and more vehicles are connected to the Internet and to each other, and advance toward higher automation levels. In order to deal with increasingly complex road situations, automated vehicles will have to rely not only on their own sensors, but also on those of other vehicles, and will need to cooperate with each other, rather than make decisions on their own. These trends pose significant challenges to the underlying communication system, as information must reach its destination reliably within an exceedingly short time frame – beyond what current wireless technologies can provide. 5G, the next generation of mobile communication technology, holds promise of improved performance in terms of reduced latency, increased reliability and higher throughput under higher mobility and connectivity density. In this White Paper, representatives from both the automotive and the telecom industry provide their vision on how 5G will enable the next generation of connected and automated driving and new mobility services, identify the limitations of present wireless technologies, and describe the key research and innovation areas that need to be explored and advanced in order to realize this 5G automotive vision.

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Definitions

For the purposes of this White Paper, the following terms and definitions apply.

Advanced Driver Assistance System (ADAS): Electronic system in an automobile that supports the driver on the driving process by providing him information, warning him and, in case it is designed for this purpose, actively intervening in the driving process. A driver assistance system can be overridden by the driver at any time.

Automated driving: Active intervention of a driver assistance system in the control of the vehicle through steering of the longitudinal axis, the lateral axis, or both axes. The driver is present and hands over the longitudinal and lateral control depending on the driving situation and degree of automation. In situations where the automation is not sufficient, the driver has to regain control.

Autonomous driving: Fully automated driving. No driver action is required at any time, i.e., no driver needs to be in the vehicle.

Broadcast: Transmission of a data packet from a source to all stations, i.e., point-to-multipoint communication. Examples are the broadcast to all neighbor stations within direct communication range, in a sub-network, or in a geographical area.

Connected vehicle: Vehicle capable of exchanging information with other vehicles, roadside infrastructure, a backend server, a pedestrian, or the Internet, using wireless communication technologies.

Contention-based medium access: Method for sharing a broadcast medium among multiple stations. Stations contend for medium access, in contrast to assignment of transmission resources (e.g., time slots) by a coordinating master, such as a base station.

Convoy: Group of vehicles that share common mobility patterns and maintain a formation (typically inter-vehicle distances and speed alignment) using Cooperative Adaptive Cruise Control (C-ACC). Contrary to a platoon, a convoy does not have a leader, i.e., it self-organizes.

Cooperative ITS (C-ITS): Intelligent transportation systems supported by communication technologies to enable the cooperation of vehicles, roadside equipment and pedestrians. Also refers to the European IEEE 802.11p-based set of standards for road safety and traffic efficiency developed by CEN and ETSI.

Decentralized Congestion Control (DCC): Set of algorithms and protocols used to maintain network stability, throughput efficiency and fair resource allocation to stations. DCC is required in decentralized communication systems, such as those based on IEEE 802.11p/ITS-G5.

Dedicated Short-Range Communications (DSRC): Set of standards relying on IEEE 802.11p and the WAVE protocols developed by IEEE and SAE.

Device-to-Device communication (D2D): Communication mode in mobile networks that enables direct communication among devices within communication range.

Future Internet: Concepts and approaches on new architectures for the Internet.

Intelligent Transport Systems (ITS): Application of information and communication technologies for the safe and efficient transport of people and goods.

Human Type Communications (HTC): Communication that mainly involves human interaction, such as voice and video, with different requirements than machine-type communication.

ITS-G5 Control Channel (CCH): Wireless channel in the 5.9 GHz frequency band allocated for safety and traffic efficiency. Also referred to as "always-on safety channel" because it carries safety-of-life messages in IEEE 802.11p/ITS-G5 based systems.

ITS-G5 Service Channel (SCH): Wireless channel in the 5.9 GHz frequency band allocated for safety and traffic efficiency. Opposed to a control channel, a service channel carries additional data. In IEEE 802.11p/ITS-G5 based systems, the use of a service channel may imply the announcement of services and channel switching.

Machine Type Communications (MTC): Communication that involves little or no human interaction and has different requirements than human-type communication.

Maneuver synchronization: Lateral and longitudinal control of a vehicle that informs other vehicles of its planned trajectory or negotiates its trajectory with other vehicles, such as for automated overtake.

Multi-link: Capability of a device to communicate via multiple wireless links in a mobile network.

Multi-RAT: Capability of a mobile network to support multiple radio access technologies with seamless interworking among them.

Network Function Virtualization (NFV): Application of IT virtualization technology to mobile networks in order to consolidate many network equipment types onto industry standard high volume servers, switches and storage, which could be located in data centers, network nodes and in end user premises.

Platoon (Platooning): Group of vehicles that share common mobility patterns, maintain a formation (typically inter-vehicle distances and speed alignment) and exchange information about intended maneuvers. Contrary to a convoy, a platoon has a leader that manages the group.

Proximity Services (ProSe): Proximity Services are services that can be provided by the 3GPP system based on UEs being in proximity to each other. These include ProSe Direct Discovery, ProSe Direct Communication and ProSe UE-to-Network Relay.

ProSe Direct Communication: A communication between two or more UEs in proximity that are ProSe-enabled, by means of user plane transmission using E-UTRA technology via a path not traversing any network node.

ProSe Direct Discovery: A procedure employed by a ProSe-enabled UE to discover other ProSe-enabled UEs in its vicinity by using only the capabilities of the two UEs with E-UTRA technology.

ProSe UE-to-Network Relay: A UE that provides functionality to support connectivity to "unicast" services for Remote UE(s) not served by E-UTRAN.

PC5 transport: Transmission of V2X data from a source UE (e.g., a vehicle) to a destination UE (e.g., another vehicle, road infrastructure, a pedestrian, etc.) via ProSe Direct Communication over the PC5 interface between the UEs (sidelink).

Radio Access Technology (RAT): Radio communication technology that provides data transmission on the physical and data link layers of the ISO OSI reference model.

Radio Resource Management (RRM): Management of radio resources for wireless transmission (e.g., physical resource blocks), either centralized or de-centralized.

Road safety: Methods and measures for reducing the risk of a road user becoming involved in an accident, such as through driver information and warnings.

Sensor data dissemination: Transmission of data collected from sensors, typically from vehicle sensors but also roadside sensors, and distribution of the data via a wireless network.

Sidelink: Direct radio link for communication among devices in 3GPP radio access networks, as opposed to communication via the cellular infrastructure (uplink and downlink). Also referred to as D2D link.

Sidelink transmission mode 1 (scheduled): One of two modes for ProSe Direct Communication, whereby sidelink radio resources are allocated by the cellular infrastructure (eNB).

Sidelink transmission mode 2 (autonomous): One of two modes for ProSe Direct Communication, whereby sidelink radio resources are autonomously selected by the UE from a (pre)configured resource pool.

Small cell: Wireless cell of small diameter (in the range of 10s of meters) deployed to increase capacity in hotspots with high user demands and to fill in areas not covered by large cells.

Software Defined Networking (SDN): Concept that decouples network control and data forwarding functions for flexibility and cost reasons.

Tele-operated driving: Driving mode whereby driving tasks are taken over by a human driver physically located outside of the vehicle.

Traffic efficiency: Methods and measures for increasing the transport efficiency on roads, such as by road traffic management.

Uu transport: Transmission of V2X data from a source UE (e.g., a vehicle) to a destination UE (e.g., another vehicle, road infrastructure, a pedestrian, etc.) via the eNB over the conventional Uu interface (uplink and downlink).

Vehicle-to-Everything (V2X): Any communication involving a vehicle as a source or destination of a message. Depending on the nature of the other communication endpoint, several special cases exist: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) (road infrastructure, which may or may not be co-located with cellular infrastructure), Vehicle-to-Network (V2N) (e.g., a backend or the Internet), Vehicle-to-Pedestrian (V2P), etc.

Virtual Machine (VM): Software that realizes IT virtualization, i.e., a software environment that emulates dedicated hardware and executes functions and applications.

Vulnerable Road User (VRU): A road user, such as a pedestrian, a cyclist or a motorcyclist, bearing a greater risk of serious injury than vehicle occupants when involved in a traffic accident.

Abbreviations

For the purposes of this White Paper, the following abbreviations apply.

3G	Third Generation of Mobile Communications
3GPP	Third Generation Partnership Project
4G	Fourth Generation of Mobile Communications
5G	Fifth Generation of Mobile Communications
5G PPP	5G Infrastructure Public Private Partnership
AC	Access Category
ACK	Acknowledgment
ADAS	Advanced Driver Assistance System
AIFS	Arbitration Inter-Frame Spacing
AM	Acknowledged Mode
ASECAP	Association Européenne des Concessionaires d'Autoroutes et d'Ouvrages à Péage
B2B	Business-to-Business
B2G	Business-to-Government
BDA2GC	Broadband Direct Air-to-Ground Communications
BSS	Basic Service Set
C2C-CC	Car-2-Car Communication Consortium
C-ACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
CBTC	Communications Based Train Control
CCH	Control Channel (ITS-G5)
CCSA	China Communications Standards Association
CDN	Content Delivery Network
CEDR	Conference of European Directors of Roads
CEN	European Committee for Standardization
CEPT	European Conference of Postal and Telecommunications Administrations
C-ITS	Cooperative ITS
CMC	Connection Mobility Control
CRL	Certificate Revocation List
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D2D	Device-to-Device

DCC	Decentralized Congestion Control
DENM	Decentralized Environmental Notification Message
DG MOVE	Directorate-General for Mobility and Transport
DL	Downlink
DMRS	Demodulation Reference Signal
DNS	Domain Name System
DSM	Digital Single Market
DSRC	Dedicated Short-Range Communications
DTLF	Digital Transport and Logistics Forum
eCall	Emergency Call
ECC	Electronic Communications Committee
EDCA	Enhanced Distributed Channel Access
E-GNSS	European Global Navigation Satellite Systems
eNB	E-UTRAN Node B
ESO	European Standards Organization
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplex
FEC	Forward Error Correction
GLOSA	Green Light Optimal Speed Advisory
HARQ	Hybrid Automatic Repeat Request
HMI	Human Machine Interface
HTC	Human Type Communications
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
IoT	Internet of Things
IRS	ITS Roadside Station
ISO	International Organization for Standardization
ITS	Intelligent Transport Systems
ITS-G5	Intelligent Transport Systems in the 5 GHz frequency band
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radiocommunication Sector
KPI	Key Performance Indicator
LAA	License Assisted Access

LDM	Local Dynamic Map
LIPA/SIPTO	Local IP Access / Selected IP Traffic Offload
LTE	Long Term Evolution
LTE-A	Long Term Evolution – Advanced
LTE-D	LTE Direct
MaaS	Mobility as a Service
MAC	Medium Access Control
MBB	Mobile Broadband
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
MJPEG	Motion JPEG (Joint Photographic Experts Group)
MNO	Mobile Network Operator
MTC	Machine Type Communications
MVNO	Mobile Virtual Network Operator
NACK	Negative Acknowledgment
NF	Network Function
NFV	Network Function Virtualization
NGMN	Next Generation Mobile Networks Alliance
NLOS	Non-Line-Of-Sight
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PHY	Physical Layer
PII	Personally Identifiable Information
PKI	Public Key Infrastructure
PLMN	Public Land Mobile Network
POLIS	European Cities and Regions Networking for Innovative Transport Solutions
PRACH	Physical Random Access Channel
ProSe	Proximity Services
PSBCH	Physical Sidelink Broadcast Channel
PSCCH	Physical Sidelink Control Channel
PSDCH	Physical Sidelink Discovery Channel
PSSCH	Physical Sidelink Shared Channel
QoE	Quality of Experience
QoS	Quality of Service
RAC	Radio Admission Control

RACH	Random Access Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RBC	Radio Bearer Control
RLAN	Radio Local Area Network
RLC	Radio Link Control
RRM	Radio Resource Management
RSU	Roadside Unit
RTS/CTS	Request-to-Send / Clear-to-Send
SA	Scheduling Assignment
SAE	Society of Automotive Engineers
SC-FDMA	Single Carrier – Frequency Division Multiple Access
SCH	Service Channel (ITS-G5)
SCI	Sidelink Control Information
SDN	Software Defined Networking
SDO	Standards Developing Organization
SISO	Single-Input Single-Output
SL	Sidelink
SL-SCH	Sidelink Shared Channel
SLRB	Sidelink Radio Bearer
SPS	Semi-Persistent Scheduling
TPC	Transmit Power Control
TRP	Time Resource Pattern
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VDA	German Association of the Automotive Industry
VM	Virtual Machine
VRU	Vulnerable Road User
WAVE	Wireless Access in Vehicular Environments
WRC	World Radiocommunication Conference

1 Socio-economic drivers of the automotive industry at the horizon 2020

This section outlines key transformations happening in the automotive industry, such as the introduction of automated driving, the provision of road safety and traffic efficiency services, and the digitalization of transport and logistics. New business models are described and a roadmap for the market introduction of vehicle communication is discussed.

1.1 Introduction

Vehicles can exchange information with other vehicles (V2V), with the roadside infrastructure (V2I), with a backend server (e.g., from a vehicle manufacturer or other mobility service providers) or with the Internet (V2N), with a pedestrian (V2P), etc. To refer to all these types of vehicular communication, the term Vehicle-to-Everything (V2X) has been proposed.

Connected vehicle services have existed in the market for more than 10 years with the provision of automated crash notifications, vehicle breakdown notifications, traffic information and infotainment services, among others. Following the heels of these commercial deployments, eCall (emergency call) will be the first regulated service mandating all new vehicles to be connected to mobile communication networks and to be capable of geo-location by means of European Global Navigation Satellite System (E-GNSS / Galileo) receivers. Thus, eCall marks the beginning of the adoption of connected services on a larger scale.

Future vehicles will be connected, as connectivity is a key enabler for the provision of value added services relating to the different types of vehicles. In the global context of road transport, connectivity will be a critical enabler to support the takeoff of new business opportunities relating to vehicles and the EU and Member states' policies in the context of transport. The Internet of Things (IoT) will contribute to collect additional data, complementing the data already collected by vehicles and traffic management centers. This data, exchanged along the roads and on the Internet, will be useful to develop new services for vehicle users. The automobile industry, for instance, sees two main trends with relevance for the 5G automotive vision: (1) *automated driving* and (2) *road safety and traffic efficiency services*. Activities from various stakeholders, including governments, in Europe and the US, are supporting or even advocating vehicle communication.

The following sections present different kinds of services that could drive new opportunities for the automotive industry and service providers.

1.2 Key transformations happening in the automotive industry

1.2.1 Automated driving

According to the US Society of Automotive Engineers (SAE) and the German Association of the Automotive Industry (VDA), six levels with increasing degree of automation are defined for automated driving (SAE Standard J3016, January 2014). Figure 1 shows an introduction scenario for automated driving with examples of possible functionalities with a time horizon until 2025.

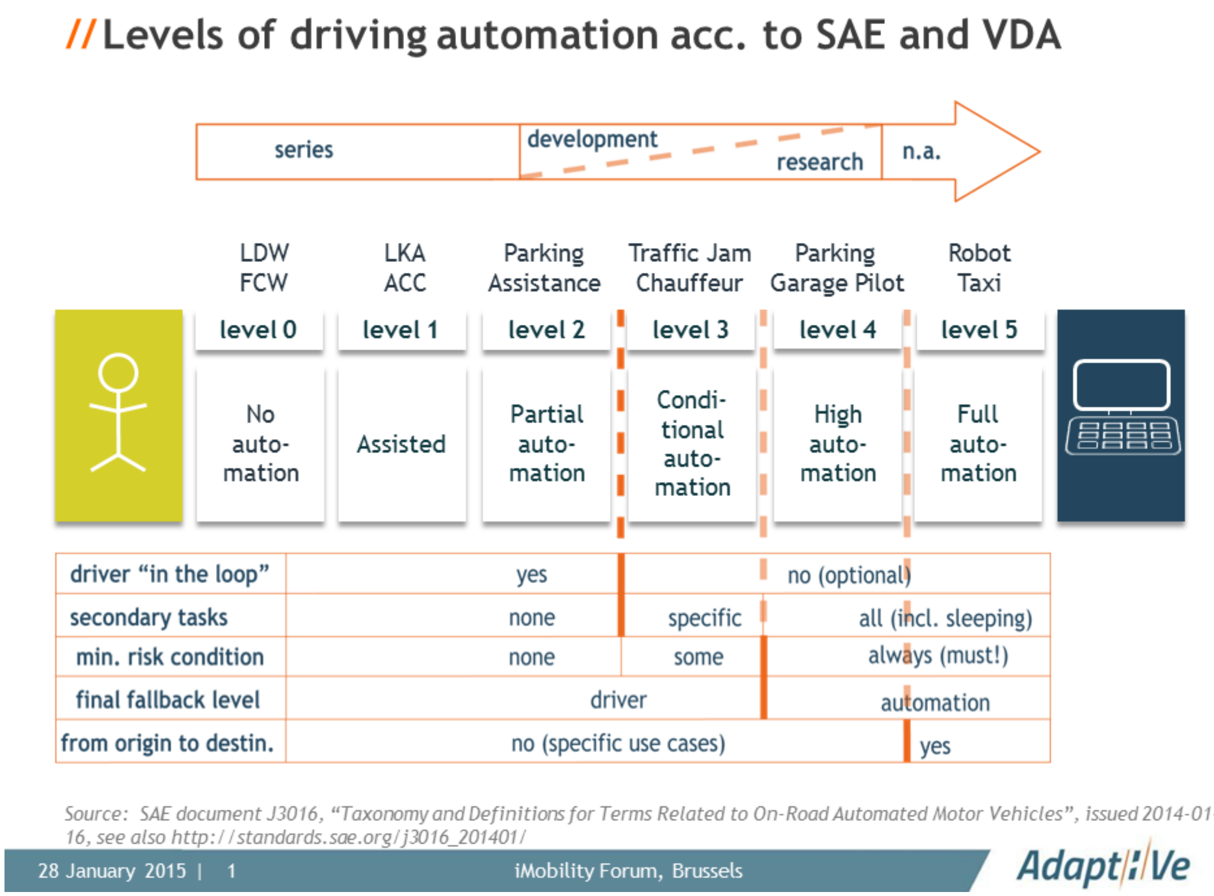

Figure 1. SAE/VDA automation levels

In principle, automated driving is possible without V2X communication, even for high and full automation. Recently, there have been several demonstrations based only on on-board sensor systems (e.g., Audi 550-mile piloted drive from Silicon Valley to Las Vegas in 2014 (Audi AG, October 2014)). However, these demonstrations used high-resolution digital maps, which were downloaded from a backend server (V2N). Fully automated driving based only on on-board sensor systems without any support from wireless communication systems is until this date not possible. In addition to V2N, automated driving can benefit from local V2V and V2I communication, as vehicle behavior is better adapted to the traffic situation, leading to greater customer satisfaction.

1.2.2 Road safety and traffic efficiency services

Vehicle automation will develop very quickly now, fostered by competition. However, will all vehicles be offered with a high level of automation? The information collected for vehicle automation through V2X connectivity also enables the provision of warning applications to the driver. Both EC and national funded projects (simTD Project, June 2013) (DRIVE C2X Project, July 2014) (Compass4D Project, October 2015) have successfully demonstrated various V2X applications supporting vehicle users towards driving more safely and efficiently. The following services were, for instance, demonstrated in the context of these projects:

- Intersection Collision Risk Warning
- Road hazard warnings (road works, car breakdown, weather conditions, etc.)
- Approaching emergency vehicle warning
- Pre-/Post-Crash
- Electronic Emergency Brake Warning
- GLOSA – Green Light Optimal Speed Advisory
- Energy-efficient intersection
- Motorcycle approaching information
- In-vehicle signage
- Red light violation warning
- Traffic jam ahead warning

1.2.3 Digitalization of transport and logistics

The first Plenary of the Digital Transport and Logistics Forum (DTLF) was held in July 1-2, 2015, in Brussels. The Directorate-General for Mobility and Transport (DG MOVE) presented the Forum as a consultative body to develop a global vision on digital transport and logistics in "the general context of the Digital Single Market" to identify initiatives and concrete recommendations for relevant European policies and legislation". DG MOVE also expressed the need to focus on a multimodal perspective looking for "synergies" between different means of transport.

DG MOVE has presented four "content drivers" concerning the digitalization of transport: harness and use data increasing the efficiency of the transport logistics chain, decarbonization, human factor and international aspects. Digital transport and logistics will concern the information and data relating to goods, means of transport, authentication and access to ports or customs clearance information. Big data will create new opportunities while exploiting the large amount of information generated along the logistics chain. The IoT will strongly contribute to generating useful information and cloud platforms will provide opportunities to exploit the data.

Beyond the eBusiness process and the related data, the vehicle will play a significant role in the logistics chain. Intelligent Transport Systems (ITS) are likely to contribute significantly to the increase of road transport efficiency. Route optimization and use of Cooperative ITS (C-ITS) are enabling significant reduction of energy consumption and travel times. Collecting useful traffic and road condition information through vehicle ITS platforms will also increase the amount of useful data provided to the supply chain actors.

Predictability of transport operations as well as the provision of real-time information about road conditions will contribute to the provision of effective track and trace tools across borders and transport modes, which are critical for improving the global logistics chain efficiency.

The next commercial vehicle platform developed by the automotive industry will have to build on the future needs of the transport and logistics actors. Vehicles will collect useful information from their own components as well as from other vehicles and roadside units. The combination of this data with other eBusiness information will support the drivers as well as other logistics chain actors in their daily business.

The exchange of large amounts of data from numerous sources will require "agile" networks. The role of future 5G networks is relevant to support the new logistics chain solutions and contribute to the vision from DG MOVE for the digitalization of transport and logistics.

1.2.4 Intelligent navigation

Navigation systems use geo-positioning and digital maps to provide navigation guidance to drivers. Navigation unit manufacturers also provide additional services to improve driving efficiency by choosing appropriate routes according to real-time traffic information. Traffic information is computed with data provided by other vehicles, road authorities or traffic management centers. More useful data will be collected in the future thanks to the IoT and Big Data, allowing for the provision of more efficient navigation services.

The increase of useful data made available to the navigation systems or the vehicle automotive platforms will enable the provision of more value added services, complementing the navigation. Point-of-interest notifications will help the driver, e.g., in finding a hotel, a restaurant, a parking place, etc. Commercial online services may also be provided on board. Beyond current online services on the Internet, vehicle data will also contribute to these added value services with additional vehicle specific or driving environment data.

Navigation systems themselves will evolve through integration of information received from extra sensors such as cameras and radars installed on the vehicle as well as relevant real-time information from other vehicles in the vicinity and road infrastructure.

1.2.5 Information society on the road

Vehicle passengers will have the same demand concerning connectivity performance in the vehicles as at home or at work. Furthermore, partial or high automation will allow the driver to use this connectivity while the car is driving autonomously.

These key transformations will trigger the evolution of vehicle dashboards providing appropriate Human Machine Interfaces (HMIs) for using leisure and entertainment services in the vehicles or allowing the drivers to use the car as a second office. Beyond the adaptation of the vehicle design, new kinds of applications that take advantage of the availability of traffic and driving information can be provided to drivers and passengers.

1.3 New business models

1.3.1 Pay as you drive

Pay as you drive services aim at defining driving service costs according to actual vehicle usage. Pay as you drive is already known in relationship with insurance services. An accurate evaluation of the actual distance driven by vehicle users, as well as the driving environment, will make it possible to better suit insurance fees to actual risks.

Collecting various types of data accurately is necessary to properly evaluate risks and assess driving costs. Not only insurance companies are interested in Pay as you drive, but also companies providing vehicles for rent or leasing, as well as for the provision of vehicle services.

1.3.2 Mobility as a Service (MaaS)

Mobility as a Service is seen as a global solution for users to find the most appropriate means of transport, with the best conditions, according to the actual needs and mobility conditions in real time. Commuters or travelers may, for example, use personal vehicles in combination with public transport. Beyond the availability of such services on the Internet, MaaS can also be used as an on-board service, using the vehicle platform and thus providing offers that are better suited to the vehicle user's situation.

1.3.3 Predictive maintenance

Predictive maintenance enabled through data captured from sensors and predictive analytics will help vendors and Original Equipment Manufacturers (OEMs) to offer long-term service based mobility solutions to customers. Manufacturers will be able to continuously aggregate the data captured from multitude of sensors on the connected vehicle and analyze it to help predict faults and errors well in advance. This information can be used to take timely actions in terms of initiation of maintenance and repair actions by alerting the customer or scheduling an appointment with a maintenance dealer. Business models will transform from merely concentrating on sale of products to offering an entire solution where long-term maintenance, repair and customer support become an integral part.

2 How can 5G be a catalyzer for the automotive industry?

This section relates the socio-economic drivers of the automotive industry described in Section 1 to the objectives of 5G and provides a number of future automotive use cases that are expected to be enabled by the introduction of 5G.

2.1 Link between socio-economic drivers and 5G objectives

Connected driving already started with 2G more than 10 years ago and has been improving over the years together with the deployment of 3G and 4G mobile communication networks. Drivers and road infrastructure operators are already sharing a considerable amount of information about road conditions, police controls, accidents, points of interest, etc. Traffic information is already available in various cities and motorways. This pervasiveness of transport information is essential to a number of the socio-economic drivers described previously, especially intelligent navigation and the digitalization of transport and logistics.

However, coverage is limited on certain roads and rural areas and sometimes the information on road conditions takes several seconds to arrive. That is why, in order to improve road safety and traffic efficiency services on the path towards automated driving, the automotive industry has developed and standardized technologies for direct communication between vehicles (V2V), as well as between vehicles and roadside infrastructure (V2I) – ITS-G5 in Europe and WAVE in the United States. These technologies act locally, with low latency, and availability is guaranteed as long as the communication partners are within a certain communication range.

At present, the V2X basic system broadcasts (a) periodic awareness information (including vehicle type, position, speed, acceleration, etc.) in the form of standardized Cooperative Awareness Messages (CAM) (ETSI EN 302 637-2, November 2014) and (b) situation-based information triggered by an event (e.g., an accident or if an emergency vehicle is in action) in the form of standardized Decentralized Environmental Notification Messages (DENM) (ETSI EN 302 637-3, November 2014). Infrastructure-based ITS Roadside Stations (IRS) disseminate information about ongoing road works or about the different phases of traffic signals. Field tests have been performed that show the suitability for its use on the road (simTD Project, June 2013) (DRIVE C2X Project, July 2014) (US Department of Transportation, Intelligent Transportation Systems Joint Program Office, 2012).

In the mobile networking industry, supporting V2X over cellular networks is rapidly gaining interest. 3GPP RAN is currently working to enhance LTE (Long Term Evolution) in Release 13 and Release 14 (beginning of 5G) to fulfill requirements for V2X over licensed and unlicensed spectrum (3GPP TSG RAN Meeting #68, June 2015).

The current IEEE 802.11-based V2X communication technology is a short-range ad hoc broadcast system developed for the exchange of object information and not for the exchange of sensor data. As vehicles advance toward higher automation levels and need to deal with increasingly complex

road situations, there will be limitations and therefore a need for a complementary communication technology for the exchange of cooperative information with higher bandwidth and improved reliability. Worth mentioning is in particular: (1) the exchange of sensor data for collective perception (e.g., video data), (2) the exchange of control information for platoons from very close driving vehicles (only a few meters away), and (3) the exchange of vehicle trajectories to prevent collisions (cooperative decision making, very fast re-planning of vehicle trajectories).
In addition, current work in 3GPP suggests that a cellular implementation of V2I could bring benefits to the ecosystem. A fundamental reason is the cost of the network. The cost of setting up a new IEEE 802.11-based infrastructure and cover all the necessary areas may be prohibitive – it could be in the order of 4000 €/km^2. Utilizing the current cellular infrastructure – with appropriate software upgrades – the goal can be achieved in a fraction of that cost. There are, however, many challenges. The business model for a Mobile Network Operator (MNO) to provide V2X services is not so straightforward. For example, some operators have been looking into opportunities in the insurance sector, or to provide services such as fleet management. Another challenge will be roaming and how a continuous service can be guaranteed. One idea could be to set up Mobile Virtual Network Operators (MVNOs) to operate such networks.

2.2 Integration of automotive industry and telecom industry

In order to ensure network efficiency from both technical and commercial points of view, the automotive and ICT sectors are looking for a single shared network infrastructure. The network management should enable easy establishment of network slices with all needed capabilities within the overall 5G infrastructure, which can be widely deployed. Network slices can then be used by specific operators offering ITS related services, which can be the present MNOs and operators of future 5G networks, but also so-called ITS service providers. These network slices should ensure the prioritization of specialized services such as road safety over other Internet traffic.

Availability of wireless services is crucial for wide deployment of ITS services. Network coverage along roads and in low-density areas will be important. Where network coverage cannot be guaranteed, Device-to-Device (D2D) communication will be essential. Data has to be available practically everywhere, not necessarily stored but transferred fast and efficiently from central and local points to various destinations, in particular vehicles on the move.

Customers of connected cars are looking for personalized, contextual and efficient services that make mobility more secure, comfortable and easy. Telecom networks provide the connectivity between the car and the corresponding backend in which these services are running. These telecom networks together with the backend operations may be considered as a supportive business platform for the automotive industry, enabling an enhanced customer experience. Such a supportive business platform needs to ensure robust, secure and agile communications to guarantee the highest traffic safety, the most efficient operations and the best customer experience.

As more and more connected services using these telecom networks are integrated in newly produced cars, the automotive and telecom industries are following more and more the same megatrends and are dealing with similar issues. Common megatrends are, e.g., the need of ultra-broadband connectivity, big data analytics, cloud services and advanced customer experience.

2.3 Automotive use cases

We present in this section several families of use cases in the automotive domain that are relevant for 5G. These are use cases with requirements beyond the capabilities of current 4G systems in terms of latency, availability or reliability among others (METIS Project Deliverable D1.1, April 2013) (METIS Project Deliverable D1.5, April 2015). These use cases are classified according to the key transformations outlined in Section 1.2.

2.3.1 Automated driving

With the advent of automated driving functions, especially with the broad availability of vehicles capable of supporting higher automation levels (3-5), the need for synchronization of the various traffic participants becomes increasingly necessary. All automated vehicles rely on the premise that they continuously plan their trajectories and, based on the observed environment, select one or another as the driving trajectory. Currently, a lot of uncertainty has to be planned since it is not 100% certain what another vehicle, or another traffic participant, will do in the next several seconds. That is why relatively large “buffers” have to be included in these trajectories, especially when planning them around other moving vehicles. If these other vehicles would share, or even constantly disseminate their own plans, other vehicles could use them to reduce the uncertainties and so minimize the buffers within their trajectories. This would enable automated driving vehicles to drive closer to each other (and so increase the capacity of roads and cities), react more quickly to maneuvers and prevent collisions.

In order to advance (and deploy) direct communication between vehicles, the automotive industry has organized itself into various consortia and standardization bodies. The consortium responsible for researching, developing and standardizing a direct communication technology in Europe is the C2C-CC (Car-2-Car Communication Consortium, 2015). Fifteen vehicle manufacturers, over thirty suppliers and more than forty research institutions have been working together over the past years and have developed all the required building blocks to enable vehicles to exchange information with each other, using initially the ITS-G5 technology in the 5.9 GHz frequency spectrum (ETSI EN 302 663, July 2013). On this common communication technology basis, various extensions have been developed in order to also enable an efficient information exchange with the roadside infrastructure, truly enabling a large-scale V2X deployment. The consortium accompanying these developments is called The Amsterdam Group (The Amsterdam Group, 2015) and comprises, besides the C2C-CC, the ASECAP (Association Européenne des Concessionaires d'Autoroutes et d'Ouvrages à Péage), CEDR (Conference of European Directors of Roads) and POLIS (European Cities and Regions Networking for Innovative

Transport Solutions) consortia, representing the various stakeholders responsible for the ITS infrastructure on highways, cities and the traffic managers.

The members of the C2C-CC, representing the automobile industry, have created a staged deployment strategy using a development roadmap structuring the past, current and future research and standardization work in the field of communicating and cooperative vehicles.

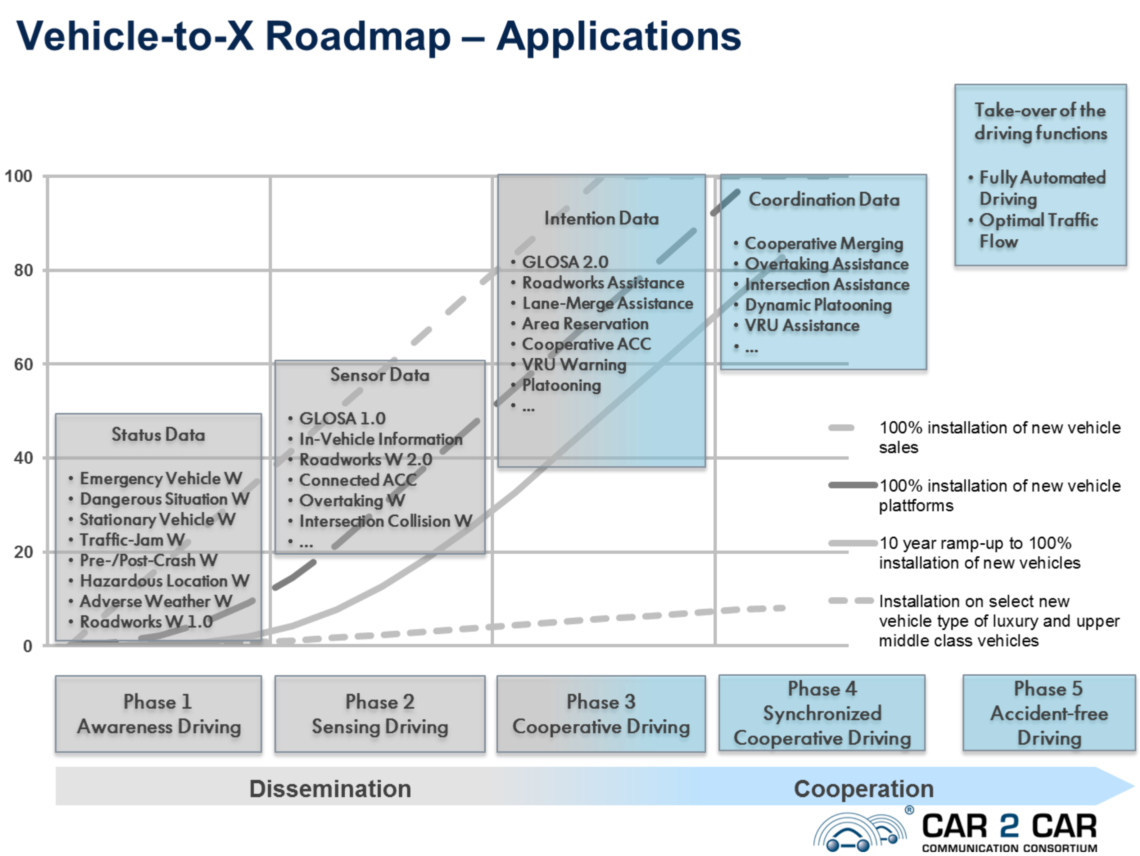

Figure 2. The Car-2-Car Communication Consortium applications roadmap

The C2C-CC applications roadmap, presented in Figure 2, envisions four deployment phases for direct V2V communication. Each subsequent phase extends the previous one by allowing vehicles to exchange additional information, thus enabling new classes of use cases to be realized. Each new phase is characterized by the new type of information it allows traffic participants to exchange:

1. The first, initial phase enables vehicles to disseminate their *status* information, thus allowing other vehicles to become aware of their presence and of eventual hazards detected on the road.

2. The second, sensing driving phase allows various traffic participants to provide additional information, namely information gained through various on-board *sensors* like cameras

and radar. This enables vehicles to “see with the eyes of others” and so detect otherwise hidden objects (e.g., around a corner) or get a more accurate view on what is happening within their environment (e.g., an intersection with various vehicles and pedestrians).

3. The third, cooperative driving phase will allow vehicles to share their *intentions* with other traffic participants, and so provide them with a glimpse into the individual future of each vehicle. This information will be used by automated driving algorithms to enable vehicles to accurately predict what other traffic participants will do in the near future and so optimize their own decisions and actions.

4. The last, *synchronized* driving phase is where vehicles are autonomously driven through almost all situations (levels 4 and 5 in Figure 1) and are able to exchange and synchronize driving trajectories among each other and so achieve optimal driving patterns.

The question is whether there are special requirements on vehicle communication for higher automation levels. For example, if a collision has to be prevented due to an unexpected event, the vehicles have to act autonomously just before the collision takes place. The vehicles would not only exchange trajectories, but also continuously re-adjust them (cooperative decision making). Higher automation levels will require lower latency and higher reliability, since the reaction time of the driver is removed from the equation. Sensor data exchange for collective perception will lead to larger message sizes. New messages carrying intention and coordination data for cooperative agreement will need to be defined. Finally, the introduction of high automation based on V2X connectivity demands appropriate security requirements to be addressed as well. These are all realms where 5G will play a central role.

Some emblematic automated driving use cases are listed below.

1. Automated Overtake

A fully autonomous self-driving car will need to perform overtake maneuvers not only on highways (unidirectional travel) but also on two-way roads, where oncoming vehicles may be well beyond the range of its sensors, but approaching very quickly. Performing such maneuvers safely will require cooperation among vehicles on multiple lanes, to create the necessary gap to allow the overtaking vehicle to quickly merge onto the lane corresponding to its direction of travel in time to avoid a collision with an oncoming vehicle.

2. Cooperative Collision Avoidance

This use case highlights the communication challenges faced by self-driving vehicles when trying to prevent collisions (e.g., at intersections in an urban environment) after all other traffic control mechanisms have failed. Collisions between two or more vehicles are prevented by controlling the longitudinal velocity and displacement of each vehicle along its path without creating hazardous driving conditions for other vehicles that are not directly involved. In such a complex and dynamic environment, upon identification of a collision risk, vehicles cannot decide individually and apply the appropriate action without prior coordination. Different individual actions might lead to additional collisions or uncontrolled situations. Hence, all involved vehicles should undertake to compute the optimal collision avoidance actions and apply them in a cooperative manner.

3. High Density Platooning

High Density Platooning, i.e., the creation of closely spaced multiple-vehicle chains on a highway, has multiple benefits, such as fuel saving, accident prevention, etc. However, this requires cooperation among participating vehicles in order to form and maintain the platoon in the face of dynamic road situations. High Density Platooning will further reduce the current distance between vehicles down to 1 meter. Since on-board sensors are not able to cope with such short distances (they measure them and then react to changes), vehicles within a platoon will constantly exchange their kinematic state information in real time. This will allow following vehicles to implement throttle and brake controls, keeping the distance constant.

2.3.2 Road safety and traffic efficiency services

When closely looking at the majority of current V2X use cases, they all focus on increasing the drivers' awareness of what is happening around and in front of them on the road. All these V2X use cases rely on the principle that connected vehicles periodically provide either status information (e.g., position, speed, acceleration, etc.) or event information (e.g., traffic jam, icy road, fog, etc.). This information is usually packed into stateless, individual messages or probes which are either locally disseminated to neighboring vehicles, or sent to a central point (base station, backend) where it can be aggregated and then again disseminated to other vehicles to make use of it.

Figure 3. Collective knowledge through collective perception

The next evolutionary step will be to extend this status information with more complex information, such as that provided by the vehicle's on-board sensors (camera, radar, ultra-sound, etc.). Although small portions of this sensor information could fit into the stateless message paradigm described above, considerable benefits could be envisioned if the sensors' data stream is disseminated in the same pattern to other vehicles or traffic participants. They could then use the remote data streams to feed their own applications and algorithms, as if the data stream had originated from their own on-board sensors. As illustrated in Figure 3, this would enable vehicles to see through obstacles (buildings, other vehicles, etc.), get a bird's eye view of intersections or assist vehicles in finding a merge point on the highway. Some emblematic road safety and traffic efficiency use cases are listed below.

4. See-Through

My car is behind a truck, as shown in Figure 4. Suddenly, a pedestrian is crossing the road in front of the truck. Fortunately, the truck camera detects the situation and shares the image of the pedestrian with my car, which sends me an alert and shows me the pedestrian in virtual reality on the windshield board.

Figure 4. See-through use case as an example of collective perception

This use case requires a very high reliability and availability (it should work even out of coverage and even if the network is loaded with other services), a low latency (a few tens of ms) and a high data rate to share all relevant data with vehicles and pedestrians in the neighborhood.

5. Vulnerable Road User (VRU) Discovery

Vehicles periodically announce their presence and position. VRUs (pedestrians, cyclists, etc., carrying a mobile device) discover vehicles in proximity and begin announcing themselves. The VRU mobile device may trigger a loud warning sound, vibration, flashing light, etc., in case of imminent danger. Vehicles in proximity of an announcing VRU incorporate the received information into their Local Dynamic Map (LDM) and potentially notify both the driver and the VRU if a vulnerability situation is detected, as illustrated in Figure 5.

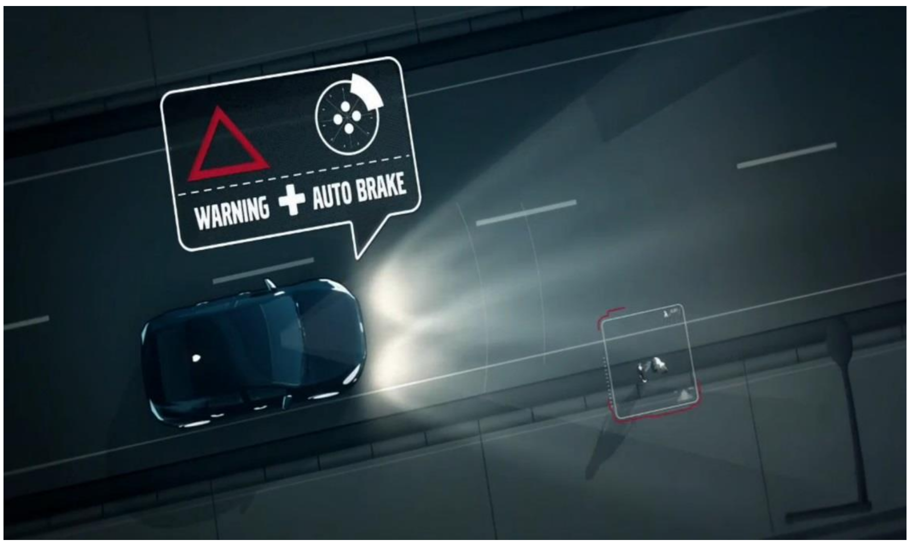

Figure 5. Vulnerable Road User (VRU) discovery

One of the most critical issues with this use case is a reliable localization of the VRUs. Combining several positioning techniques – including satellite and natively integrated in 5G – should be able to increase the accuracy of the positioning, especially the relative positioning to vehicles in all environments (urban and rural).

6. Bird's Eye View

An intersection – either in a city or on a highway at a merge-in location – equipped with sensors such as cameras or radar can provide this streaming information to approaching vehicles. The vehicles use this data stream (maybe in conjunction with other similar data streams provided by vehicles equipped also with camera and radar sensors) and identify eventual pedestrians or free places, which they could not detect with their on-board sensors, so that they can better plan their future trajectories – to merge in on a highway or navigate through an intersection. The data streams have to be provided with very low latencies in order to allow vehicles to use the data streams similarly to the data streams provided by on-board sensors.

2.3.3 Digitalization of transport and logistics

We identified two main 5G use case families that would be beneficial for this transformation of the sector.

7. Remote sensing and control

This family of use cases encompasses a series of automotive applications within the so-called Internet of Things (IoT), in which a vast amount of devices, such as sensors and actuators, are interconnected and can exchange data with each other or with a backend server located in the Internet. It is the data acquisition component in the digital transport and logistics services value chain. In particular, this includes, on the one hand, the remote control of vehicle functions – such as the air conditioning and the heating, the engines, the headlights, the horn, the (un)locking of doors, etc. – and, on the other hand, the transmission of vehicle information – such as the battery level – to a backend server (METIS Project Deliverable D1.5, April 2015). Information related to status and health of different components can be used by vehicle vendors and OEMs to perform predictive analytics and unearth any impending faults.

8. Remote processing for vehicles

Compute and storage resources in 5G infrastructures would also allow for the relocation of certain complex tasks from vehicles to a remote server, so that vehicles can relieve its own local processor units. Contrary to consumer devices, which are generally replaced every 1-2 years with higher processing capabilities, the longer development and ownership cycles of vehicles (which in total might extend beyond 10 years), are a significant limitation for the provision of processing-intensive applications in the automotive domain. The advantage of remote/cloud computing lies in the fact that complex applications – such as augmented reality displayed on the windshield – could be accessible to all vehicles regardless of their processing power capabilities. Remote applications and services can also be easily and centrally maintained and updated without any user interaction or software updates. In general, the automotive and transportation industry could rely on remote processing to ease vehicle maintenance and to offer novel services to customers with very short time-to-market.

2.3.4 Intelligent navigation

Navigation systems can be enhanced leveraging augmented reality and real-time video feeds. Real-time traffic information including video feeds for a complex intersection can be received from sensors such as cameras and radars installed as part of roadside infrastructure and from other vehicles in the vicinity and overlaid with geographic information so as to provide enhanced situational awareness and augmented reality based navigation. This would require that high bandwidth data streams from other vehicles and roadside infrastructure are provided to the navigation system with very low latency.

2.3.5 Information society on the road

The information society in 2020 will demand high data rate and low latency connectivity at any place and at any time. People will demand similar levels of connectivity regardless of whether they are at their workplace, enjoying leisure activities such as shopping, or being on the move with their vehicles (METIS Project Deliverable D1.1, April 2013). Moreover, the introduction of highly automated driving could boost the consumption of data traffic on the move, as drivers no longer need to be focused on driving and can divert their attention to other activities. Besides classical services such as web browsing, file download, email, social networks, etc., a strong increase is expected in high-definition video streaming and video sharing, possibly also with higher requirements for image resolution, e.g., 4K standard. This trend will, for instance, be fostered through the availability of new user interface improvements like resizable portable screens, or screens embedded into watches or glasses (METIS Project Deliverable D1.1, April 2013). This represents a significant challenge as a result of the sparse network infrastructure generally deployed in motorway scenarios and the high velocity of vehicles, which hampers the implementation of massive MIMO (Multiple-Input Multiple-Output) techniques. Capacity requirements, especially due to consumption of high-definition video by multiple passengers in each vehicle, will create significant load on the mobile network, even in dense urban scenarios having adequate network coverage but constrained network capacity.

2.3.6 Nomadic nodes

This use case does not come from a transformation of the automotive sector but from a transformation of the telecom sector. This use case considers the utilization of vehicles as small cells while parked in order to improve the capacity, data rate, energy efficiency and/or coverage of the mobile network (METIS Project Deliverable D1.1, April 2013). Due to the introduction of smartphones and tablets, the demand for very high data rate Internet access at any time and at any place is constantly increasing. However, the Quality of Experience (QoE) can be significantly degraded in certain areas due to the lack of radio resources and/or low coverage caused by insufficient network deployment. Moreover, in areas with weak coverage, higher propagation losses are generally compensated with higher transmission power, which shortens the battery life of consumer devices. While cell densification is a promising way to boost capacity in future urban environments, flexible, energy- and cost-efficient solutions must be developed in future wireless communication systems to provide ubiquitous coverage with tolerable cost. In this context, it is possible to exploit the natural high correlation between the data demands of users and the distribution of vehicles. In other words, the more vehicles are located in a certain area, the higher the amount of data traffic that must be delivered by the network. In addition to this, vehicles generally enjoy better connectivity compared to consumer user devices, since more and higher gain antennas can be implemented thanks to lesser space constraints. Battery life is also not as big a concern as it is for consumer user devices. The main challenges of nomadic nodes are related to management issues in heterogeneous networks (e.g., interference management) as well as handover and cell reselection. Although nomadic nodes are stationary in principle, the inherent uncertainty with regard to their availability (e.g., vehicular relay nodes) resembles a network that is “moving” or “movable”.

3 Technical requirements from the automotive industry and 5G overview

This section provides precise technical requirements associated with some of the V2X use cases identified in Section 2.3, followed by an overview of 5G and its benefits for the considered use cases. The numbers presented in this section strongly depend on details such as the scenario and the driving situation. It is infeasible to consider all possible situations. As a consequence, the numbers are based on experience, experts' opinions, and simulation results. They are intended to provide the reader with an order of magnitude rather than an exact value.

3.1 Technical requirements and KPIs for V2X use cases

The following definitions are used to provide precise application-specific requirements.

1. **End-to-end latency** (ms)
   Maximum tolerable elapsed time from the instant a data packet is generated at the source application to the instant it is received by the destination application. If direct mode is used (PC5 transport), this is essentially the maximum tolerable air interface latency. If infrastructure mode is used (Uu transport), this includes the time needed for uplink, any necessary routing in the infrastructure, and downlink.
2. **Reliability** (10^{-x})
   Maximum tolerable packet loss rate at the application layer (i.e., after HARQ, ARQ, etc.). A packet is considered lost if it is not received by the destination application within the maximum tolerable end-to-end latency for that application. For example, 10^{-5} means the application tolerates at most 1 in 100,000 packets not being successfully received within the maximum tolerable latency. This is sometimes expressed as a percentage (e.g., 99.999%) elsewhere.
3. **Data rate** (Mbit/s)
   Minimum required bit rate for the application to function correctly.
4. **Communication range** (m)
   Maximum distance between source and destination(s) of a radio transmission within which the application should achieve the specified reliability.
5. **Node mobility** (km/h)
   Maximum relative speed under which the specified reliability should be achieved.
6. **Network density** (vehicles/km^2)
   Maximum number of vehicles per unit area under which the specified reliability should be achieved.
7. **Positioning accuracy** (cm)
   Maximum positioning error tolerated by the application.
8. **Security**
   Specific security features required by the application. These include user authentication, authenticity of data, integrity of data, confidentiality, and user privacy.

A. Key Performance Indicators (KPIs)

1. Automated driving, road safety and traffic efficiency

Table 1 provides KPIs and security requirements for automated driving as well as road safety and traffic efficiency use cases, providing some background to justify the figures given.

Table 1. KPIs and security requirements for V2X use cases

	Use Case	KPIs	Background	Security Requirements
1	**Automated Overtake**	10 ms 10^{-5} 30 cm[1]	On two-way roads, automated overtake maneuvers will require cooperation among vehicles on multiple lanes, to create the necessary gap in time to avoid a collision with an oncoming vehicle. Lateral and longitudinal controllers need updates within their 10 ms cycle time.[2] This is a safety-of-life use case with ultra-high reliability requirements.[3]	Client authentication Authenticity Integrity Confidentiality User privacy (optional)
2	**Cooperative Collision Avoidance**	*Trajectory handshake:* 100 ms 10^{-5} *Status updates:* 10 ms 10^{-3} *Positioning:* 30 cm	In a critical driving situation, trajectories have to be exchanged, rated and agreed upon in order to avoid a collision. This handshake must be completed within 100 ms and shall not fail with a probability higher than 10^{-5}. Upon agreement, during the execution phase, lateral and longitudinal controllers need status updates within their 10 ms cycle time. The status information is used by each vehicle to update its trajectory and inform its controllers (in case of minor deviations from the agreed trajectory) or cancel the maneuver (in case of major deviations). A status message shall be received within 10 ms with a probability of 99.9% (packet loss rate of 10^{-3}).	Mutual authentication Authenticity Integrity Confidentiality

[1] *The accuracy of 30 cm is derived as follows. On a standard road with a lane width of 3.5 m, taking a typical car width of 2 m leaves 1.5 m width, i.e., 0.75 m on each side. To position a car on this lane, we would allow for an error of half the width, leaving us with 0.375 m accuracy and still being in the lane. A grid of 30 cm allows for additional errors due to different car widths and lane widths (Alieiev, Kwoczek, & Hehn, April 2015). The same argumentation is used to derive the positioning accuracy of 10 cm for a vulnerable road user, i.e., a pedestrian or a cyclist.*

[2] *The maximum steering frequency realizable by a car is around 10 Hz. Experience shows that an oversampling factor of 10 is reasonable for updating the controller, which results in an overall update cycle of 10 ms (Van Ende, June 2014).*

[3] *The reliability of 10^{-5} is derived based on statistics for certain kinds of fatal accidents. For example, there are 35 000 frontal crashes in Germany per year. If we have a function that could prevent such an accident, we must make sure that this function is more reliable than (1 - 1/35000)*100% = 99.997%. 99.997% means that we still have one accident. If the reliability of this function is more than 99.999%, it should result in less than one accident per year.*

3	**High Density Platooning**	10 ms 10^{-5} 30 cm	The idea behind high-density platooning is that vehicles will be driving very close to each other. Thus, latency and reliability become the KPIs. The control cycles of typical longitudinal controllers are in the range of 10 ms (as above). The platoon must have their own synced timing. Kinematic data needs to reach all participants of the platoon within a single cycle (10 ms) with ultra-high reliability, and, optionally, all participants need to acknowledge that they can provide the necessary control within this cycle.	Mutual authentication Authenticity Integrity Confidentiality User privacy
4	**See-Through**	10 Mbit/s 50 ms	The main KPIs for this use case are channel capacity/data rate and tolerated latency. We assume that view-sharing is usually done one way. It requires a data rate of 10 Mbit/s and a delay of 50 ms (e.g., 720p video @ 30 fps, MJPEG).	Client authentication Authenticity Integrity Confidentiality User privacy (optional)
5	**Vulnerable Road User Discovery**	10 cm	This use case mainly requires highly accurate localization. For vulnerable road users, the positioning error needs to be less than 10 cm (sigma_1) for a 1 m width pedestrian/bike lane. Relative localization must be supported by 5G.	Authenticity Integrity User privacy (VRU)
6	**Bird's Eye View**	40 Mbit/s 50 ms	This setting is similar to the See-Through use case, but with four cameras pointing at an intersection. Consequently, the required data rate reads 4 x 10 Mbit/s and the required latency 50 ms.	Client authentication Authenticity Integrity Confidentiality

These uses cases can be developed in two different types of architecture, depending on whether onboard decisions are based on low-level data (e.g., video streaming from other vehicles) or based on high-level data (objects detected, processed and transmitted by other vehicles).

- High-level data (objects) transmission: In this architecture, high-level data generated after sensor processing (object recognition, radar or lidar target lists) is transmitted to neighboring users (vehicles, infrastructure, etc.) to be fused by the receiving systems (ADAS control unit), in conjunction with its own sensors. This architecture requires a medium data rate (up to 1 Mbit/s) with a very low tolerance on errors (10^{-5}).

- Low-level data (video streaming) transmission: In this architecture, low-level data generated by sensors (cameras, lidars, etc.) is transmitted towards neighboring users (vehicles, infrastructure, etc.) to be fused and/or processed by the receiving system, in conjunction with its own sensors. This architecture requires a high data rate (up to 10-20 Mbit/s) with a medium tolerance on errors (10^{-2}).

Figure 6 summarizes the connectivity demands (bandwidth and latency) of future connected vehicles, considering Phase 2 (cooperative perception), Phase 3 (sharing of intention data), and Phase 4 (cooperative maneuver and trajectory planning), as described in Figure 2. In case of high automation levels, the driver is only informed and not part of the decision making process.

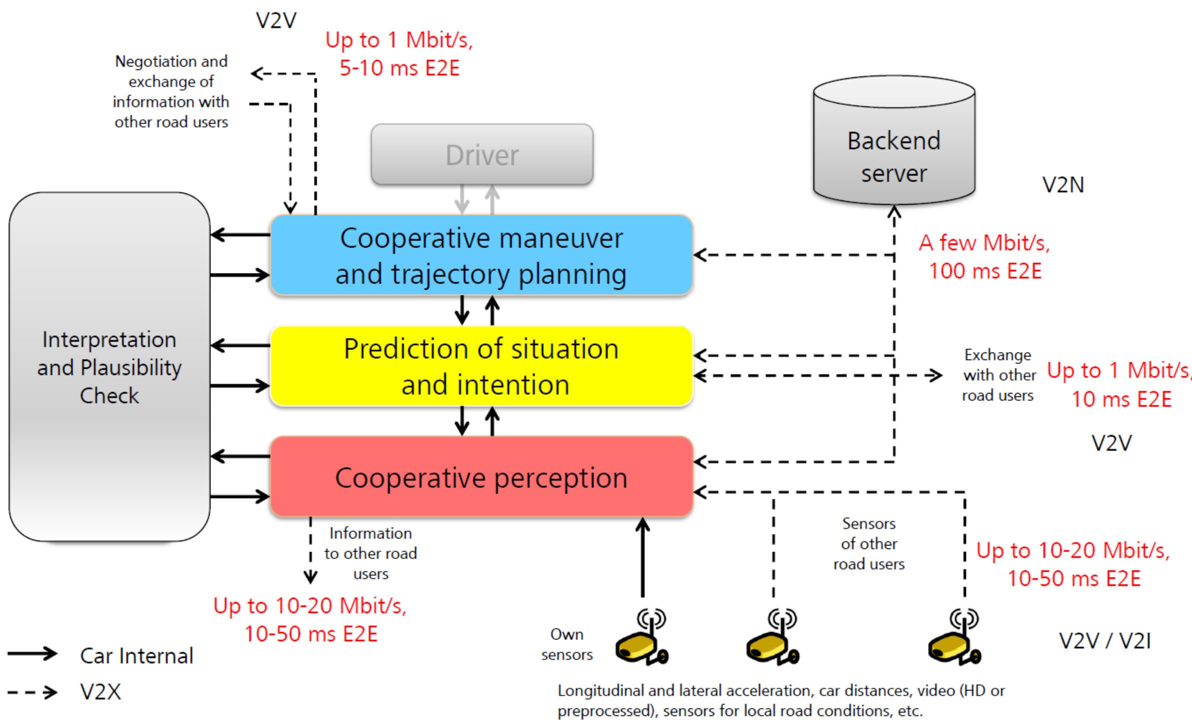

Figure 6. Connectivity demands of future connected vehicles
(adapted from (DFG-Schwerpunktprogramm SPP 1835, April 2014))

2. Digitalization of transport and logistics

Remote sensing and control

Similarly to other use cases within the IoT world, remote sensing and control of vehicles is based on the transmission of small telemetry and command messages, and therefore does not possess stringent requirements in terms of latency or data rate. Nevertheless, they must operate in challenging reception scenarios such as underground parking places and while the vehicle is shut down.

This calls for penetration capabilities (especially through walls and floors) and power efficiency beyond those provided by the current commercial 4G networks in order to achieve good coverage levels and to increase the battery life of vehicles, respectively. These aspects have been addressed in recent standardization work and LTE Rel-12 specifies solutions to reach 10 years battery life with two AA batteries. Coverage extension in the order of 15 dB is also being specified for Rel-13. But we could go further with 15 years battery life and 30 dB coverage extension in 5G releases.

Furthermore, since vehicles can, for example, be unlocked or even started remotely, security aspects are fundamental in order to avoid the hacking and potential theft of the vehicle. The main requirements of this use case can be summarized as follows:

- Low power consumption (comparable to or lower than 4G).
- High penetration through walls and floors in order to reach, among others, underground parking spots.
- End-to-end latency at the application layer below 1 s.
- Very strong security mechanisms.

Remote processing for vehicles

Depending on the processes which would be outsourced from the vehicle to the communication infrastructure, the requirements in terms of latency may be very stringent or not. For example, the calculation of an up-to-date itinerary after a change in road conditions may take a few seconds without big problems, whereas the rendering for augmented reality applications on the windshield should be done in a few milliseconds.

In general, remote processing would require uploading via the communication infrastructure all the information captured by the vehicle sensors, so the bandwidth requirements can go up to 100 Mbit/s.

In addition, the remote processing units should follow the vehicle while it is moving on the road. As a result, there is a need for a specific handover mechanism in case of low latency requirements, so that the virtual machines are moved from one base station to the next sufficiently quickly.

3. Information society on the road

This family of use cases requires communication links with high data rates (tens of Mbit/s) and low latencies, while moving at velocities close to 200 km/h and with good coverage levels along the road infrastructure. Moreover, it is necessary to compensate for the high penetration losses caused by the vehicle body, which can reach values between 15 and 20 dB.

B. Physical conditions under which KPIs must be achieved

The KPIs provided above must be achieved under different physical circumstances – such as distance and relative velocity of transmitting and receiving vehicles, vehicle density and offered load per vehicle – depending on the scenario. For example, it may be relatively easy to achieve 10 ms latency with 99.999% reliability when vehicles are 10 meters away, traveling in the same direction at the same speed in an otherwise empty street. It will be much more challenging to achieve such targets if the vehicles are 500 meters away, traveling fast in opposite directions in a crowded street where they need to share the wireless channel with many other vehicles. Table 2 provides indicative values for the conditions under which the latency and reliability requirements should be met, for three different scenarios: urban, suburban, and highway.

Table 2. Conditions under which the latency and reliability figures should be achieved

Scenario	Vehicle density (vehicles/km²)	Relative velocity (km/h)	Communication range (m)	Offered load (Mbit/s/vehicle) (average/peak)
URBAN	1000-3000	0-100	50-100	1.0 / 10
SUBURBAN	500-1000	0-200	100-200	0.5 / 10
HIGHWAY	100-500	0-500	200-1000	1.0 / 10

The rationale behind these conditions is as follows:

- Vehicle density: For urban environments, we assume that each vehicle occupies 6-12 meters of space (4 meters for the vehicle plus 2-8 meters gap). We assume three lanes per direction and 2-3 roads of this type, which leads to 1000-3000 vehicles/km². The value for suburban environments is derived similarly using 2 roads and 8-20 meters gap. For the highway scenario, one road is considered, and a 60-meter safe distance (12-meter for high density) between vehicles on the same lane is assumed, corresponding to a reaction time of 1.8 s and an average speed of 120 km/h (24 km/h for high density).

- Relative velocity: In order to derive these values, we consider the maximum allowed speed (50 km/h, 100 km/h) and maximum possible speed in a car (250 km/h), respectively. The standard car from an OEM is limited in speed to 250 km/h (sports cars may not be limited).

- Communication range: In urban environments, the cars within close vicinity are the major interaction partners, and hence a range of 50-100 meters is deemed appropriate. The ranges for the other speeds were chosen such that they scale like the stopping distance of a car (at the corresponding speed).

- Offered load: The highest amount of data traffic, on average, is expected in urban and highway environments. Urban environments offer a high density of information and thus many objects to be signaled to the car. Highway scenarios can include fast traffic which requires more foresight and thus more information to be signaled to the car. The suburban environment is usually less dense and traffic is comparably slow.

It should be noted that the maximum density and velocity values given will usually not occur simultaneously, e.g., in a highway with 100 vehicles/km², vehicles will usually travel much slower than the maximum velocity of 250 km/h. In rough terms, vehicle density and velocity tend to be negatively correlated – the denser an area is populated, the slower the vehicles move – whereas velocity and required communication range are positively correlated – the faster a vehicle is moving, the farther it needs to communicate. As a result, density and required range tend to be negatively correlated – the denser an area is populated, the shorter the distance within which vehicles need to communicate.

3.2 Overview of 5G

5G is the next generation of mobile communication technology. It is expected to be defined by the end of this decade and to be widely deployed in the early years of the next decade. There are a great many researchers studying 5G and its component technologies – in funded EU projects, in national programs, in individual companies and in research institutions.

Many bodies have developed visions of 5G, including NGMN (NGMN Alliance, February 2015), ITU-R (Recommendation ITU-R IMT Vision, July 2015) and 5G PPP (5G Infrastructure Association, February 2015). Together, they describe the primary aspects of 5G:

- Increased performance of mobile technology in terms of more throughput, lower latency, ultra-high reliability, higher connectivity density, and higher mobility.
- Support for the convergence of vertical applications onto a single common wireless network. This is enabled by a flexible usage and configuration of network functions to enable use cases with very diverse requirements by means of network slices. 5G should become the first radio communication system designed to smoothly integrate Human Type Communications (HTC) with Machine Type Communications (MTC), thus becoming an enabler for the Internet of Things (IoT).
- A new flexible radio interface or radio interfaces as enabler for the items above, for deployment both in current mobile bands and new spectrum that could go as high as up to the millimeter wave range.

5G will help to reach a better coverage through the integration of various access technologies, including Device-to-Device (D2D) communication, and is envisioned to support higher mobility, e.g., 500 km/h for high-speed trains (5G Infrastructure Association, February 2015). Regarding road safety information, 5G is envisioned to improve network reliability, with a 10^{-5} packet loss rate for safety-critical services, yet it should be noted that for some industrial automation use cases, which have different conditions and requirements than road safety use cases, a network reliability of 10^{-9} packet loss rate may be required for 5G.

Automated driving will be available in a more comfortable and efficient way with 5G. Indeed, it requires a very low latency to be able to react in real time to drivers' behavior and to moving obstacles. 5G is envisioned to provide a latency of 1 ms for the air interface (5G Infrastructure Association, February 2015) (NGMN Alliance, February 2015) – with a resulting 5 ms end-to-end latency for infrastructure mode (Uu transport) and 1 ms end-to-end latency for direct mode (PC5 transport) – which is compatible with the stringent requirements of automated driving. In addition, 5G targets an accuracy of 1 meter for the positioning system, which will be very useful for automated driving. The security-by-design principle which will be followed by 5G will also be key to inspire trust from end users.

Due to the wide range of 5G requirements, it will not be feasible to support all different applications and deployments with a single radio access configuration. A flexible radio access network design is required, where different configurations are used depending on the application and deployment. Further, 5G is foreseen to integrate a mix of Radio Access Technologies (RATs) enabling a combination and cooperation of various RATs, some already existing (e.g., IEEE 802.11p), others to be designed (e.g., future releases of LTE).

In addition, the concept of network slicing is expected to improve the operation of communication networks. This concept essentially consists in creating different instances of network technologies suitable for different applications with different requirements. Such a dynamic and flexible communication network paradigm will be enabled by a new cloud-based network architecture, encompassing Software Defined Networking (SDN) and Network Function Virtualization (NFV) and increasing use of open source software.

SDN and NFV may be widely deployed within the next few years, and will therefore be used with LTE networks even before 5G radio access technologies become available. Increasingly, LTE supports vertical applications but with some limitations as described in Section 4. The new radio interfaces for 5G are intended to support a wide range of applications in vertical sectors from the outset – and the automotive sector is one of the most important verticals.

3.2.1 Development of 5G radio interfaces

3GPP and ITU-R are the key players in the standardization of new 5G radio interfaces. For 3G and 4G, ITU-R defined requirements[4] and made a call for technology proposals, which were subsequently evaluated against these requirements. It intends to follow the same process for 5G. The Vision Recommendation (Recommendation ITU-R IMT Vision, July 2015) describes the framework of the future development of 5G, including the capabilities associated with envisaged usage scenarios. The goals for these capabilities are summarized in Figure 7; some of these capabilities will be more relevant than others for automotive applications. Which of these performance requirements must be met at the same depends on the particular use case. As an example, mission-critical communication demands very low latency of a few ms; however, the required peak data rate may be orders of magintude below the 20 Gbit/s indicated in Figure 7. 3GPP intends to develop a candidate 5G technolology to meet the ITU-R requirements and timetable, with studies starting at the end of 2015.

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[4] *The ITU terms for 3G and 4G are IMT-2000 and IMT-Advanced. It is expected that the term IMT-2020 will be adopted for 5G. Collectively, they are known as IMT.*

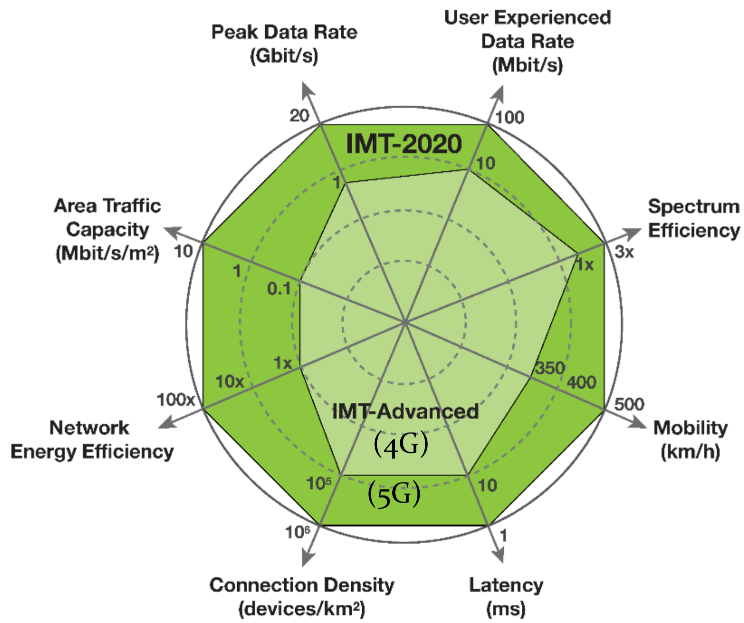

Figure 7. Key capabilities of 5G compared to 4G[5]

3.2.2 Spectrum for 5G

The international use of spectrum is defined by ITU though the international treaty called *The Radio Regulations*[6]. Mobile networks operate within the bands allocated to the mobile service; some of these bands are also 'identified for IMT' (International Mobile Telecommunications), which is a non-binding recommendation that they can be used by technologies the ITU defines as IMT. Changes to the Radio Regulations are made by World Radiocommunication Conferences (WRCs), which take place approximately every four years.

The next World Radiocommunication Conference will occur in November 2015 (WRC-15). Likely outcomes are an agreement on an increase in the spectrum allocated to the mobile service and identified for IMT, and increased global harmonization for some bands that are currently only identified for IMT in certain parts of the world. WRC-15 is also expected to agree an agenda item for WRC-19, the following conference, to consider identifying frequency bands above 6 GHz for IMT.

[5] *These goals are described in the Recommendation as being "only targets for research and investigation and may be further developed in other ITU Recommendations, and may be revised in the light of future studies." Some targets differ in the NGMN 5G White Paper.*

[6] *Global and regional allocations to various radio communication services are shown within the Table of Allocations, and multi-national allocations are described in footnotes to the Table. ITU-R divides the world into three Regions; Region 1 – EMEA, Region 2 – The Americas and Region 3 – Asia-Pacific.*

Following WRC-19, the technical conditions for use of the identified bands will be developed by CEPT[7]. They may then be included in a Commission Decision, which would be binding on EU Member States. The process of national spectrum licensing would then follow.

3.2.3 5G for automotive applications

There are two broad categories of potential automotive applications; those based on wide-area infrastructure-based communications (V2N), and those based on short-range communications (V2V, V2I, V2P, etc.). Many infrastructure-based applications are likely to require reliable contiguous coverage, and therefore need mobile bands preferably below a few GHz. Additional spectrum is likely to be required for shorter range and extreme traffic density. This is likely to be identified at WRC-19 as part of a dedicated agenda item for IMT-2020 spectrum above 6 GHz.

[7] *CEPT is the European Conference of Postal and Telecommunications Administrations, which consists of 48 European Countries cooperating in the regulation of posts, radio spectrum and communications networks.*

4 Limitations of existing communication technologies

Two major standardized technologies are currently being considered for V2X communications: IEEE 802.11p and 3GPP Long Term Evolution (LTE) with Proximity Services (ProSe). This section provides a brief summary of the main limitations associated with each of these approaches with respect to the performance requirements of the use cases described above.

4.1 IEEE 802.11p / ITS-G5

The IEEE 802.11p standard[8] incorporates, with some modifications, the PHY layer based on Orthogonal Frequency Division Multiplexing (OFDM) from the IEEE 802.11a standard, and the MAC layer based on the Enhanced Distributed Channel Access (EDCA) from the IEEE 802.11e standard. The EDCA protocol is contention-based and uses Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CSMA/CA) and four different access categories (ACs) in order to achieve data traffic prioritization. The IEEE 802.11p PHY and MAC provide services for upper layer protocols for Dedicated Short-Range Communications (DSRC) in the US (Kenney, July 2011) and for Cooperative ITS (C-ITS) in Europe (Festag, December 2014).

The IEEE 802.11p standard has certain desirable features for V2X communications. Because the communication is direct between source and destination endpoints, it can operate without network coverage by an infrastructure network, in a fully distributed fashion. Unlike regular legacy Wi-Fi operation, endpoints start the communication without first forming a Basic Service Set (BSS), which effectively allows vehicles to immediately transmit data without prior exchange of control information. This implies a significant advantage in terms of latency, since V2X network topologies change quickly over time and the BSS re-formation and its related signaling could result in undesirable delays in data communication. Roadside Units (RSUs) can be deployed to increase the communication range, especially in challenging non-line-of-sight (NLOS) scenarios, such as urban intersections. It is important to note that some kind of network infrastructure is needed for management and security functionalities – e.g., Certificate Revocation List (CRL) distribution – as well as for providing connection to the Internet. However, creating countrywide coverage by means of RSUs for such Internet access might not be economically justified, as cellular networks already provide such coverage.

One of the main drawbacks of IEEE 802.11p is that its throughput and delay performance degrades quickly as network load increases (e.g., due to high user density). This is caused by the behavior of the contention-based medium access strategy (CSMA/CA) at the heart of EDCA, which follows the *listen before talk* principle. In order to minimize collisions in channel access, when a user has

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[8] IEEE 802.11p has been integrated into IEEE 802.11-2012 (IEEE 802.11-2012, March 2012). ITS-G5 is the European variant and specified in ETSI EN 302 663 (ETSI EN 302 663, July 2013). For simplicity, we refer to IEEE 802.11p throughout this document.

data to transmit, it senses whether the channel is occupied. If the channel is perceived as idle for a predetermined listening period – known as Arbitration Inter-Frame Spacing (AIFS) in EDCA – the node can start to transmit immediately. If the channel becomes occupied during the listening period, the node will perform a backoff procedure, i.e., it will defer access for a randomized time period within a contention window. The higher the number of stations transmitting in a certain area, the higher the probability that a station postpones a transmission as a result of the channel being occupied. Because of this, the latency generally increases with the number of stations, and a maximum latency cannot be guaranteed. For unicast communication, the latency can even be higher because for re-transmissions, the contention window from which the backoff delay is chosen, increases with every transmission attempt.

The EDCA access categories define four queues with different values for the contention window (min and max) and the AIFS. Data packets of a specific priority are mapped to the EDCA access categories, such that safety-of-life information is handled in the queue with the highest priority; packets with a lower priority are handled by other queues. The parameters for the highest priority are chosen to keep the listening period as short as possible, such that more data traffic can be squeezed into the channel (i.e., the channel utilization is increased because nodes listen for a shorter time period before transmission). One drawback is that, for the highest priority, there are just a few contention window sizes to select from when performing the backoff procedure, leading to an increased probability of simultaneous channel accesses during high network utilization periods (i.e., nodes will often reach a backoff value of zero at the same time).

Moreover, the "hidden node" problem is a well-known limitation of the CSMA/CA mechanism in which collisions cannot be avoided. In particular, the *listen before talk* approach does not detect the presence of transmissions located outside of the range of a transmitter but within the range of a potential receiver. A station can therefore decide to transmit after sensing the channel free of transmissions, and still the information might "collide" at the receiver with another transmission originated outside of the range of the first transmitter. The probability of collision increases with the number of transmitters in a certain area. If the vehicle density is high, data transmission can be highly unreliable as a result of high packet error rate. Although the so-called Request-to-Send / Clear-to-Send (RTS/CTS) mechanism is incorporated in the IEEE.802.11p family of standards to cope with the hidden node problem, this results in an increase of the system latency and in a reduction of the overall spectral efficiency, and therefore it has been ruled out for the provision of V2X Communications.

To cope with data congestion of wireless channels, Decentralized Congestion Control (DCC) aims at maintaining network stability, throughput efficiency and fair resource allocation to stations. In European deployments, DCC is a cross-layer feature of the protocol stack, allowing DCC components to jointly work to fulfill fair channel access among all stations in the same communication zone, keep channel load below a predefined threshold and provide fast adaptation to a changing environment (busy / free radio channel). The DCC algorithm is based on measurement of the load on the wireless channel (or channel busy ratio, CBR). For high CBR (either measured locally or including two-hop neighbor information piggybacked in the packet header, depending on the network protocol), DCC reduces the repetition rate of periodic safety messages. This approach solves the data congestion problem, but introduces a new limitation, i.e., the heartbeat rate (broadcast periodicity) may be reduced below acceptable values.

From the PHY point of view, assigning a fixed bandwidth of 10 MHz per channel for a single V2X transmission is a compromise solution. The resource allocation is straightforward, which significantly simplifies the synchronization problem from the network dimension to a point-to-point problem. However, due to the quickly varying mobile channel (both in time and frequency), frequency-selective resource allocation could increase the overall data throughput, in addition to the per-link rate adaptation via modulation, channel coding and power adjustment. This is not supported by IEEE 802.11p. Furthermore, the multi-user throughput gain is not exploited. IEEE 802.11p employs convolutional Forward Error Correction (FEC) channel coding and Single-Input Single-Output (SISO) transmission. Although this leads to a low implementation complexity and cost, the spectral efficiency is far less than, say, turbo coding with Multiple-Input Multiple-Output (MIMO) transmission as used in an LTE/LTE-A system.

Another limitation is the communication range of IEEE 802.11p, which is typically several 100 meters, given the propagation properties at the operating frequency of 5.9 GHz and depending on environmental conditions (highway, intersections, etc.). Some V2X applications may require reliable transmission beyond the communication range of IEEE 802.11p. For coverage extensions, wireless multi-hop communication can be applied, for example introduced by GeoNetworking in the European C-ITS protocol stack. However, this multi-hop functionality at the network layer increases protocol complexity and overhead. Extending the communication range of a single IEEE 802.11p link is challenging. The pilot symbols provided in IEEE 802.11p (preamble combined with comb pilots) are suboptimal for highly time-variant radio channels and especially for long data frames, as channel information quickly becomes outdated. In such cases, the accuracy of the channel estimation may be insufficient for data detection. The main reason for this is the fact that the IEEE 802.11 family of standards were originally designed for stationary indoor reception (e.g., office environment).

The efficient utilization of the allocated spectrum for safety and traffic efficiency applications in the 5.9 GHz frequency band using IEEE 802.11p represents another challenge. The spectrum is split into several channels of 10 MHz each. One of the channels is designated to be the main safety channel, referred to as Control Channel (CCH); the others are additional Service Channels (SCH). While the basic V2X system based on IEEE 802.11p, which is expected to be deployed in the next few years, uses the CCH only, future V2X system will need to exploit the full spectrum, potentially using a dual transceiver. While the final solution for multi-channel operation is not finalized yet, it is clear that the transmission on one channel creates interference on other channels and can additionally reduce the communication reliability. A strict time-wise coordination of transmissions as an alternative reduces the utilization of the allocated spectrum.

In contrast to IEEE 802.11 local area networks, where a passphrase is sufficient to get access to the local network access point, vehicular networks need to offer a secure communication in a highly mobile environment for time-critical messages from a large number of mobile stations.

In this context, secure communication requires that each device can decide whether a received message is trustworthy or not. The security system used for vehicle ad-hoc communication over IEEE 802.11p uses digital signatures to guarantee the integrity and authenticity of a message. To generate signatures and allow for verification, private-public-key pairs and certificates are required, and the latter are retrieved from a Public Key Infrastructure (PKI). Beyond the security issues, the privacy of the connected vehicles needs to be preserved to prevent personal data, e.g., location and driving habits, to be revealed to unauthorized entities. To provide the required level of privacy, the PKI issues batches of certificates that can be used in a random fashion to prevent long-term tracking by outsiders. These certificates are referred to as pseudonym certificates. [9]

Vehicles that are identified as misbehaving should not be trusted any longer. This can be achieved by active dissemination of revocation information or, alternatively, by not fulfilling any future requests for pseudonym certificates by these vehicles.

The security concept with a centralized management entity, however, has the drawback that it relies on a sporadic connection between the vehicle and the infrastructure to manage and revoke certificates initiated by the infrastructure. This procedure can lead to a large delay to revoke certificates and, hence, can be harmful to safety applications. Furthermore, the decentralized approach results in a large overhead for cryptography to be signaled and processed. Additionally it prevents simple update procedures of cryptographic algorithms. The discussed security concept is defined outside of IEEE 802.11p communications standard but was created with transmission of safety messages over IEEE 802.11p in mind. Hence, security design choices are strongly influenced by the properties of 802.11p. Using the cellular network as a trusted entity might help to accelerate revocation of certificates, simplify update procedures and lower the required overhead to achieve future-proven secure vehicle communications.

4.2 3GPP Long Term Evolution (LTE) infrastructure-based communication

Often, vehicles and vulnerable road users (e.g., pedestrians, bicycles, etc.) find themselves within coverage of a Public Land Mobile Network (PLMN), providing cellular radio coverage, e.g., based on the 3GPP LTE standard (3GPP TS 36.300, July 2015), also known as E-UTRAN (Evolved Universal Terrestrial Radio Access Network). This affords the opportunity to exploit the cellular

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[9] *Note that there exist two variations of the security concept for ad-hoc vehicular communications over IEEE 802.11p: The US version is defined in IEEE 1609.2 and there exist appropriate equivalents in Europe as well.*

infrastructure for V2X communication. In contrast to 802.11p, cellular transmissions are *scheduled*, i.e., transmission rights are granted by a network scheduler, located in the E-UTRAN Node B (eNB), in such a way that collisions are avoided and mutual interference is minimized (3GPP TS 36.321, July 2015). This is of utmost importance under high network load, as the scheduler may be able to provide Quality-of-Service (QoS) guarantees (e.g., a guaranteed bit rate or delay) to different applications by allocating radio resources based on their priority and QoS class parameters and by performing admission control. This is a major departure from CSMA/CA.

However, LTE was originally designed for mobile broadband (MBB) traffic, which has very different properties and requirements from V2X traffic. Thus, it may have certain limitations due to original design choices.

The areas where LTE requires improvements are discussed below.

1. Latency rises with higher numbers of users in the cell. For instance, it has been shown in (Phan, Rembarz, & Sories, October 2011) that with LTE technology, the capacity limit for distributing event-triggered messages to all devices in the same cell can reach up to 150 devices in urban scenarios and about 100 devices in rural scenarios, maintaining an end-to-end delay below 200 ms.

2. Every data packet (e.g., between two nearby vehicles) must traverse the infrastructure, involving one uplink (UL) and one downlink (DL) transmission, which may be suboptimal compared to a single radio transmission along the direct path between source and destination nodes, possibly enjoying much lower delay (especially in an overloaded cell). In addition to being a potential traffic bottleneck, the infrastructure may become a single point of failure (e.g., in case of eNB failure).

3. Since the LTE system was originally designed for broadband traffic, it may not always be optimal for transmitting small amounts of data. This translates into suboptimal usage of radio resources. Many V2X use cases will require support for a large number of very small-sized packets. This can lead to three potential problems within the traditional cellular design: (i) channel coding, (ii) resource granularity and (iii) control and channel estimation overhead. In particular, typical control and channel estimation overhead quickly becomes very inefficient for very short payloads.

4. A major problem for many automotive use cases is the introduced delay until the actual payload can be transmitted. The random access procedure in LTE is a multi-stage protocol with several messages in both uplink and downlink. Although simplifications of the existing LTE procedure can provide some benefit, at least one preamble transmission and one downlink feedback (Random Access Response) will always be required prior to the payload transmission due to the need of tight synchronization in the uplink. The set of available preambles (at most 64 per sub-frame and consuming around 1 MHz bandwidth) are shared among all users in a cell, regardless of their applications, and are utilized for many purposes (initial access, re-synchronization for data transmissions, handover, and

radio link failure recovery). Therefore, the preamble design has to consider many constraints with respect to expected delay spreads and Doppler spreads, which limit the spectral efficiency of the Physical Random Access Channel (PRACH). As a consequence, scalability may become a problem. If the number of users per cell increases, additional delays due to failed or blocked random access attempts will occur. The collision rate is expected to increase rapidly as the number of devices increases, making the scalability of the Random Access Channel (RACH) questionable. For example, assuming a typical PRACH configuration with one slot per time frame, 64 available preambles and 30 ms packet arrival interval in a cell with 1000 users, the collision probability is almost certain (99.97%) (Zhou & Nikaein, April 2013). In addition, an increasing number of Random Access Responses (56 bits per user) limits the overall downlink capacity.

5. Another major drawback of infrastructure-based approach is that it is not available out of coverage (and may not satisfy the stringent reliability requirements under weak coverage), e.g., in a tunnel, underground parking lot, rural area, mountainous terrain, etc., all of which are important places where road safety must be ensured. This implies that additional infrastructure would need to be deployed if coverage is to be guaranteed in these areas.

4.3 3GPP Long Term Evolution (LTE) Proximity Services (ProSe)

The next logical step is to bypass the infrastructure (when necessary or optimal), and transmit the data directly among users. This strategy, known in the research literature as Device-to-Device (D2D) communication (Lin, Andrews, Ghosh, & Ratasuk, April 2014), makes it possible to offload the infrastructure and achieve significantly lower delay performance. The infrastructure may still retain control of radio resource allocation and other control plane functions.

Starting from Release 12, a new feature known as Proximity Services (ProSe) is being specified within 3GPP (3GPP TS 23.303, July 2015). ProSe Direct Discovery and ProSe Direct Communication allow UEs (User Equipments) within communication range, regardless of whether they are in or out of E-UTRAN coverage, to discover and communicate with each other directly, i.e., without traversing the network infrastructure.

ProSe Direct Discovery and Direct Communication are enabled by a new E-UTRA capability known as “sidelink” (SL) (3GPP TS 36.201, April 2015), which refers to the direct radio link between two (or more) UEs, as opposed to the conventional uplink and downlink radio links between UE and eNB. Sidelink transmissions occur within a subset of the uplink time-frequency resources (PSCCH for Sidelink Control Information (SCI), PSSCH for sidelink data, PSDCH for discovery announcements and PSBCH for broadcast of system information) (3GPP TS 36.211, July 2015) and use the same transmission scheme as uplink transmissions, i.e., Single Carrier - Frequency Division Multiple Access (SC-FDMA). There are two sidelink transmission modes (3GPP TS 36.213, July 2015): in *scheduled* mode (“mode 1”), the eNB determines the radio resources used for sidelink communication; in *autonomous* mode (“mode 2”), the UE selects the radio resources on its own from a (pre)configured resource pool. The former mode is only available when in coverage.

The current release of the ProSe specification (3GPP TS 23.303, July 2015) has been designed with the requirements of public safety and commercial consumer applications in mind – in particular, low mobility, no QoS, and one-to-many (i.e., multicast) communication. Future V2X applications will need to work under high speeds (e.g., in highway scenarios), possibly with guaranteed QoS on a sidelink radio bearer (SLRB) basis and support for one-to-all (broadcast) as well as one-to-one (unicast) communication. ProSe Direct Discovery procedures may need to be optimized to work under high mobility, while obtaining radio resources for ProSe Direct Communication in sidelink transmission mode 1 may take too long and incur excessive overhead for certain delay-critical and small-sized V2X messages. Some other limitations relate to the sidelink frame structure and synchronization procedures that were designed for lower mobility than what is typically assumed in V2X scenarios and thus require some changes. Further limitations relate to the autonomous resource allocation scheme that was designed assuming the typical traffic patterns and load of Public Safety communication and commercial discovery, which differ substantially from the operating conditions of V2X traffic.

In terms of radio access, current sidelink specifications need to be enhanced in several ways. Table 3 summarizes identified limitations of ProSe (Rel-12) from the V2X perspective.

Table 3. Limitations of ProSe in LTE Rel-12 from the V2X perspective

	ProSe limitations / missing features
Primary (consensus at 3GPP)	1. Collision risk in sidelink transmission mode 2 (UE autonomous resource selection) as a result of random resource selection from (pre)configured resource pool.
	2. Time Resource Pattern (TRP) length (8 bits for FDD mode) for PSSCH subframe allocation insufficient for high density situations involving many simultaneous transmission sources within close proximity, due to half-duplex constraint (i.e., a UE cannot transmit and receive on sidelink in the same subframe).
	3. Handover of Mode 1 resource allocation needs further optimization. This is key as many vehicles will cross cell boundaries at any given time.
	4. Suboptimal pilot scheme for sidelink channel estimation in highly time-variant channels.
	5. Limitations of ProSe security mechanisms. ProSe security, as well as LTE security, are not yet applicable for V2X due to the differences in use cases (this may change in Rel-14). Therefore, new mechanisms may need to be adopted.

Secondary (to be further discussed)	6.	Inefficient resource allocation and link adaptation – Transmit Power Control (TPC), transport format selection, MIMO, etc. – in sidelink transmission mode 1 (eNB scheduled resource allocation) due to lack of sidelink Channel State Information (CSI) at eNB. Even for broadcast scheduling, without some sort of sidelink interference measurements, it is difficult to schedule efficiently.
	7.	No Semi-Persistent Scheduling (SPS) for SL. For small-sized periodic transmissions, dynamic scheduling (i.e., requesting a resource again and again) is inefficient.
	8.	Current Transmission Time Interval (TTI) length (1 ms) may be too long to fulfill ultra-low delay requirements under high vehicle density for certain V2X applications, such as Cooperative Collision Avoidance (see Section 3.1), with a maximum tolerable radio access delay of 1-5 ms (given the 10 ms cycle time for trajectory update required by the application).
	9.	Too slow acquisition and connection setup procedures (synchronization, link establishment and resource allocation, especially in sidelink transmission mode 1) prevent quick access to resources needed for ultra-low delay V2X applications. An example is an emergency brake notification, for which there may be no time to request a resource from the eNB.
	10.	No HARQ feedback in SL. May or may not be a limitation, depending on the use case and type of traffic. For unicast traffic of high reliability, HARQ feedback may be required to trigger a retransmission.
	11.	No RLC (Radio Link Control) Acknowledged Mode (AM) for SL. Same as above.
	12.	No dynamic ProSe Group management, as may be needed for certain V2X applications such as lane merging, platooning, etc., to inform the scheduler about the intended recipients of a groupcast message (e.g., when allocating a radio resource, the half-duplex constraint need only be satisfied by members of the group).
	13.	No QoS support for SL. QoS class differentiation of V2X traffic may be required to prioritize safety-of-life messages over less critical messages, both within and among vehicles.

3GPP RAN is currently working to enhance ProSe (PC5 interface) – as well as LTE UL/DL (Uu interface) – in Release 13 in order to fulfill the requirements of V2X services over licensed and unlicensed spectrum (3GPP TSG RAN Meeting #68, June 2015). The proposed enhancements include:

- Support of PC5 transport for V2V services (highest priority, to be completed by December 2015)
    - Identify necessary enhancements (e.g., mitigate impact of half duplex constraint, reduce resource collision, enhance pool structure, enhance resource patterns, Scheduling Assignment (SA) information / Sidelink Control Information (SCI) transmitted in same subframe as the associated data) to the resource allocation mechanism to meet identified requirements for robustness, latency, overhead and capacity.
    - Identify any necessary PC5 enhancements for high Doppler case (e.g., up to 280 km/h up to 6 GHz) such as enhanced Demodulation Reference Signals (DMRS), and also synchronization based on GNSS at least for out-of-coverage operation.
- Support of Uu transport for V2V, and PC5/Uu transport for V2I/N and V2P services (to be completed by June 2016)
    - Evaluate the feasibility of Uu transport for V2V and V2P in terms of meeting latency requirements, required network coordination, resource efficiency, and energy efficiency of UE.
    - Enhancements required to support eNB-type RSU and UE-type RSU.
    - Identify and evaluate the necessity of enhancements to multi-cell multicast/broadcast for reduced latency and improved efficiency.

The above enhancements are expected to address the ProSe limitations listed above and to enable integration of LTE cellular and direct (D2D) modes for efficient delivery of V2X traffic.

4.4 Service architecture

Apart from the limitations of the access technologies, outlined in Sections 4.1 to 4.3, there are particular problems stemming from the current service architecture, intertwined with the particular radio access network architectures.

One such particular problem is that of supporting flexible content and service surrogate placement that would evolve the current Content Delivery Network (CDN) model towards a model where server surrogates could be placed within the vicinity of vehicles, in order to satisfy strict latency requirements of future 5G vehicular scenarios, as well as address strict service availability requirements and avoid single points of failure. Although proxy deployments in street furniture have been under experimentation for many years (The Register, April 2004), such approach has not seen entry into the various access network architectures. While advances in NFV and SDN have increased the ability to flexibly allocate computing resources within the network, NFV-based flexible surrogate placement is still in its infancy. One limitation is that of Virtual Machine (VM) granularity, where network functions (NF) are treated at the level of heavyweight VMs, making a flexible and fast deployment difficult (e.g., for overload situations in vehicular congestion scenarios). Another problem is that of routing inflexibility, where current CDN redirections (even in the possible presence of lightweight VM techniques) lead to inefficient routing from clients to possible surrogates due to the necessary Domain Name System (DNS) manipulations that come with such surrogate injections. Routing simplification is difficult to achieve without re-thinking the overall routing approach within the radio access network as well as re-thinking the insertion of surrogates without the need for DNS manipulation.

4.5 Summary

In terms of availability, IEEE 802.11p has the desirable features of not relying on network infrastructure (other than for security management and Internet access) and being fully distributed, with the consequent benefits of not posing a traffic bottleneck or single points of failure, as is the case with an infrastructure-based approach such as LTE. On the other hand, the uncoordinated channel access strategy used by 802.11p is unable to fulfill the (deterministic) latency, reliability and capacity requirements of future V2X use cases, which may only be achieved by means of a coordinated channel access strategy (i.e., involving a scheduler) and with admission control, both of which are integral parts of LTE.

ProSe Direct Communication via E-UTRA sidelink appears to be the most promising way forward for V2X, as it combines the best of both worlds. However, the current ProSe specification (Release 12) has not been designed with the stringent requirements of vehicular use cases in mind. Thus, new technology solutions are needed to make ProSe capable of satisfying tomorrow's V2X communication requirements.

Table 4 summarizes the strengths and weaknesses of IEEE 802.11p and 3GPP LTE, with and without ProSe (Release 12) (*green* indicates a strength, *red* indicates a weakness, *yellow* indicates further work is needed). Note: Some of the weaknesses of ProSe are being addressed in Rel-13/14 (3GPP TSG RAN Meeting #68, June 2015).

Table 4. Comparison of existing candidate technologies for V2X

Features	**IEEE 802.11p / ITS-G5**	**3GPP LTE without ProSe**	**3GPP LTE with ProSe (Rel-12)**
Availability	Everywhere. Infrastructure needed only for security management and Internet access.	Only when in coverage.	Everywhere (with sidelink transmission mode 2).
Traffic Bottleneck	No (fully distributed).	Yes (eNB).	No (except possibly in control plane under sidelink transmission mode 1).

Single Point of Failure	No (fully distributed).	Yes (eNB failure).	No (if eNB fails, mode 1 falls back to mode 2).
Spectral Efficiency	Low (throughput performance degrades under high load due to backoff procedure).	High (channel dependent scheduling in frequency selective channels).	Medium (channel dependent scheduling possible in principle in mode 2 without CSI feedback under the assumption of channel reciprocity; link adaptation needs further work).
QoS Guarantees (latency, bandwidth, reliability)	Not guaranteed (due to probabilistic nature of CSMA/CA backoff procedure).	Guaranteed after connection establishment. However, future V2X use cases may require more advanced QoS mechanisms than can currently be provided.	Guaranteed under mode 1, collision risk under mode 2. However, future V2X use cases may require more advanced QoS mechanisms than can currently be provided.
QoS Class Differentiation	Probabilistic (EDCA Access Categories, no admission control).	Yes (QoS guarantees can be provided by scheduler, admission control).	No QoS support for SL.
Security	Yes. Certificate-based solution is designed specifically for V2X communication.	Yes. Symmetric-key solution via eNB. Further work is needed for V2X support.	Yes (Group-based security solution) but further work is needed for V2X support.
Range	Medium. Depends on scenario. Typically 250-350 m on highways, 80 m in urban environment.	Long. Typical macro-cell coverage.	Medium. Due to UE transmit power constraints.
Robustness to Doppler Effect	High. Due to large inter-carrier spacing.	Medium. Doppler effects need to be compensated at the receiver.	Medium. Doppler effects need to be compensated at the receiver.
MIMO Support	Not supported.	Yes.	Not supported yet. But can make use of LTE Cellular MIMO design.
Channel Coding	Weak. Convolutional coding.	Strong. Turbo coding.	Strong. Turbo coding.
Synchronization	Receiver-side synchronization; relaxed frequency synchronization requirements due to large inter-carrier spacing.	Requirements can be met by well-known estimation algorithms at receiver side.	When in coverage, coexistence of SL and UL transmissions may need further study if they use the same carrier frequency. Future 3GPP releases will tackle this

			issue.
Pilot Design	Combination of preamble and comb pilots. Channel estimation is challenged by high mobility, especially for long data packets. Improved by blind channel estimation capabilities.	Well-suited pilot design for LTE mobility scenarios in DL (scattered pilots), suboptimal in UL (midamble).	Suboptimal midamble pilot scheme in SC-FDMA for highly time-variant channels. Higher mobility on SL, compared to UL, makes the pilot scheme even more unsuitable for time interpolation to cope with channel time variance.

5 Business and regulatory aspects

This section discusses the transformation of business models and evolution of business roles around 5G and automotive industries, as well as spectrum considerations, standardization issues and regulatory barriers to the introduction of 5G in the automotive domain.

5.1 Transformation of business models

The mobile telecom industry in Europe accounts for about 1.3 million jobs and represents an economy worth about €160 billion. Future 5G communication systems aim at boosting this market and at the same time challenging current telecommunication industry players. 5G is expected to lower the threshold for access of new actors into the market, requiring new investments and opening new opportunities. Mobile's reach is wider and deeper than any other technology in Europe, constituting a major driver for economic growth, technology advancement and innovation. Investment in research and innovation is becoming increasingly important for creating value and maintaining competitive jobs. The average R&D investment as a percentage of revenues for the mobile industry (3GPP members) in the period 2005-2012 has been around 13%.

5G has a unique opportunity to play a key role in substantially transforming our lives by connecting all sectors of our society and economy. 5G will represent the backbone of the future digital economy, creating more and better jobs and contributing to a sustainable economic growth worldwide. Furthermore, communication networks in the 5G era will also take on more important societal roles than today; by connecting people, machines and things on a massive scale, they will facilitate the delivery of personalized healthcare and support to an aging society, help to optimize transport and logistics, enhance access to culture and education for all, and virtually revolutionize public services. 5G is not just a new generation of technologies, but a new communication paradigm with the user at the center. 5G is rather seen as a Future Internet, the infrastructure platform supporting a variety of new services for all citizens worldwide, and not only the next generation of mobile broadband networks.

5G PPP research and innovation projects will be used to build a common vision among European networking industry players regarding functional and non-functional requirements for 5G. It is crucial to take into account the needs and concerns of citizens and enterprises in this vision, which will be reused by the telecommunications industry to motivate 5G infrastructure investments and build the rolling plan according to related business.

When adopting an automotive centered global view on V2X, two intertwined activities can be observed. On one side of the Atlantic, a US rulemaking process is currently ongoing with the clear target to make direct V2V communication based on IEEE 802.11p mandatory (US National Highway Traffic Safety Administration (NHTSA), August 2014) in the next years. It is therefore expected that new vehicles will have to be equipped in the coming years with the IEEE 802.11p technology, most likely over a ramp-up phase of around 4 years. On the other side of the Atlantic, the market introduction of ITS-G5 (the European variant of IEEE 802.11p) will be most likely voluntary in nature and currently expected to start in a similar time frame. This is especially relevant when considering that the same stakeholders are active on both sides and following similar initial V2X applications and scenarios. In addition, the ministries of transportation of the Netherlands, Germany and Austria have started a deployment project (Cooperative ITS Corridor, 2015) for the equipment of roadwork protection systems on highways with ITS Roadside Stations (IRS) using ITS-G5 for communication with vehicles, with a plan to finalize the rollout by the end of 2018.

Finally, 3GPP is currently working to enhance LTE V2X in upcoming releases (3GPP TSG SA Meeting #67, March 2015). We should accelerate these evolutions in order to benefit as soon as possible from the differentiated characteristics of 3GPP, as explained at the end of Section 4 (e.g., throughput under high load, QoS guarantees, etc.). Based on these developments, 5G will most likely be in a position to integrate already available communication technologies like LTE V2X and IEEE 802.11p (both under a service provisioning architecture as well as under a multi-RAT point of view) and provide the necessary extensions to enable the future V2X use cases described in Section 2.3.

New business models have already started to emerge with the integration of connectivity in cars. These will be spurred by the availability of eCall in Europe and with the rapid growth and penetration of 4G, enabling a host of telematics and security applications. This will transform the relationships between car manufacturers, network and technology providers and services, such as insurance, driver assistance, security or content delivery. 5G will benefit from this trend and see a multiplication of new partnerships, also enabled by concomitant enhanced safety, mobility and environmental stewardship of 5G networks. In this context, it is of utmost importance to consider all aspects, related to cars, intelligent and connected transport infrastructures, technology and connectivity solutions and finally the data generated.

Regarding the automotive sector, in order to capture the value of new opportunity areas like the creation of a service platform for Business-to-Business (B2B) or Business-to-Government (B2G), with an estimated potential of 30$/vehicle/year, equipment manufacturers need to connect in a secure and trusted way, vertically and horizontally, their value chain with wireless service providers, potential clients, fleet management companies, car rental and car-sharing services, infotainment content providers and developers of location-based services. Opportunities generated by 5G ecosystems for the automotive industry range from savings in public safety through a reduction in the number and severity of accidents (with both costs in terms of lives and property damage), savings in infrastructure planning and maintenance, to reduction in CO_2 emissions. Assuming complete penetration of V2X applications, annual economic damage from accidents might be reduced by up to EUR 6.5 bn in Europe alone. Furthermore, up to EUR 4.9 bn of economic losses might be avoided due to improved traffic efficiency and reduction of environmental damage (simTD Project, June 2013).

5.2 Evolution of business roles between players from the automotive industry and ICT industry

5G will enable new services, connect new industries and devices, and empower new user experiences to support expanded connectivity needs for the next decade and beyond. 5G will enhance mobile broadband, telematics services and applications and intelligent transport systems, but more importantly, have the scalability and adaptability to support an extreme variation in use cases which spans over a massive number of connected things, as well as enable new services like mission-critical tasks with reliability and latency beyond what humans can perceive. For example, ever-increasing levels of Advanced Driver Assistance System (ADAS) functionality and mobility performance using this 'digital infrastructure' will lead to a transformation of mobility, from both local and regional networks, through very localized, high-reliability connectivity between cars and the infrastructure. Cooperative driving, which is a difficult but revolutionary "end state" in automated driving, can be ushered in by 5G.

Scaling for billions of connected things and enabling instantaneous experience will require a user-centric approach around human, machine and things. Content, connectivity, security and computing will need to be brought closer to the user; human and things will communicate with the network and with each other and will be an integral part of the network, which will be flexible and scalable with virtualized and distributed functions to reduce latency and costs and improve energy efficiency. 5G research and innovation activities will have to continue improving efficient use of spectrum and data throughput. Key aspects will have to guide all the 5G research and standardization phases: energy efficiency, total cost of ownership reduction, network services flexibility, and trust and security. 5G networks will leverage key evolutions towards network convergence, cognitive network management, network virtualization and software networks and network edges.

In the 5G era, vast amounts of data will be created, leading to the emergence of the user's digital personal identity and becoming the new fuel of the digital economy. Trust of consumers in a new user-centric paradigm is a key ingredient for the development and take-up of 5G. A chain of trust throughout the mobile ecosystem based on secure systems and products shall be implemented in hardware and start at the level of the connectivity modem and continue both vertically, from the modem to the mobile device (or machine), as well as horizontally, from the device (or machine) through the network to the edges and the Cloud.

The ecosystem enabled by 5G meeting the long-awaited V2X communication requirements will at the same time bolster new business models and opportunities. Cooperation between Original Equipment Manufacturers (OEMs) and telecom operators will reduce cost of infrastructure deployment and at the same time lower barriers for other sources of data to enter the ecosystem, improving the richness of data available to build the Local Dynamic Maps (LDMs) in the cars. The 5G network, as a ubiquitous means of connecting all data sources, and the need for this data to be shared among the business actors to create truly automated driving solutions, will create new business opportunities hand in hand with potentially new services not foreseen so far.

5.3 Spectrum considerations

5G will drive demand for more and diverse spectrum and, as a unified platform, will be designed to operate in a large portfolio of frequency bands and licensing regimes, leverage 4G investments, be scalable for new deployments and business models and support a wide range of new services for the next decade and beyond.

In the meantime and in parallel, 4G LTE Advanced will continue to evolve to its full potential. Simultaneous 5G, 4G, 3G and Wi-Fi connectivity and a single common 5G core network will ensure a seamless 5G introduction that fully leverages earlier network investments.

In order to seize the first-mover advantage, the European Commission needs to:

- Enable new frontiers in mobile connectivity (Machine Type Communications, Device-to-Device, broadcast, automotive, small cells) in the period 2015-2020 using LTE Advanced evolution to prepare to be first mover in 5G starting from 2020.
- Implement radio spectrum management policies that enable sustainable consumer benefits and increased competition. Exclusive licensing should continue as the main lever for creating regulatory and legal certainty in the market and help operators provide the best quality of service.
- Make additional spectrum available on shared license and unlicensed bases within higher bands (e.g., above 6 GHz). This will help operators deliver extra capacity for the best possible user experience in a consistent manner and in line with what customers require.
- Cooperate internationally to timely harmonize and make available radio spectrum for 5G. In particular, the 700 MHz band and its availability currently in many EU member states already represents the potential to lay the stepping stone for the future spectrum policy that will benefit 5G.

In the framework of automotive connectivity, ITS applications are intended to be operated in the 5.9 GHz band. ETSI EN 302 663 specifies the channel allocation of the ITS-G5 access layer for the 5 GHz frequency range (ETSI EN 302 663, July 2013). In addition, future releases of LTE (e.g., LTE V2X) will provide additional technology options to satisfy the requirements of new services and applications, as described in detail in Section 4.

Spectrum options

By using spectrum specifically designated for this application, we can take advantage of the fact that there is no sharing with other applications, therefore a tighter security control and integrity can be applied. This security and integrity element is very important as we focus on applications that are immediately relevant to the safety of people. We would not like this band to be easily accessible for other applications and create interference. Imagine the scary scenario of some gamers accessing this band while your car depends on reliable data to drive safely. A designated band can also simplify roaming as end users drive between different countries or regions. Use of an unlicensed band could simplify access, without any license fee burden, which finally comes to the end user. In this sense, the unlicensed bands may be suitable for V2V communication. Integrity is still very important in this scenario, and it may be provided by higher layers of the protocol stack. There are security provisions in the ETSI ITS standard which cover all the layers.

5.4 Standardization approach

High-quality standards are a fundamental requirement to connect devices and industries through fast, secure and reliable wireless communications and to enable truly interoperable pan-European IoT services. In this line, it is important to encourage standards based on open solutions, developed on a voluntary and consensus approach by industrial stakeholders for the broadest level of marketplace acceptance and interoperability. The alternative – creating proprietary solutions or vertically integrated business models – will lock players out and will fragment the Digital Single Market (DSM), thus frustrating the European growth potential and potentially delaying the roll-out of V2X.

As part of the recent DSM announcements, it is important to note the following:

- Europe should support a standardization system that respects the variety of innovation business models, in particular ensuring reasonable intellectual property protection and adequate returns on investment. This guarantee is important for the industry to invest billions of Euros to develop innovative technologies. In practice, the support can be done by actively promoting standards that fulfill the requirements of openness, interoperability and consensus.
- There should be a close coordination among European Standards Organizations (ESOs), as well as other Standards Developing Organizations (SDOs), to leverage existing standardization efforts related to the deployment of C-ITS. This can be done, for example, by integrating 3GPP/ETSI timelines when it comes to 5G developments.

Future 5G studies and projects will be the place to benchmark and select technologies and architectures for future standards and infrastructure enablers.

The relevant SDOs that will play an important role in the specification of future 5G technologies and services in the automotive domain are the following:

- ETSI TC ITS – Release 2 of the ETSI TC ITS standards will integrate the new 5G connectivity framework into the ETSI ITS reference architecture and study the impact of the mapping of the new technology into each ITS stack layer. The improved 5G architecture will be promoted in the scope of the ETSI ITS Release 2 standard development, and it will incorporate future automated driving systems and services.

- 3GPP – Current 3GPP activities include a "Study on LTE Support for V2X Services" , describing use cases and requirements for V2X communication. Research focuses on the area of D2D communication (ProSe Direct Communication) for the purpose of efficient V2V communications, enabling short-range communications and multi-link traffic flows, delay-optimized protocols and 5G coexistence and augmentation with other access technologies (e.g., ITS-G5 for vehicular communications).
- IEEE – While 3GPP standardization is the central pillar of future 5G technology, the use of IEEE standards as extensions of LTE and LTE-A is considered fundamental as interworking networks in a multi-link / multi-RAT approach. Heterogeneous access strategies must be designed to make sure that all available technologies are efficiently put to service to meet the QoS requirements of V2X applications. This drives requirements for critical delay guarantees, high reliability, energy efficiency and scalability. The coordination and usage of multi-link and multi-RAT approaches for 5G should consider heterogeneous scheduling and traffic flow management with various traffic flows and various available RATs.

5.5 Regulatory barriers

Continuous investments in R&D and infrastructure are constantly needed in order to boost data speed as users' needs grow, strengthen connectivity, tighten security, ensure networks robustness as well as enhance consumers' experience. The need for rolling investments to improve, evolve and optimize networks is particularly relevant in the case of new connected services in the automotive space and Intelligent Transport Systems. Specific attention must be given to security and privacy in the context of automotive connectivity because mission-critical applications and future automated driving systems and services will require real-time availability and integrity, in an environment subject to personal data protection.

Policies that promote innovation and reward investment in communication networks and innovative standards are needed, together with preserving a technology-neutral approach on use of spectrum. Indeed, European investment in networks has been decreasing over the past few years as a result of falling mobile revenues and profits – a dangerous trend for Europe's digital future. The new regulatory framework under the DSM needs to make sure that operating a mobile network remains a viable business. This is even more important as it is the condition for the emergence of 5G and the IoT economy.

Wireless network operators should be allowed to invest in network capacity and improvements with the assurance that they can offer specialized services to end users – in particular IoT services, such as mobile health, smart cities and connected cars – that are based on specific commercial agreements and Quality-of-Service levels. The stimulation of network investment should be ensured by a fully reviewed telecommunications regulatory framework in a way that reduces sector-specific *ex ante* regulation and ensures a level playing field across market players in the digital value chain.

Finally, regulators need to address security, integrity, data protection, and privacy in the data economy in a holistic manner from a user's point of view, in particular by setting rules that apply to all providers offering equivalent services.

6 Research and innovation

In order to overcome the limitations of current wireless technologies, described in Section 4, many research issues must be addressed. This section describes the topics which should be covered in upcoming collaborative research and innovation projects in order to deliver the 5G automotive vision presented herein.

6.1 Main research and innovation areas for 5G V2X vision

There are several initial research studies and field tests of connected vehicles in some countries or regions, such as US, Europe, Japan, Korea and China. In particular, the China Communications Standards Association (CCSA) has finished a feasibility study for vehicle safety applications based on Time-Division LTE (TD-LTE) in 2014 and begun a series of industrial standards of communication based on LTE for vehicle applications. Further, in March 2015, a frequency study for V2X also started in CCSA and some vehicular industrial alliances in China. Based on this study, the National Regulatory Authority in China will allocate spectrum for connected vehicles.

In order to respond to this situation, SA1#69 recently agreed a new Rel-14 study on LTE support for V2X services to investigate the essential use cases and requirements for the following (3GPP TSG SA Meeting #67, March 2015):

- V2V (Vehicle-to-Vehicle): covering LTE-based communication between vehicles.
- V2P (Vehicle-to-Pedestrian): covering LTE-based communication between a vehicle and a device carried by an individual (e.g., handheld terminal carried by a pedestrian, cyclist, driver or passenger).
- V2I/N (Vehicle-to-Infrastructure/Network): covering LTE-based communication between a vehicle and a roadside unit/network. A Roadside Unit (RSU) is a transportation infrastructure entity (e.g., an entity transmitting speed notifications) implemented in an eNB or a stationary UE.

6.1.1 Architecture design

A generic architecture approach for 3GPP based V2X is urgently required from the market. The market for V2V communication in particular is time sensitive. Therefore, it is important to develop a 5G V2X architecture, based on identified novel use cases, market trends, MTC technical requirements, and limitations. Such an architecture should allow smooth transition from existing techniques to 5G and enable fast implementation of the best 5G V2X solutions, at the same time making sure that investments like ITS-G5 are protected. The architecture design should be addressed following the analysis in Sections 2, 3, 4, and 5, where the main use cases are identified and the practical issues in relation to use case operational requirements and limitations are highlighted.

V2X data can be transported from a source UE (e.g., a vehicle) to a destination UE (e.g., another vehicle, road infrastructure, a pedestrian, etc.)

- via ProSe Direct Communication over the PC5 interface between the UEs (sidelink), and
- via the eNB over the conventional Uu interface (uplink and downlink).

6.1.2 Direct V2X communication (PC5 transport)

For support of PC5 transport for V2V services, 3GPP RAN is in the process of identifying necessary enhancements to the resource allocation mechanism (e.g., mitigate impact of half duplex constraint, reduce resource collision, enhance pool structure, enhance resource patterns, SA information transmitted in same subframe as the associated data) to meet identified requirements for robustness, latency, overhead and capacity. Also, they plan to identify any necessary PC5 enhancements for high Doppler case (e.g., up to 280 km/h up to 6 GHz) and also synchronization based on GNSS, at least for out-of-coverage operation.

Support for PC5 transport for V2V services is of highest priority in 3GPP. Some important research objectives are as follows:

- Develop communication protocols and schemes for mission-critical (i.e., ultra-reliable, low-latency) network-assisted communication suitable for automotive use cases.
- Provide V2V multi-link connectivity mechanisms to increase robustness and network coverage in delay- and reliability-critical deployment scenarios. Radio Resource Management (RRM) and Medium Access Control (MAC) should be flexible enough to leverage the wireless network coverage whenever possible, and degrade gracefully as coverage is limited or non-existing.
- Design network-assisted radio resource scheduling algorithms and RRM procedures to provide robust interference management and coordination mechanisms for broadcast and unicast V2V communication channels.
- Develop mechanisms and procedures that allow optimized integration between network-assisted and non-assisted V2V channel access mechanisms while satisfying stringent latency requirements.
- Design novel discovery, synchronization and context-aware mechanisms to provide increased reliability/dependability of V2X communication links.
- Extend and design RRM procedures and interference management schemes in order to maximize system performance and provide guaranteed QoS for V2V communication.

6.1.3 Infrastructure-based V2X communication (Uu transport)

3GPP is in the process of evaluating the feasibility of Uu transport for V2V and V2P in terms of meeting latency requirements, required network coordination, resource efficiency, and energy efficiency of UE. Also under evaluation are enhancements required to support both eNB-type and

UE-type RSU for V2I. When the RSU is eNB-type, V2I occurs over the Uu interface; when the RSU is UE-type, V2I occurs over the PC5 interface.

Compute and storage resources in the 5G infrastructure can be used to optimize the data chain from sensors distributed in vehicles and transport infrastructure to central data centers. Local breakout using distributed gateways – based on LIPA/SIPTO (Local IP Access / Selected IP Traffic Offload) or a new 5G mechanism – or RAN based Mobile Edge Computing (MEC) techniques can be used to extend the connected car cloud into the highly distributed environment, and enable data and applications to be housed close to the vehicles. This can help to reduce the round trip time of data and enable a layer of abstraction from both the core network and applications provided over the Internet. The distributed car cloud could receive local messages directly from applications in vehicles and roadside sensors, analyze them and then propagate (with extremely low latency) hazard warnings and other latency-sensitive messages to other cars in the area. This enables a nearby car to receive data in a matter of milliseconds, allowing the driver to react immediately, for example by avoiding the lane hazard, slowing down or changing the route. The roadside applications can inform adjacent application servers about the event(s) and in so doing, enable these servers to propagate hazard warnings to cars that are close to the affected area. The roadside application can send local information to applications at the connected car cloud for further centralized processing and reporting.

Some important research objectives are as follows:

- Advanced flow control schemes and policy-based traffic engineering for V2X in order to optimize robustness (e.g., system availability, communication reliability) and latency.
- Address system aspects and develop RRM solutions to enable low latency and high reliability via infrastructure-based communication (PHY enablers, Layer 2 and Layer 3 solutions, U-plane and C-plane design).
- Design advanced solutions for QoS and traffic flow management in order to support, on the one hand, a massive number of machines, and on the other hand, the requirements for low latency and high reliability.
- Traffic engineering schemes addressing SDN enabled core and access networks.

6.1.4 Flow optimization and usage coordination of multi-link and multi-RAT

For optimized support of Uu transport for V2V, it is important to identify and evaluate the necessity of enhancements to multi-cell multicast/broadcast for reduced latency and improved efficiency, as well as potential UE-to-UE relaying, and find ways to integrate already available V2V technologies like IEEE 802.11p.

Some important research objectives are as follows:

- Flow based coordination schemes for multi-RAT V2X communication.

- Design dedicated multi-link and multi-RAT solutions for efficient QoS and traffic flow management.
- Design procedures for multi-RAT interworking that allow embedding existing communication solutions (including short-range technologies) comprising multi-RAT mode selection.
- Design and optimize routing protocols for multi-RAT and multi-interface communications.
- Traffic off-loading/balancing for multi-RAT and multi-interface communication.

6.1.5 Context awareness

Cloud based approaches will be key for the uptake of vehicle services and applications. An important enabler for niche services and applications is the advanced context management and big data management capacities of future communication systems.

Some important research objectives are as follows:

- Address efficient context management schemes for information generated by inbuilt device sensors for the RRM and radio protocols. Examples could be positioning information, proximity or moving patterns. Big data analytics for V2X could serve for optimized planning of available networks and respective traffic engineering.
- Application and service aware traffic flow management is also a challenging topic. A negotiation mechanism between the application and the system that provides the service should be supported.
- Address the signaling overhead, the computational load and the relatively big delay caused by the centralized nature of existing solutions.
- Reliability and efficiency of data delivery can be improved depending on context.

6.1.6 Multi-antenna solutions

As already discussed, the future information society will demand higher levels of connectivity not only at home but also while traveling on the road inside a vehicle. In order to satisfy the connectivity demands beyond 2020 (in terms of data rate, latency, reliability and availability), 5G is expected to rely on densification (i.e., deployment of small cells) as well as on massive MIMO techniques (i.e., high number of antenna elements in the base stations), among other techniques. In this sense, vehicular reception in motorway scenarios must cope with a series of challenges compared to stationary reception in urban environments. On the one hand, the amount of deployed infrastructure on motorway scenarios is significantly lower than in urban centers (inter-site distances up to 10 km), and so, high levels of densification are not to be expected. On the other hand, the high velocity at which vehicles travel on motorways hampers the operation of massive MIMO techniques, as a result of outdated channel information. In addition to this, the utilization of frequency bands located beyond 6 GHz (e.g., millimeter waves) might not be feasible on motorway scenarios because of high propagation losses and limited coverage.

This situation demands the investigation of new solutions capable of coping with the impairments of the motorway reception scenario, in order to fulfill the requirements of the future information society on the road. In particular, multi-antenna algorithms that are robust against imperfect channel information and advanced handover techniques might be essential, as well as receiver implementations that take advantage of vehicle characteristics. This includes the possibility to integrate a higher number of antennas at lower frequencies (< 6 GHz) compared to traditional consumer devices, together with advanced channel estimation and equalization techniques. The gained diversity can be exploited, e.g., for simple antenna selection. It is important to note that, even though the form factor of vehicles allows for a potentially higher number of antennas, some additional aspects related for example to the design and construction of the vehicle might limit their integration in practice, and might demand new approaches for the vehicle architecture.

6.1.7 Security

The ubiquitous connectivity of vehicles envisioned for 5G V2X networks demands strong security mechanisms to prevent unauthorized access to vehicles and related personal data. The IEEE 802.11p systems used today offer basic authentication and provide mechanisms to protect private data. However, the centralized management of certificates in combination with only sporadic connections between vehicles and infrastructure lead to a long delay for certificate revocation and result in a large communication overhead. The 5G V2X approach should reduce this delay to enable a timely response to misbehaving vehicles. Further development of security mechanisms should also reduce the overall overhead needed to provide security to support the increasing amount of connected vehicles expected in the future. Physical layer security mechanisms might be an option to reduce overhead while maintaining the desired level of security.

Given the expected lifetime of these systems, the further development of security mechanisms should consider the ability to update the cryptographic algorithms to adapt to upcoming challenges.

Some important research objectives are as follows:

- Identity management: Networks should uniquely identify and authenticate users/vehicles and control access to remote services with a timely update of certificates.
- Misbehavior detection: V2X communication systems have to be secured from tampering and new mechanisms for analyzing and detecting misbehaving nodes should be designed.
- Privacy protection: Personally Identifiable Information (PII) is any information such as one's name and phone number that can be used to distinguish or trace an individual's identity. PII may be disclosed, but only with the individual's knowledge and consent.

- Update of security mechanisms: The security mechanisms and algorithms should be developed such that they can be updated.
- Reduction of overhead: The overhead needed for security features should be reduced to support the expected number of connected vehicles.
- Data and message encryption and protection: Data and messages exchanged should be secured and checked for consistency.

6.2 Summary

Table 5 summarizes the research and innovation topics identified to address the limitations of the current 3GPP system and enhance it to support the stringent requirements of future automotive use cases.

Table 5. Summary of research and innovation areas for 5G based V2X

	Research and Innovation
V2X Spectrum	New mechanisms for the provision of more and diverse spectrum, innovative spectrum management techniques under a unified platform, designed for licensed and unlicensed spectrum, leverage 4G investments, be scalable for new deployments and business models and support a wide range of new services for the next decade and beyond. New standardization and regulation approaches for uplifting the barriers for secure, robust and highly manageable spectrum usage.
ProSe Direct Discovery	Optimization of ProSe Direct Discovery procedures for highly mobile vehicular scenarios. Interaction of Cooperative Awareness Messages (CAM) with ProSe Direct Discovery.
ProSe UE-to-Network Relay	ProSe Relay to provide network access for remote vehicles/UEs beyond network coverage. ProSe Relay discovery, selection and load balancing (network- vs UE-initiated). Multihop (nested) relay. Soft handover of relay functionality.
PHY	New approaches that will optimize the tradeoff between implementation complexity and spectral efficiency. New radio frame structure with shorter TTI length. New waveforms (non-orthogonal, etc.). MIMO on Sidelink. New pilot design.
Scheduling and Rate Adaptation	New schemes based on ProSe Direct communication to fulfill the (deterministic) latency, reliability and capacity requirements of future V2X use cases. Measurements to support eNB scheduler operation for SL-SCH (mode 1). Improved autonomous radio resource selection (mode 2). Quick access to resources. Semi-Persistent Scheduling (SPS) SL Grant for periodic CAM messages. Extended TRP (Time Resource Pattern) length for PSSCH subframe allocation in high density scenarios.
Retransmission Protocols	Enhancements for reducing the latency of re-transmissions due to resource collisions or packet errors. HARQ feedback (ACK/NACK) for ProSe Direct Communication. RLC AM (Acknowledged Mode) ARQ for ProSe Direct Communication.
Connection Management	Uu vs PC5 transport selection and, in case of PC5 transport, sidelink transmission mode selection (eNB scheduled vs UE autonomous resource allocation). Scalability of connection establishment procedure via RACH (mode 1) in high density scenarios.
Mobility Management	Sidelink Connection Mobility Control (CMC). X2/S1 signaling procedures for Sidelink handover management (e.g., exchange of sidelink resource allocation information among neighboring eNBs).

QoS Management	QoS support for ProSe Direct Communication. Advanced QoS mechanisms to provide Radio Admission Control (RAC) and QoS guarantees through Radio Bearer Control (RBC). Priority handling both within a vehicle and among vehicles. Novel access strategies to ensure that all available technologies are efficiently put to service to meet the QoS requirements of V2X applications. Design advanced solutions for QoS that will support massive number of machines and fulfill the requirements for low latency and high reliability.
Context Awareness	New approaches for efficient context management schemes for information generated by inbuilt device sensors for the RRM and radio protocols. Big data analytics for V2X could serve for optimized planning of available networks and respective traffic engineering. Application and service aware traffic flow management is also a challenging topic. Issues related to the signaling overhead, the computational load and the relatively big delay caused by the centralized nature of existing solutions should be considered along with reliability and efficiency of data delivery and context.
Security	Novel schemes to ensure required security features should be developed based on established security mechanisms. The demand for authentication, protection of private data, consistency, and misbehavior detection need to be addressed in 5G V2X networks. The overhead introduced by the security features should be reduced and the timeliness of authentication management should be ensured.
Group Management	Novel schemes for dynamic ProSe Group setup and update (join/leave) to support multicast communication (e.g., for maneuvers involving only a small subset of vehicles within an area).
Load Balancing	Novel SL schemes for offloading the infrastructure and achieving significantly lower delay performance, while working under high mobility, requiring QoS guarantees and unicast as well as one-to-all (broadcast) communication. Novel propositions to avoid overload situations in vehicular congestion scenarios. Balancing of sidelink traffic load from highly loaded cells to underutilized cells.
Multihop Routing	Novel schemes for efficient path selection with low protocol complexity and overhead in cases where coverage extension via multihop routing is required.
Positioning	New techniques for increased positioning accuracy (in cm range) of vehicles and VRUs relying on 5G communication systems.
Power Control	New mechanisms for Sidelink (PSSCH, PSDCH) Transmit Power Control, including network controlled and UE autonomous power control.
VRU/V2P	New mechanisms for fast discovery of vehicles and VRUs within close proximity (e.g., via ProSe Direct Discovery) in case of imminent danger, and quick notification to the driver and the VRU in case of detecting a vulnerability situation. New approaches to exploit the forthcoming enhancements of ProSe that 3GPP RAN is currently working on so as to support PC5/Uu transport for V2P services.
Multi-Operator	Inter-PLMN (multi-operator) and roaming procedures for V2X communication.
Multi-Link Connectivity	Novel schemes for the coordination and usage of multi-link (e.g., simultaneous transmission of V2X data over PC5 and Uu interfaces, or even satellite) and multi-RAT approaches for 5G, considering heterogeneous scheduling and traffic flow management with various traffic flows and various available RATs. Optimized routing protocols for multi-RAT and multi-interface communications.

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