



V2X White Paper

v 1.0

V2X White Paper

by NGMN Alliance

Version:	1.0
Date:	17-06-2018
Document Type:	FINAL DELIVERABLE (APPROVED)
Confidentiality Class:	P - Public
Authorised Recipients: (for CR documents only)	

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Approved by / Date:	NGMN Board / 10th July 2018

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Abbreviations

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

3GPP	3rd Generation Partnership Project
APT	Asian-Pacific Telecommunity
BSM	Basic Safety Message
CA	Certificate Authority
CAM	Cooperative Awareness Message
C2C-CC	Car-2-Car Communication Consortium
CCSA	China Communications Standards Association
CDF	Cumulative Distribution Function
CEN	Comité Européen de Normalisation
C-ITS	Cooperative Intelligent Transport System
CRL	Certificate Revocation List
C-V2X	Cellular Vehicle to Everything
DENM	Decentralized Environmental Notification Message
DoS	Denial of Service
DSRC	Dedicated Short-Range Communications
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunications Standards Institute
eDRX	Enhanced Discontinuous Reception
eMBMS	Enhanced Multimedia Broadcast Multicast Service
eMTC	Enhanced Machine Type Communication
FDM	Frequency Division Multiplex
GBA	Generic Bootstrapping Architecture
GLOSA	Green Light Optimized Speed Advisory
GNSS	Global Navigation Satellite System
HAD	Highly Automated Driving
IoT	Internet of Things
ITS	Intelligent Transport System
ITS-G5	Intelligent Transport System @5.9GHz
I2N	Infrastructure to Network
I2N2V	Infrastructure to Network to Vehicle
I2V	Infrastructure to Vehicle
IVI	In-Vehicle Infotainment
KPI	Key Performance Indicator
LTE	Long Term Evolution aka 3GPP 4G system
LTE-A	LTE Advanced
LTE-A Pro	LTE Advanced Pro aka 4.5G system
LTE-M	Long Term Evolution for Machines
LPWA	Low Power Wide Area Network
MAP	MAP data, in conjunction with SPAT messages
MEC	Multi-access Edge Computing
MIMO	Multiple Input Multiple Output
MBB	Mobile Broadband
NB-IoT	Narrow Band IoT
N2V	Network to Vehicle
OBU	On Board Unit
OEM	Original Equipment Manufacturer
OOB	Out of Band



PCA	Pseudonym Certificate Authority
PLMN	Public Land Mobile Network
ProSe	Proximity Services
PRR	Packet Reception Ratio
PSK	Pre-Shared Key
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SCMS	Security Credential Management System
SC-PTM	Single-cell Point to Multipoint
SDO	Standards Developing Organization
SPAT	Signal Phase and Timing Message
TCU	Telematics Control Unit
TLS	Transport Layer Security
UE	User Equipment
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2N2V	Vehicle to Network to Vehicle
V2N2I	Vehicle to Network to Infrastructure
V2X	Vehicle to Everything
VRU	Vulnerable Road User
WLAN	Wireless Local Area Network

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Executive Summary

In June 2016, NGMN created a V2X task force to study and evaluate V2X technologies and requirements and harmonise Mobile Network Operators (MNOs) views on LTE-based V2X and DSRC/IEEE-802.11p. The task force objectives were to reduce time to market of C-V2X technology, and trigger cooperation with the automotive industry in order to create a common understanding and promote NGMN's V2X views. During the work in the NGMN task force the following areas were investigated:

- Technology evaluation of LTE-based V2X and DSRC including link and system level simulations for various scenarios,
- Identifying opportunities in LTE-based V2X for mobile network operators and other stakeholders,
- Various deployment aspects of Connected Car including multi operators and roaming,
- Business model of operating an Intelligent Transport system (ITS),
- Examining available spectrum and regulatory aspects,
- Reviewing security aspects and privacy.

In the study, eight V2X use cases were chosen to reflect the three ITS application types: 1) road safety, 2) traffic management & efficiency and 3) infotainment. They encompassed various C-V2X communication methods: V2V, V2I, V2P, I2V, V2N2V, and N2V. A brief analysis of the technology requirements such as message communication range, vehicle speeds and density, the need for a connection to the application server, and implementation possibilities were examined in task force reports. The work has consciously focussed on the sidelink use cases because network link use cases were expected to be available in most cars in the next few years. Various deployment aspects were extensively discussed amongst MNOs including unmanaged and managed deployments. Unmanaged deployments without MNO involvement are expected initially. Managed deployments where both MNOs and road operators are involved is expected at later phases and was studied extensively.

A generic business model looking at different aspects of investment and revenue models, in addition to the traditional infotainment model has been discussed. This is especially important when legislations are in place for the provision of regulated safety features in cars. It also touched on the anticipated benefits from road safety to the car manufacturing industry and to society in general.

Spectrum and regulatory aspects of the existing ITS spectrum in different regions in the world were surveyed. A recommendation for handling coexistence and harmonisation aspects of ITS spectrum allocation in ETSI were explicitly provided in the reports. In addition, an outline of the latest developments in China on ITS systems deployments was detailed. This is important because C-V2X as the technology of choice in China might have an impact on other regions and regulators in Europe, Japan, and in the US.

Finally, security and privacy of 3GPP V2X was investigated compared to IEEE 802.11p by the NGMN security group and is included as a section in this paper. The section discusses the facilitation of provisioning and management of security certificates by inherent cellular wide area connectivity, and more specifically by using

3GPP's Generic Bootstrapping Architecture. The ways by which 3GPP V2X allows vehicle manufacturers to differentiate were also investigated.

This paper presents a summary of the findings of the NGMN V2X task force and concludes with the following key points:

- To date, NGMN members have provided cellular connectivity to more than 30 million vehicles worldwide which are used for a variety of safety related use cases (e.g. distribution of end of traffic jam warning, black ice warnings, etc.). It is expected that in the near future every vehicle will be equipped with cellular connectivity. This is a good and market driven basis for further deployment of further C-V2X technology and services.
- With the finalization of 3GPP Rel. 14 specifications at the beginning of 2017, NGMN members now have a 3GPP standardized solution, which supports both long range as well short range communication, and which fulfils all the requirements of a C-ITS eco-system.
- After already ongoing tests, the technology will be deployed by 2020.
- NGMN believes that C-V2X is not only able to enhance safety features for vehicles, but also supports use cases for other traffic participants, like pedestrians and cyclists.
- NGMN has investigated and concluded that C-V2X technology is superior to IEEE 802.11p standards, technically, economically, and eco-system wise, and can well satisfy the basic safety applications.
- NGMN studies found the following technical advantages of C-V2X:
 - It has better performance than IEEE 802.11p, e.g. in communication range, latency and scalability;
 - It can be harmonized with cellular technology and easily utilize the benefits of cellular technology, such as improving the penetration of C-V2X based on high penetration of cellular vehicle terminals and mobile phones, disseminating information using cellular broadcast and decrease the investment in infrastructure by reusing already deployed cellular networks.
 - It has a natural evolution path to future advanced applications by updating current networks to 5G.
- NGMN supports the go to market statements from major industry stakeholders, such as car manufactures and chip-set suppliers, and collaborates with the relevant industry associations, like 3GPP, ETSI, and 5GAA.
- NGMN members are engaged with other partners of the eco-system in ongoing tests in various trials worldwide; NGMN fully supports the timeline of go to market for C-V2X technology using chipsets commercially available from major chipset vendors by Q3/2018 for deployment in vehicles at the beginning of 2020.
- There are solutions for major topics for C-V2X market introduction such as security, spectrum, multi operator deployments and others, which are described in detail in this white paper. There are of course also some open issues, which are described in the paper as well.

The paper recommends to the players in the C-V2X eco-system to take notes of the NGMN V2X Task Force studies and findings.

1 Introduction of V2X

1.1 Introduction

In order to reduce the number of road accidents and enhance road safety, vehicles should be able to observe what is happening around them, foresee what will happen next, and take protective actions accordingly. This requires that vehicles have the ability to exchange messages with each other. V2X is one kind of solution which can be considered as a wireless sensor system that allows vehicles to share information with each other via a communication channels. Compared with standard sensors (such as radar, LIDAR, lasers, ultrasonic detectors, etc.) the utilization of a V2X system can get information out of sight, testing hidden threats, expanding the scope of the driver's perception, and as a result improve driving safety, efficiency and comfort as a result of driving automation. C-V2X is therefore also considered more than ever to be one of the key enablers of cooperative automated driving [1].

Today, vehicles are equipped with a range of sensors, driver assistance and safety related systems. Safety and comfort have been further improved by adding cellular communication capabilities to millions of cars and this number is growing rapidly. Many of the use cases described in the ETSI ITS specifications and other documents are already implemented using existing cellular network connections. For example, cellular networks already enable features like slow or stationary vehicles in traffic ahead warnings, road works warnings, weather conditions, hazard warnings, in-vehicle signage and speed-limits.

The telecom industry and the 3GPP standards organization in particular have analysed the ITS use cases and have derived related requirements to LTE. With Rel. 14 of its standard, LTE is enabled to support V2X services taking into account V2X services and parameters defined in organizations e.g. in ETSI ITS or US SAE or by similar governmental organizations. This LTE-V2X Rel. 14, complements cellular connectivity between vehicles and networks/cloud (V2N) with connectivity between vehicles and other vehicles (V2V), road side infrastructure (V2I) and also pedestrians (V2P). In particular, enabling direct V2V and V2I communications in and off network coverage as well as the availability of a proven evolution of cellular network generations are essential steps to support all ITS use cases with a single cellular network technology, keeping the costs in the vehicle at a minimum.

C-V2X which refers to smooth evolution from LTE-V2X to 5G V2X will not only support existing use cases but will also enable completely new applications which will increase traffic safety, transport efficiency and driving comfort to a level which cannot be achieved with the traditional ITS communication technology based on IEEE 802.11p. Since C-V2X relies on 3GPP cellular technologies which have proven ability to adapt to market needs and retain continuous compatibility over several generations of systems, NGNM believes that C-V2X is a superior technology which has the potential to realize the full benefits of C-ITS. It also takes into consideration the huge investment which has already gone into the deployment of cellular networks and will continue to go into their evolution, the large and further growing number of vehicles connected via cellular networks as well as the huge 3GPP based ecosystem of equipment, devices and applications. All those factors will guarantee cost efficient evolution and increasing benefits such as road safety, comfort and traffic optimization.

This white paper describes the technical advantages of C-V2X as well as technological, security/privacy, business and regulatory aspects of its introduction. It also looks at specific developments in various parts of the world.

1.2 General description of the Connected Car Eco-System

Various stakeholders are involved when a vehicle uses a road and other traffic infrastructure, like a parking garage, and every of the involved stakeholders would like to benefit from the added value provided by connectivity. The connected car therefore serves a variety of eco-system stakeholders, each with different requirements.

Car manufacturers and their suppliers are improving the functionality of the vehicle continuously, with the additions of safety functions, comfort functions, efficiency functions and others. For all topics, not only cellular connectivity to backend services, but also direct connectivity between vehicles and vehicles and infrastructure plays an important role for high innovation. Examples are

- **Smart sensors:** with the development of V2V and V2I services 15 years ago, smart sensors didn't exist with mass market characteristics. Also, in this time cellular networks were not able to fully meet the requirements of sharing smart sensor information. Nowadays these sensors (speed limit alerts, distance control, lane keeping sensors, visual object recognition sensors, etc.) together with V2N capabilities (e.g. hazard warnings) are fulfilling a wide range of safety and comfort related services.
- **Crowd sourcing data / swarm intelligence:** Started with traffic flow information and the detection of traffic jams, data analytics based on sensory information of a fleet of vehicles is in the market. Examples of services based on crowd sourced data are the detection of free parking spaces for on-street parking, the detection of road hazards, and of course the widely used real time traffic information services. Sensory information is transmitted via V2N to backend systems, there, the data is analysed and distributed again as a service to other vehicles.
- **Backend processes** become more and more the brain of the vehicle. Therefore, the vehicle must be connected to a variety of backend-services via V2N connectivity. The vehicle might be connected to the **user's/customer's** service environment, for example to the home of the user, the calendar of the user, or the banking account. The vehicle might be connected to services operated by the **car manufacturer** itself, or a fleet operator: Examples are remote software updating procedures, tele-diagnostics and tele services. Alternatively, the vehicle might be connected to **third party service providers**, such as insurance companies, electric power companies, parking service providers, telco operators, and others. Backend services are connected to the vehicle based on cellular connectivity.

Road operators and other **traffic infrastructure providers** are mainly interested in a safe and efficient use of their infrastructure. From a road operator's perspective, a safe traffic flow on the road must be assured. The parking space provider is aiming to organize the usage of parking services as efficient as possible. Every traffic infrastructure provider therefore is providing information about the actual state of their infrastructure, together with predictions via the internet to their customers. V2N connectivity is widely used for the distribution of this kind of

information. It should also be noted that the ITS-RSUs, with the single purpose of the collection and distribution of traffic related information, requires a substantial investment. Existing cellular networks are already being used for a variety of V2V and V2I services initially planned for direct communication, such as weather information, traffic jam ahead warnings, or emergency vehicle approaching warnings. In addition, the deployment of security credentials, their renewals or the distribution of certificate revocation lists, could be distributed via cellular networks. From a customer's perspective, every customer knows about such services based on his or her smartphone experiences.

Regarding V2I and I2V use cases, like GLOSA or speed alerts, it is still an open question as to how to overcome the investment challenge for traffic road side infrastructure. Since this is typically a public infrastructure, public funding is difficult to justify because the benefits of such investments will be perceived in the far future, more than 10 years starting from introduction, and assuming a significant installation rate in vehicles and infrastructure. A parallel introduction therefore of the same use case, but based on an indirect communication path (V2N2I resp. I2N2V) would create benefits much quicker for road users as well as for road operators. One example is the emergency vehicle approaching warning use case: An emergency vehicle is not approaching within a couple of msec, but has its planned path; if such path together with the actual position is distributed via cellular networks, there would be an immediate customer benefit, together with a safer and faster trip of the emergency vehicle itself.

If the customer must pay for road usage, very often special road infrastructure based on CEN-DSRC, or number plate recognition techniques are operated by the road operator (tolling gantries). But even for tolling, systems based on V2N connectivity are in place, producing the tolling transactions with sensorial information of the vehicle and transmitting the transactions via V2N services to backend systems e.g. road pricing systems in EU countries like Belgium and Germany.

As already mentioned above, a variety of **other service providers** around the vehicle need to be connected as close as possible to their customers and their vehicles. Examples are insurance companies and maintenance and repair shops. They get their relevant data, either based on the vehicles installed V2N communication, or based on the connectivity the customer brings into the vehicle with his cellular devices and contracts. V2N communication plays an important role to get access to this kind of information, such as Baidu map providers.

The **mobile network operators and their suppliers** are providing connectivity in various forms as an enabler function for the services mentioned above.

Within the past 5 years, assisted and automated driving functions have had a very high rate of innovation. Together with higher levels of driving automation, now V2V/V2I address mainly new functionalities around situational awareness and cooperative driving needs. Automated driving will be programmed in a conservative driving mode due to safety reasons. With the growing penetration of highly automated driving vehicles, the need for cooperation between the vehicles will increase, which instantly will lead to a broader exchange of information between the vehicles, other traffic participants, and the related traffic infrastructure. Sensor sharing between vehicles, the exchange of planned paths and the negotiation between the vehicles about the driving manoeuvres are examples

for the exchange of rich information. This kind of communication creates new connectivity requirements, which are covered by new standardization efforts in 3GPP and other SDO's (SAE, ...).

If traffic safety is in focus, from an ethical point of view safety should not be related to the individual ability to pay for safety functions. Sometimes it's argued that safety for everybody can only be achieved by mandating V2V/V2I connectivity, to get V2V technologies even into low budget vehicles without investing into high-end sensors. As it would still be a low budget vehicle the customer would be able to benefit from an informational service, still with the need of driver interaction. Generally, informational safety is a low-cost variant. Conversely, active safety includes active control of vehicle behaviour, which results in high costs in the vehicles.

Regarding "safety for everybody", low cost vehicles are equipped already with cellular connectivity. Because its "only" informational safety, the distribution of safety relevant information out of backend-systems via V2N would create much faster a positive safety effect than a distribution via direct communication only. Also, the higher latency would create only a minor negative impact, because the driver has to react anyhow with a latency of about 200 msec.

Prerequisite for V2N is sufficient coverage and throughput of the cellular network. Statistics show that in all industrial countries network coverage has been and will be even more increased to levels above 95%.

1.3 Description of V2X connectivity

Cellular connectivity in the vehicle is a matter of fact because nearly every car manufacturer is equipping newly produced vehicles with cellular connectivity for the following reasons:

- Functional reasons: more and more vehicle related functionality needs backend connectivity, such as map updates, software updates over the air, traffic information and online navigation, remote control functions and others.
- Driver safety reasons: a variety of safety services relying on cellular connectivity, such as eCall, or hazard warnings out of backend services (see e.g. Daimler V2X services[2])
- Customer relationship reasons: because the OEMs can get a much closer contact to their customers, examples are services e.g. tele-diagnostics or preventive maintenance.
- Customers' experience: the customer expects to use the services which they are accustomed to using outside, also inside the vehicle, regardless whether they are the drivers or the passengers. In an automated driving mode the customer will be both the driver and the passenger.

So there is no doubt in the automotive industry that vehicles have to be equipped with cellular technology. With regard to the safety use cases mentioned above, also from a political point of view, the need for cellular connectivity

is evident, as indicated for example in major ITS programs, such as the ITS masterplan of the EU¹, the mandate for the introduction of eCall, and others.

Regarding the V2V/V2I safety use cases which were initially planned in the C-ITS masterplan of the EU, some OEMs have already implemented the majority of these use cases by a combination of smart sensors in the vehicle and information collected from backend services (based on V2N communication). Examples in this area include:

- Forward collision warnings based on crowd sourced sensor information of location and the speed of multiple vehicles (see for example commercial services at HERE, TomTom, Inrix et al.), and
- Hazardous location warnings emanating from a backend service based on emergency brake lights or blocked lanes indicated by crowd sourced vehicle sensor information (see e.g. Daimler, V2X series product).

If a safety function relies on data coming from other cars, and shall provide active safety, the latency of the network must be very limited to not more than 100ms. Otherwise the information has to be transmitted directly between the vehicles, the traffic infrastructure, or the pedestrians, with lower latency. Examples for active safety use cases in ITS are

- direct V2V (Vehicle to Vehicle): e.g. a driving ahead vehicle transmits the CAM (Cooperative Awareness Message) to surrounding vehicles that it brakes, a vehicle which is planning to overtake transmits the CAM to overtake, etc.), and
- V2I (Vehicle to Infrastructure): e.g. a traffic light transmits the estimated signal phase to the surrounding vehicles (SPAT (Signal Phase and Time)), a (mobile) construction works vehicle transmits information about speed limits, blocked lanes and others to surrounding vehicles.

Since more than 15 years in Intelligent Transport Systems (ITS) a worldwide harmonized spectrum in the 5.9 GHz band is dedicated to traffic safety-applications. The IEEE standard 802.11p was chosen as the communication stack for active safety functions. Within that time frame of the past 15 years, authorities, the automotive industry, as well as road operators tried to deploy communication infrastructure in a broader range. But besides a variety of research prototypes and deployments with a small number of vehicles and/or traffic RSUs, this approach was never successful. The only exception is the implementation of Cadillac Vehicle-to-Vehicle in 2017[3] and the announcement of VW to equip their group vehicles (with IEEE 802.11p) from 2019 on.

Now, with the availability of a 3GPP based functionality for direct communication, an alternative to the traditional IEEE 802.11p communication exists, which can combine the strengths of cellular connectivity based on V2N communication with the strengths of direct communication within one, harmonized technology stack. Since in the automotive industry cellular connectivity is needed for a variety of other purposes, the direct C-V2X communication can be established in conjunction with the deployment of cellular connectivity which is done anyway.

¹ EU C-ITS masterplan: a hybrid communication approach is proposed which combines cellular technology with other technologies, e.g. for short range communication. <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016DC0766>



C-V2X entails the Uu based V2N/V2N2V/V2I/V2N2P connectivity with the PC5 based V2V/V2I/V2P connectivity. But because there is no fundamental discussion about the need of cellular based backend connectivity, this white paper concentrates on the benefits of PC5 technology for V2X and how to deploy it. On the other hand, it takes all V2N aspects into account, which needs to be clarified for the introduction of a PC5 based connectivity:

Operationally PC5 can be established between

- vehicle and vehicle (V2V),
- vehicle and traffic-infrastructure or other RSU's (V2I), and
- between vehicle and so-called Vulnerable Road User's (VRU's), whether they are pedestrians, cyclists, motor-cyclists, or other traffic participants (V2P).

Therefore, all the above-mentioned entities are described in the white paper.

The automotive use cases attached to a direct communication mode are mainly safety relevant use cases. So, the communication needs to be established, regardless of network availability. In the case a backend connection cannot be established, the direct (PC5) communication has to function. Because, most likely the entities are using their Uu based V2N connectivity in parallel for other services beside safety, various network operator subscriptions are used. A PC5 based ecosystem therefore needs to be able to work regardless to what mobile operator network the UE is belonging to, which is also discussed in the white paper.

Besides all technical aspects, the direct communication is a specific matter of trust, because normally, no 3rd party, like a network operator, is involved in establishing the communication. If one vehicle is not able to trust the information transmitted via PC5 communication, e.g. a hazard warning as a DENM, it might not make use of this information. The already specified security systems for direct communication are supported fundamentally by C-V2X, because on the one hand all security and data privacy rules can be deployed for the C-V2X direct communication in the same way as they are specified for IEEE 802.11p, on the other hand they benefit from the V2N capabilities for the operational purposes, such as distribution and renewal of certificates and certificate revocation lists.

These are the reasons why this C-V2X white paper focuses on the PC5 direct communication with special regard to

- different types of C-V2X UE's (vehicles, pedestrian, road side infrastructure) involved,
- different network providers involved, including that no network coverage exists, and
- The security management system components which establishes a level trust between the various entities.

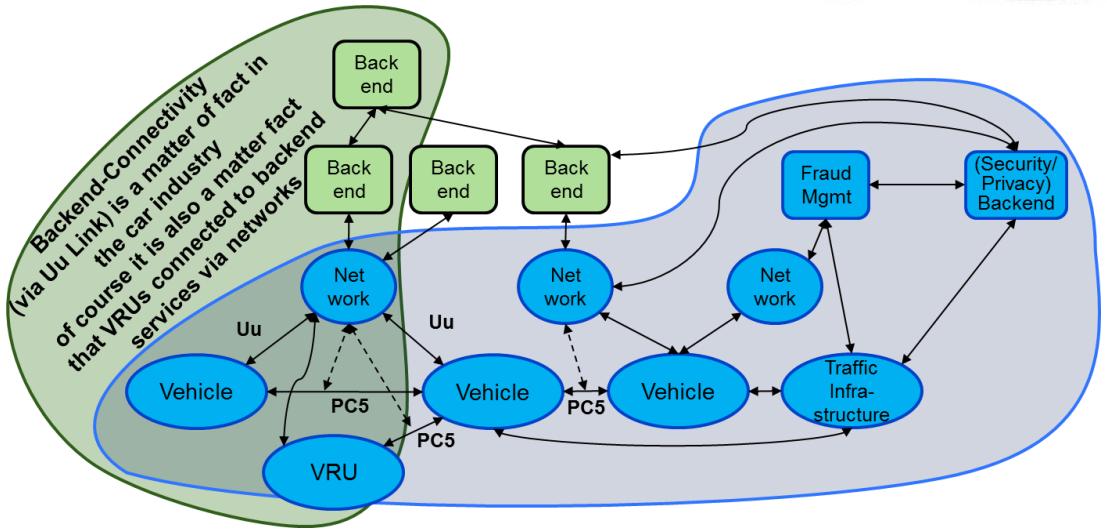


Figure 1.3-1 Illustration of the Focus of the White paper in blue

1.4 Use cases and application requirements

Different standard organizations and industry alliances have defined the use cases and application requirements of V2X. Some of them are global standard organizations, such as 3GPP. The others are regional standard organizations such as ETSI, C2C-CC in Europe, US-SAE, CCSA, C-ITS and SAE-china in China. In general, the V2X applications can be categorized into three types: road safety, traffic management & efficiency and infotainment. Annex A describes some typical use cases. Some of the use cases are event triggered such as traffic jam or road work warnings and some require frequent and periodical transmission such as Intersection Collision Warning. The requirements of the different use cases in each application type are very similar however, the requirements for different application types are diverse. The following are requirements of these typical applications.

Road safety application

The main objective of road safety application is to reduce traffic collision and improve road safety. The main requirements are the following:

- ✓ **Coverage**

Vehicle/pedestrian/RSU shall be able to communicate with adjacent vehicle/pedestrian/RSU. The communication happens mainly in a single hop coverage. It requires that vehicle/pedestrian/RSU shall be able to transmit and receive messages in and off network coverage.

- ✓ **Latency**

In order to avoid collision, the end to end latency is required to be very low between a vehicle, a pedestrian and a RSU.

- ✓ **Reliability**

For road safety applications, the reliability of communication shall be very high regardless of in coverage and off coverage.

- ✓ **Throughput**

Throughput is very limited.

- ✓ **Predictability**

Because the network is not able to provide coverage, latency, reliability in every kind of situation, it is important to get information about when and where network KPI can't be fulfilled.

- ✓ **Communication range**

The communication range is mainly determined by vehicle velocity, the driver reaction time and acceleration.

- ✓ **Velocity**

The vehicle could be at a very high absolute velocity (250 km/h). The maximum relative velocity is twice as high as the absolute velocity.

- ✓ **Multi-operator's operation**

It requires that the communication system shall be able to support message transfer between a vehicle, a pedestrian and a RSU when served or not served by the same Public Land Mobile Network (PLMN) supporting V2X communications.

Traffic management & efficiency application

The primary objective of traffic management & efficiency applications is to improve traffic fluidity. The main requirements are as follows:

- ✓ **Coverage**

Vehicle/pedestrian/RSU shall be able to communicate with adjacent and remote vehicle/pedestrian/RSU. It requires that vehicle/pedestrian/RSU shall be able to transmit and receive messages in and off network coverage.

- ✓ **Latency**

Different use cases have different latency requirements.

- ✓ **Reliability**

The reliability of communication should be high because a loss of communication would result in a loss of traffic management services.

- ✓ **Throughput**

Throughput can be high, e.g. navigation map data has been provided and updates continuously

- ✓ **Predictability**

Because the network is not able to provide coverage, latency, reliability in every kind of situation, it is important to get information about when and where network KPI can't be fulfilled.

- ✓ **Communication range**

The traffic management services have a long communication range as well as a short communication range.

- ✓ **Velocity**

The vehicle could be at very high absolute velocity (250 km/h). The maximum relative velocity is twice as high as the absolute velocity.

✓ **Multi-operator's operation**

It requires that communication system shall be able to support message transfer between a vehicle, a pedestrian and a RSU when served or not served by the same PLMN supporting V2X communications.

Infotainment application

Infotainment application provides the local and global internet services by advertising and providing on-demand information to passing vehicles on either a commercial or non-commercial basis. The objective of infotainment applications is to make drivers and passengers convenient and comfortable, and allow the OEMs to manage the customer relationship over the vehicles life cycle.

✓ **Coverage**

Vehicles can move everywhere. Coverage is a prerequisite to provide the continuous infotainments.

✓ **Latency**

The latency is not critical for infotainments reliability

✓ **Reliability**

a prerequisite to provide the continuous infotainments.

✓ **Throughput**

Throughput can be very high. For example, the throughput requirements of several passengers in one vehicle watching individual video streams.

✓ **Predictability**

Because the network is not able to provide coverage, latency, reliability in every kind of situation, it is important to get information about when and where network KPI can't be fulfilled.

✓ **Communication range**

The infotainment services have a long communication range as well as a short communication range.

✓ **Velocity**

The vehicle could be at very high absolute velocity (250 km/h). The maximum relative velocity is twice as high as the absolute velocity.

✓ **Multi-operator's operation**

There are no additional requirements for multi-operator operation, compared to today's mobile broadband services and existing roaming agreements.

To summarize, communication varies from in coverage to off coverage scenarios. The latency ranges from 50 ms and below to more than 1s. The reliability varies from low (best effort) to high ("five 9's"). The throughput ranges from several kbit/s to tens of Mbit/s. The communication range varies from short range (300 m and below) to long range above 2 km. The absolute velocity ranges up to 250km/h and the relative velocity is up to 500km/h. Actually, some use cases have been deployed by current cellular communication technology, except for those use cases requiring low latency and high reliability. In order to support all these use cases and meet these diverse requirements of V2X, the enhancements of Rel. 14 based on LTE are introduced.

2 Technology overview of C-V2X

In 2015, 3GPP specified V2X features to support V2X services based on the LTE system in Rel. 14. The V2X specifications cover vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) requirements and the first publication of the specifications were in September 2016. Further enhancements to support additional V2X operational scenarios in Rel. 14 were completed in June 2017 [4]. V2V communications are based on Device-to-Device (D2D) communications defined as part of Proximity Services (ProSe) services in Rel. 12 and Rel. 13 of the specifications [5]. As part of ProSe services, a new D2D interface designated as PC5 was introduced to support enhanced vehicle to vehicle communication use cases, specifically addressing enhancements to support vehicles communications V2X requirements. Enhancements were introduced in order to handle high relative vehicle speeds (Doppler shift/ frequency offset) up to 500Km/h, synchronisation operation outside eNB coverage, improved resource allocation, congestion control for operation in high traffic load, and sensing and traffic management for different V2X services.

Two modes of operation for V2V communications for LTE based V2X were introduced in Rel. 14: 1) communications over peer to peer PC5 interface (V2V) and 2) communications over LTE-Uu interface (V2N). V2V communication over PC5 interface is supported via two modes: managed mode (PC5 Mode 3) which operates when the Vehicle UE is scheduled by the network, and unmanaged mode (PC5 Mode 4) which operates when the vehicle UEs communicate independently from the network as shown in Figure 1.4-1. PC5 Mode 4 scheduling and interference management of traffic is supported based on distributed algorithms between vehicles while PC5 Mode 3 scheduling and interference management of V2V traffic is assisted via the base station (eNB) by control signalling over the Uu interface. Both single and multi-operators, deployment scenarios are supported with the additional benefits arising from the use of the Uu based connectivity in conjunction with broadcast services.

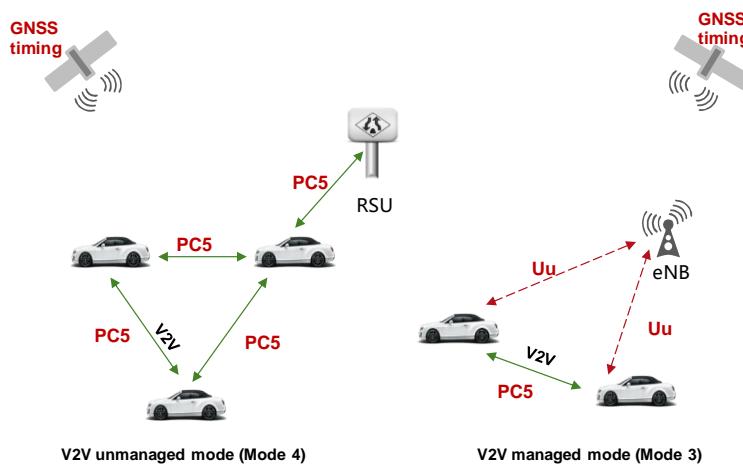


Figure 1.4-1 Vehicle to Vehicle direct communication modes of operations

2.1 Description of C-V2X Technology

3GPP both enhanced the Uu interface (indirect communication) and PC5 interface (direct communication) to support the low latency and high reliability V2X service. The sidelink was specified to operate either overlaid to cellular spectrum or in dedicated bands. Device-to-Device (D2D) operates on Uplink (UL) carrier for FDD spectrum while for TDD spectrum it operates on UL subframes. In terms of the communication link D2D communication can be either unicast or broadcast using open-loop communication. Support of Quality of service (QoS) via per packet priority and UE-to-network relaying were added later on in Rel. 13. D2D communications operate in two modes: Mode 1 (network scheduled) in which the UE requests resources and eNB schedules; Mode 2 works as an autonomous mode which uses a resource pool configuration, e.g. via eNB, and the UE selects autonomously D2D resources from the pool. In order to have an efficient D2D communication, a common time reference is needed. Local synchronization is achieved by a distributed synchronization protocol, which includes relayed distribution. Detail descriptions of the D2D feature can be found in[6][7][8].

Some of the key areas of enhancements were added to the D2D feature in order to support V2V communications:

- Mode 1 from D2D was enhanced to mode 3 for V2X, similarly, mode 2 from D2D was enhanced to mode 4 for V2X.
- Additional reference symbols to handle high Doppler associated with relative vehicle speeds up to 500km/h were introduced.
- A new arrangement of scheduling assignments and resource allocation to allow reduced latency and better performance in high vehicle densities was developed.
- Sensing with semi-persistent transmission based mechanism for the unmanaged or off coverage mode (mode 4) was incorporated, in order to sense congestion on resources and estimate future congestion on those resources.
- Enhancements were included to use GNSS for time synchronization in the off coverage scenario.

Additional enhancements to the Uu interface to improve the latency, capacity, and reliability performance of LTE Uu interface by enhancing UL unicast and DL multicast/broadcast including:

- eMBMS enhancements by shortening the Multicast Control Channel (MCCH) repetition time
- introducing the new QoS for V2X services
- localize the eMBMS deployment to minimum backhaul delay

2.2 Architecture of C-V2X Technology

As shown in Figure 2.2-1, the UEs within the system can communicate with each other through PC5 and LTE-Uu interface. A new module “V2X control function” is introduced in the V2X architecture. The V2X Control Function is a logical function that is used for network related actions required for V2X which is used to provision the UE with necessary parameters in order to use V2X communication. It is used to provision the UEs with PLMN specific configuration parameters that allow the UE to use V2X in this specific PLMN. V2X Control Function is also used to provision the UE with configuration parameters that are needed when the UE is not served by the network (off coverage).

It should be noted, that mode 4 works even without a valid MNO subscription in the vehicle (e.g. the subscriber contract is not prolonged). In that case, mode 4 operates with the parameters preloaded to the PC5 modem.

For the application domain, a new server called “V2X Application Server” is introduced into V2X communication system to process the data of V2X communications. V2X server is an important carrier of V2X applications. Currently, there are many possibilities for the operation of V2X application servers such as OEMs, MNOs, ITS service providers, and third parties. In order to meet different needs of V2X applications, V2X application servers can be deployed in different places, e.g. at the edge of the network. For this purpose, there is currently a work-item in ETSI MEC on V2X API, standardizing solutions in that perspective. Such edge application servers can co-exist with the central application servers, and will play an important role in many V2X use cases such as HD map download.

Also, security in a V2X system is important. All communication through LTE Uu and PC5 interfaces need to be protected. Security features will have to provide original message authentication, integrity, optional encryption, and privacy protection in either network or application layer.

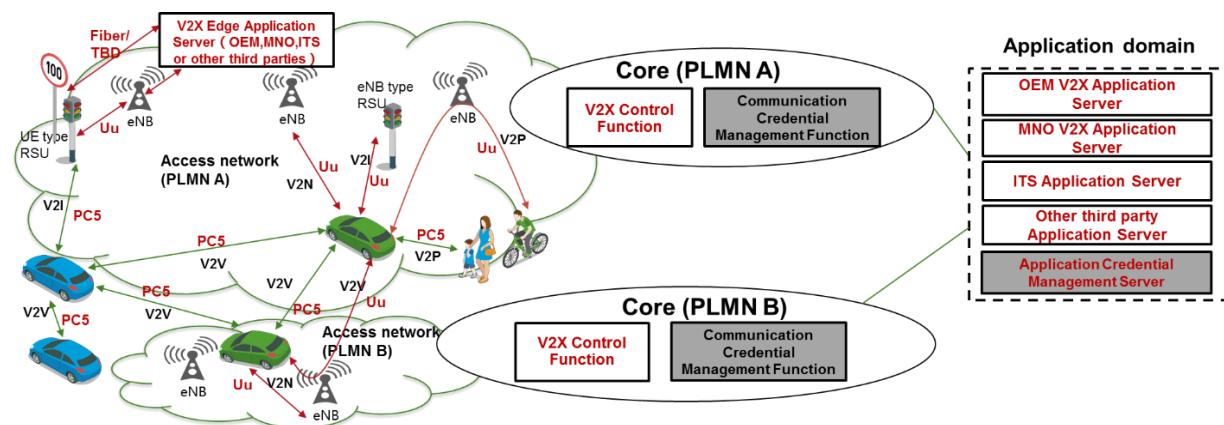


Figure 2.2-1 Architecture of C-V2X technology

3 Advantages of C-V2X

Adding to V2N the introduction of C-V2X for V2V and V2I has a variety of advantages.

There are technical advantages described in various white papers and documents; e.g. from GSMA [9][10] and 5GAA[11][12], like

- technical performance,
- scalability,
- harmonized cellular technology stack,
- usage of cellular broadcast technologies, and
- functional redundancy.

There are also several non-technical advantages, like

- penetration with communication technology and the size of the eco-system,
- ease of upgrading of existing networks,
- possibility of including other traffic participants, such as Vulnerable Road Users (VRUs), into the eco-system,
- synergies of infrastructure investments between road operators and telco operators, and
- future proof and evolution road-map in 3GPP standardization, which has its evidence in the track record of innovation in the 3GPP eco-system.
- Synergies with other verticals that are currently supported by 3GPP such as IoT, public safety, etc.

In the following chapters, the technical as well as the non-technical advantages are described in detail.

3.1 Performance comparison between IEEE 802.11p (DSRC) and LTE-V2X

Within the NGMN task force on V2X, a number of companies (Datang, Ericsson, Huawei, LGE, Nokia) provided comprehensive simulation results on link level as well as system level for LTE-V2X PC5 compared to DSRC/802.11p. The simulation considered both mode 4 and mode 3 on system level. The simulation assumptions and parameters are described in Annex B. The results in this section are excerpts from the detailed system level simulations.

The following three figures show the system performance results that are provided by different companies to compare 3GPP LTE-V2X Mode 3, Mode 4 and IEEE 802.11p. The bar graphs show on the y-axis the communication range achieved in the specific scenario that is stated on the x-axis, assuming in Figure 3.1-3 a PRR of 80%, a PRR of 90% in Fig. 3.1-4 and a PRR of 95% in Fig. 3.1-5. Each figure covers results related to four scenarios:

- Urban environment with average speeds of 15 km/h and 60 km/h
- Freeway environment with average speeds of 70 km/h and 140 km/h

For each scenario and technology, the middle bar shows the average value of SLS results provided by the different companies. In those simulations where only one company provided simulation results, only the middle bar is presented. The narrow bars beside the average present minimum and maximum values. It is obvious from the results that 3GPP LTE-V2X outperforms IEEE 802.11p in all scenarios. The communication range for LTE-V2X mode 3 and mode 4 is always larger than the range achieved with IEEE 802.11p.

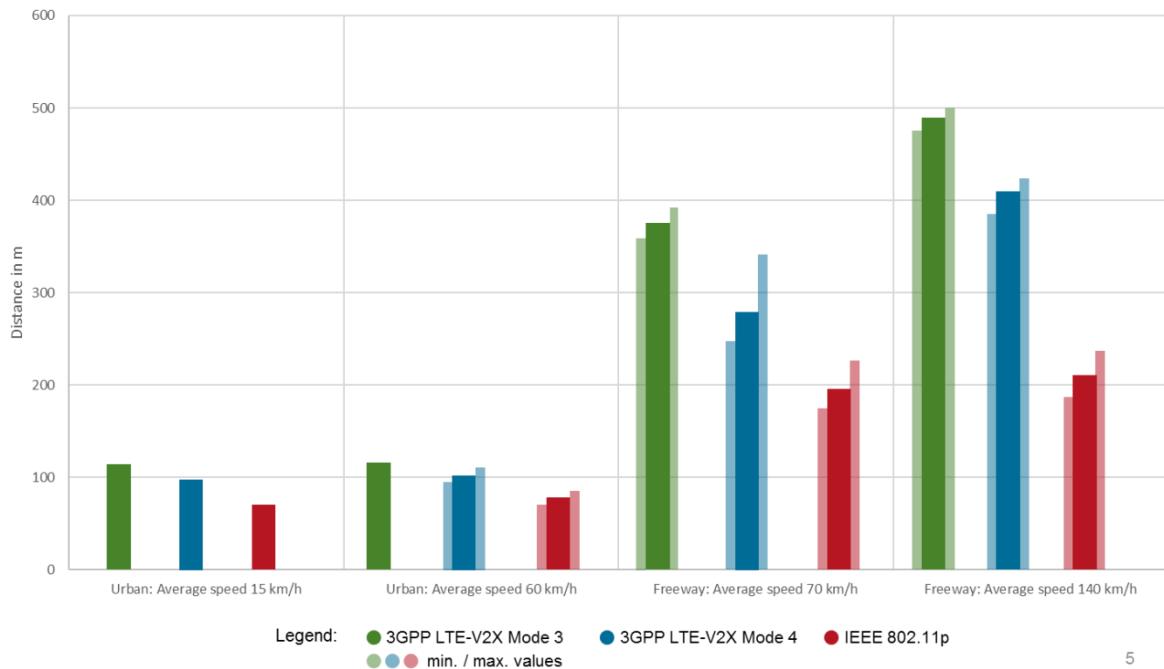


Figure 3.1-1 Comparison SLS Results – 80% PRR – IEEE 802.11p vs Mode 4 vs Mode 3, driving scenarios Urban (15 km/h and 60 km/h), and Freeway (70 km/h and 140 km/h)

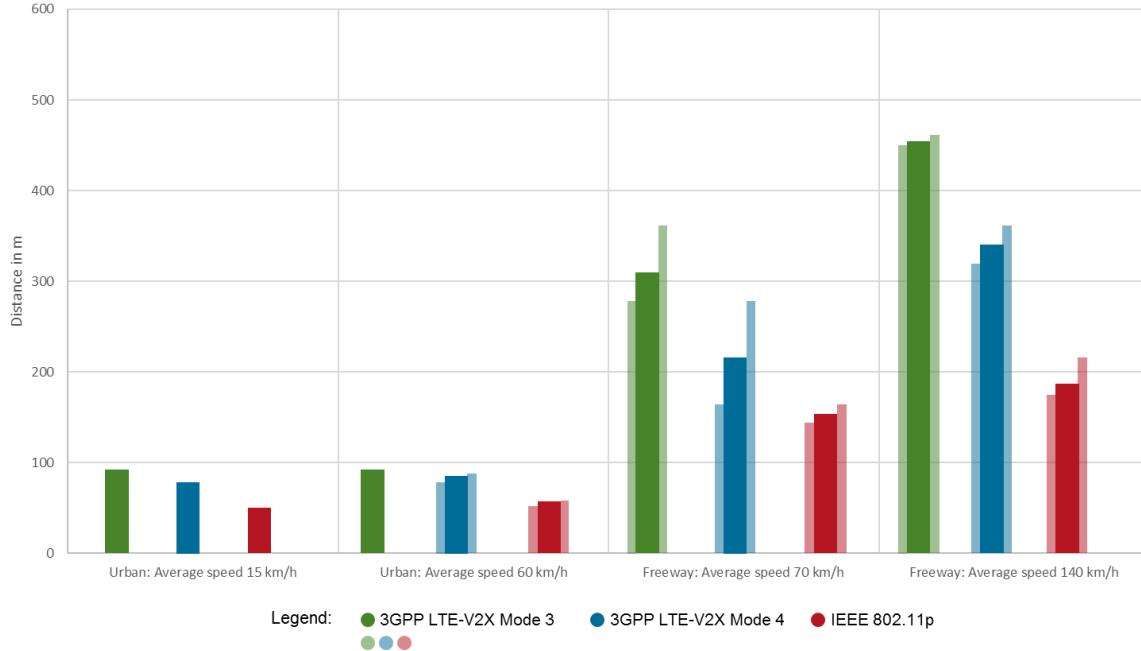


Figure 3.1-2 . Comparison SLS Results – 90% PRR – IEEE 802.11p vs Mode 4 vs Mode 3, driving scenarios Urban (15 km/h and 60 km/h), and Freeway (70 km/h and 140 km/h)

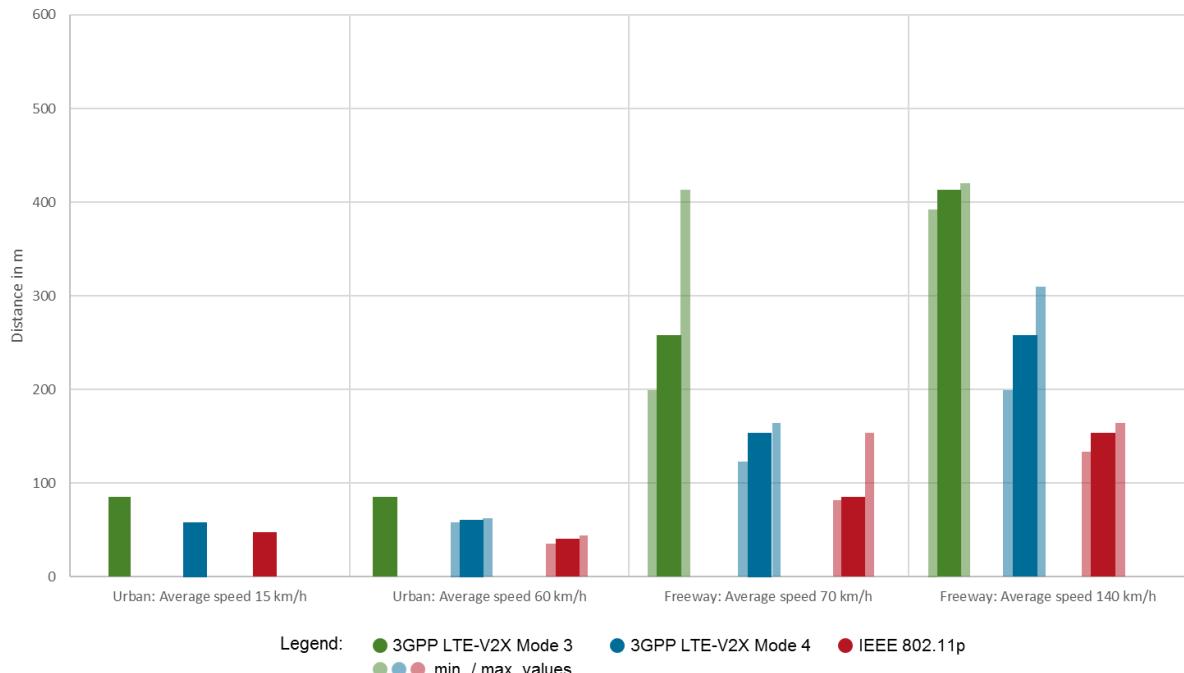


Figure 3.1-3 . Comparison SLS Results – 95% PRR – IEEE 802.11p vs Mode 4 vs Mode 3, driving scenarios Urban (15 km/h and 60 km/h), and Freeway (70 km/h and 140 km/h)

The SLS result, when operating 3GPP LTE-V2X mode 3, shows in all evaluated scenarios the largest (green bars) communication range, whilst IEEE 802.11p shows the smallest communication range (red bar). The results for

3GPP LTE-V2X mode 4 shows communication range larger than IEEE 802.11p, but smaller than 3GPP LTE-V2X mode 3. For 3GPP LTE-V2X mode 4, the channel resources are scheduled in a decentralized manner among UEs based on channel sensing. The main contributing factors to the improved performance of 3GPP LTE-V2X mode 4 over DSRC include

- Sensing capability: Utilizing the periodic nature of ITS messages in both time and frequency domains
- Frequency Division Multiplex (FDM): Radio resource multiplexing amongst vehicles
- Link level performance: Improved channel coding and FDM gain

The main improvement from 3GPP LTE-V2X mode 3 is the centralized scheduling mechanism, which: improves interference avoidance through eNB controlled radio resource assignment²

LTE-V2X mode 3 shows some gains compared to LTE-V2X mode 4 in scenarios where vehicles are exposed to high interference power from nearby UEs transmitting at the time. Note, some simulations of LTE-V2X mode 3 have been done in ideal conditions, not taking into account low accuracy of vehicle positions, the number of served vehicles, and the changing periodicity of the ITS messages (CAMs and BSMs). Moreover, semi-persistent scheduling is assumed. Also, in reality, there will be a mix of vehicles in mode 3 and mode 4, which has not been considered in the simulations.

From the larger communication range of 3GPP LTE-V2X compared to IEEE 802.11p an equivalent benefit for the drivers can be derived:

- The increased communication range of 3GPP LTE-V2X with respect to IEEE 802.11p provides evident safety benefits, as the drivers have a higher chance to get safety information sooner due to the larger communication range. As a consequence, more time is given to a driver to prepare, since the approaching vehicles can be informed in advance by LTE-V2X in comparison to IEEE 802.11p. This gives an evident additional gain for the driver in terms of time margin for reacting to sudden behaviours or accidents;
- A larger communication range includes more vehicles. Drivers can also have a higher chance to get informed in time as they have more vehicles within the communication range.

3.2 Scalability

Scalability issues are attracting attention especially in the presence of both a high density of vehicles and complex movement behaviours. The high vehicle density scenario, such as speed of 15km/h in urban, is evaluated in SLS to investigate the scalability performance, i.e., to examine how reliably basic safety features can be served in such a high vehicle density case. The average PRR performance versus distance is compared of LTE-V2X PC5 mode 3 and mode 4 with that of the IEEE 802.11p. The asynchronous Enhanced Distributed Channel Access (EDCA) mechanism of IEEE 802.11p is considered. The congestion control schemes defined in 3GPP Rel-14 however are

²Compared with the decentralized scheduling of Mode 4 operation, the centralized scheduling of mode 3 operation requires additional signaling communication over the Uu interface between the UE and the eNB on a separate frequency band.

not included in SLS results. Based on the results of SLS in Section 3.1, it demonstrates that both LTE-V2X PC5 mode 4 and mode 3 can guarantee a significantly larger communication range than IEEE 802.11p for a given reliability requirement both in urban scenarios and in freeway scenarios (in particular in the urban scenario of absolute speed 15km/h). Under the same density of vehicles, the performance of LTE-V2X is better than IEEE 802.11p, which also means that 3GPP LTE-V2X is more scalable than IEEE 802.11p. Based on the SLS results, for the given reliability, the larger communication range of LTE-V2X PC5 mode 4 and mode 3 than IEEE 802.11p can be achieved. The spectrum for vehicular communications can therefore be more efficiently utilized. In the particular area, a higher amount of vehicular communication links can be supported with an acceptable reliability.

It is noted that simulations under ideal conditions show that performance of LTE-V2X PC5 mode 3 is slightly better than LTE-V2X PC5 mode 4, however considering the penetration rate (discussed below in Section 3.4) mode 4 would suffice for many years to come. NGMN believes therefore that mode 4 is a good starting scenario for V2X/PC5 communication, which can be easily scaled up to a mode 3 operation when needed.

3.3 Harmonized Cellular Technology

Cellular modem chipsets have been already integrated into commercial modules that are an integral part of the Telematics Control Unity (TCU) of modern vehicles. The modules are designed by specialized suppliers and prepared to fulfil the automotive requirements, the so-called automotive grade, e.g. temperature resistance, vibration etc.. Those existing automotive cellular modules enable current and future automotive and ITS applications, such as toll collection, on-board vehicle telematics and fleet management, in-vehicle infotainment (IVI) systems, breakdown support or roadside assistance. Those modules also typically combine cellular modems with GNSS receivers, WLAN capabilities, application processors, etc. Inside the modules, the cellular modem chipsets are integrated systems compatible with 2G, 3G and 4G technologies. More recently, modem chipset vendors have also added 5G to this list for future products.

With the 3GPP LTE Rel.14 specifications, cellular modem chipset vendors started to introduce sidelink/PC5 in the feature set of their cellular V2X products. There are two basic approaches for the introduction of V2X sidelink/PC5 enabled chipsets:

- Standalone cellular V2X sidelink in a companion chip, or
- Integrated cellular V2X in a single chip.

Each of the approaches can be detailed as follows:

- Standalone V2X chip is a dedicated sidelink/PC5 chip package that provides only V2V capabilities. It can provide mode 4 only capabilities providing a similar solution as a DSRC standalone chip. It has the potential to be combined with different cellular products and possibly with chipsets from other vendors. It is a foreseen solution for the short term and initial deployments. Those standalone chips allow module

manufacturers to combine cellular modem chips from different manufacturers allowing them a higher level of flexibility. On the downside it increases the system integration effort and the number of suppliers in the chain, resulting in higher overall costs.

- An integrated V2X solution shares existing modem features, capabilities and resources between sidelink/PC5 and downlink/uplink/Uu interfaces. It clearly reduces area and system integration effort for module and TCU manufacturers, and, as a consequence, for automotive OEMs. Fully integrated solutions also permit an easier future deployment of sidelink/PC5 in smartphones and wearables to support V2P and P2V use cases. It is much simpler and straightforward to provide mode 3 support in an integrated modem. Moreover, an integrated modem is a long-term solution and extremely necessary due to the support of several generations of cellular technologies, i.e. 2G, 3G, 4G and 5G.

Independent if the sidelink/PC5 modem is provided as a standalone or integrated solution, chipset vendors are able to reuse a number of intellectual property blocks developed for cellular technology, especially in the physical layer subsystem.

The protocol stack of the sidelink/PC5 access layers has many commonalities with the 3GPP downlink/uplink/Uu interface, such that an integration further reduces complexity, software and memory size, and therefore further reducing chip area.

Higher layer protocols, i.e. above the access layer, are the same for DSRC and 3GPP LTE-V2X systems. In some use cases the higher layer protocols will be employed for communication through the downlink/uplink/Uu interface. An integrated sidelink/PC5, uplink and downlink/Uu solution would be beneficial for those use cases also.

This all reduces the development time, complexity and overall chipset costs.

3.4 Penetration rate challenge for sidelink communication

As C-V2X sidelink (PC5) as well as 802.11p are a direct communication technology, the user perceives only a benefit, if the vehicle is in the near vicinity (approx. 300-400m distance) of another vehicle which is also equipped with C-V2X sidelink (PC5) or 802.11p respectively. The penetration rate of vehicles equipped with direct communication is therefore highly critical for the effectiveness of V2V use cases.

As an example, in Europe there are approx. 290 Mio passenger vehicles registered. Every year, approximately 16 Mio new passenger vehicles are sold in the market. Based on different introduction scenarios, such as mandating for every sold vehicle, mandating for every new vehicle type-approval, etc., studies showed that a penetration rate of 20% is realistic between 6-8 years from the point of starting the delivery of sidelink-equipped vehicles (see. e.g. introduction scenarios Figure 3.4-1). For the day-one use cases of the EU C-ITS masterplan, first effects of a direct communication technology are perceived with a penetration rate of more than 20%.

Every technology which uses direct communication methods has to overcome the introduction barriers of sidelink. Whether it's the private investment into a new vehicle, or the public investment into a traffic roadside infrastructure, the investor has to accept that only after a period of 6-8 years the first benefits of the investment can be achieved.

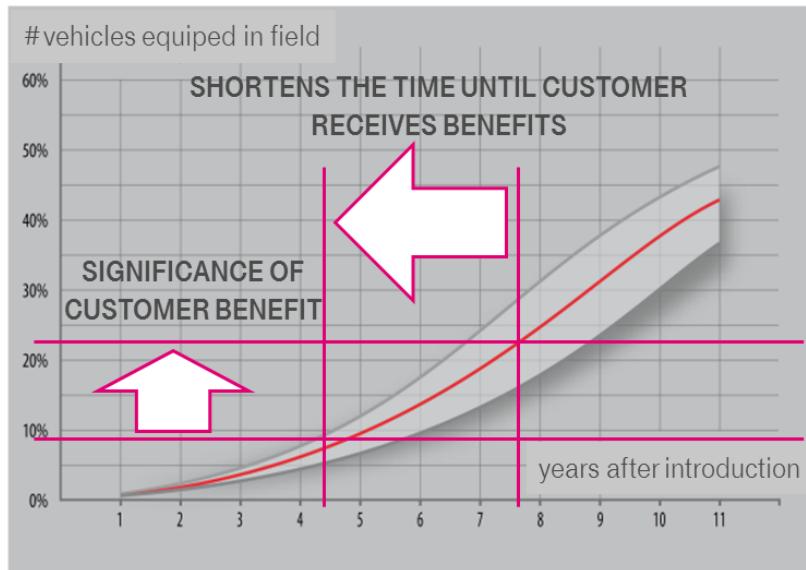


Figure 3.4-1 Expected penetration rate of sidelink communication technology in the field after start of deployment (see SimTD³), and the effect of parallel communication of messages on sidelink (PC5) and network (Uu) channel

NGMN therefore believes that the mixed introduction of C-V2X sidelink (PC5) and C-V2N (Uu) connectivity is the appropriate way to get the customer's acceptance. If for example a DENM or BSM was sent out in parallel on sidelink/PC5 channel and network/Uu channels, it would enable vehicles that are equipped with V2N only modules to receive this message. This would instantly generate a benefit for vehicles equipped with PC5 capable modules, because other vehicles not equipped with PC5 are able to react accordingly. Also, vehicles equipped with V2N/Uu only modules would transmit and receive DENM/BSM on the Uu, and would be able to benefit from these messages even without the presence of PC5 capable modules in the vehicle.

³ http://www.simtd.de/index.dhtml/object.media/deDE/8013/CS-/backup_publications/Informationsmaterial/simTD_factsheets_2013_de_web.pdf, page 24

Table 3.4-1 Car-to-X via Cellular Radio in E-Class 2016 (presented by Daimler at 5GAA policy debate “Cellular V2X technology paving the road to 5G”, Dec. 5th, 2017, Brussels. Presentation title: “Daimler’s perspective on Car-to-X Technologies”)

Event	Triggering Conditions	Icon on Map	Speech output
Broken down vehicle	Vehicle system signals		Yes
Vehicle accident	Air bag inflation and others		Yes
Hazard lights	Hazard light on		Yes
Heavy Rain	Highest wiper level for 20 s		No
Slippery road	Antilock braking system intervention		No
Fog	Rear fog light on		No
Mobile work zone	External data from work zone trailers		Yes
General Warning	Driver manual input		Yes

Table 3.4-1 shows, how a premium vehicle manufacturer already uses the V2N/Uu for message distribution to other vehicles in the vicinity. Several announcements of car OEMs indicates, that V2X messages are not only distributed within a dedicated OEM fleet, but also are shared between several car OEMs. To that effect, data aggregators and map providers, e.g. HERE and TomTom are playing an important business role in sharing and distributing of such safety related messages.

Also for traffic road side units, e.g. traffic lights, the parallel distribution of some of the messages for a GLOSA (Green Light Optimal Speed Advisory) service, e.g. SPAT/MAP message, via I2V/sidelink (PC5) and I2N/network (Uu) would create instant benefits for those vehicles that are equipped with a V2N capability only⁴. Also for signage applications, which are already supported by advanced sensor technology like in-vehicle signage, in-vehicle speed limits, or signal violation, the distribution via I2N would create immediate benefits.

NGMN believes therefore that for investments in traffic infrastructure, it is worth to invest into a combined message distribution with C-V2X technology, PC5 and Uu.

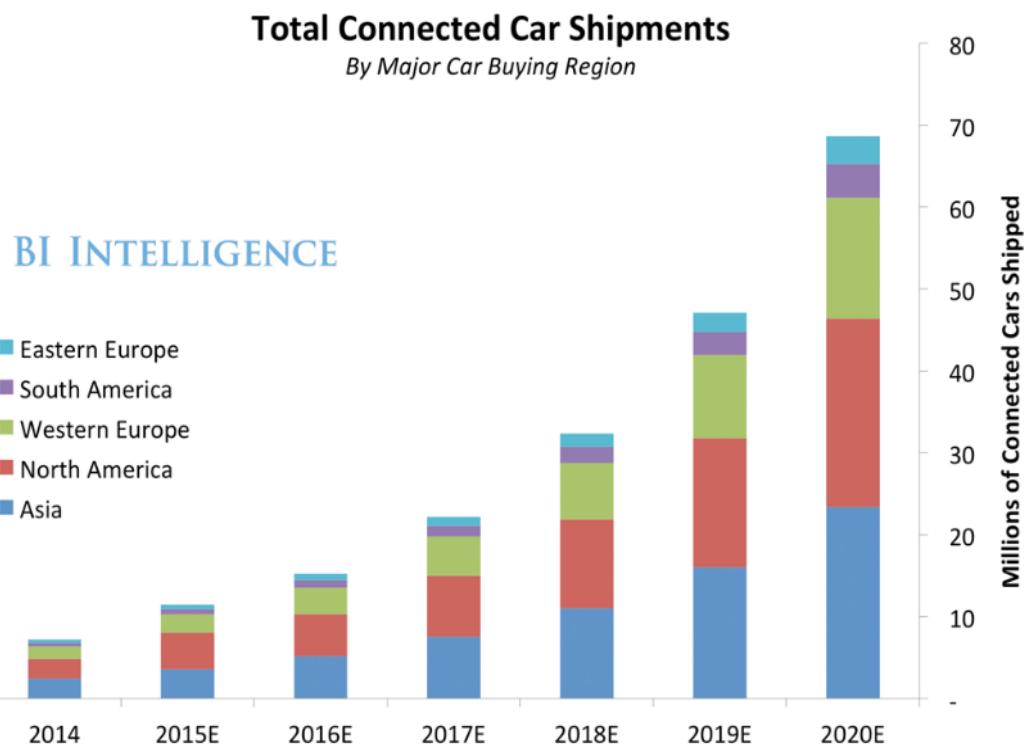
3.5 Dissemination of information using cellular broadcast

With over 30 Millions of connected cars running on the road worldwide, automotive OEMs are finding ways to produce vehicles that are more aware of their surroundings. Key OEMs are planning to spend \$35 billion per year⁵ across autonomous, connected and electrification strategies until 2025 to develop advanced vehicle technologies globally. Autonomous technologies continue to be the largest investment, averaging \$1.4 billion per OEM between

⁴ Note that for these kind of use cases the latency argument is not the relevant argument for PC5, but the reliability argument, because the PC5 would work regardless whether the network is available (V2N) or not (PC5).

⁵ per Frost and Sullivan research in August 2017

2015 and 2025. Sending information to these cars is important for a variety of different use cases. Mobile network operators have the tools and capabilities to disseminate C-V2X information to vehicles via different transmission methods such as unicast, multicast and/or broadcast. The choice of the transmission method depends on many factors and up to operators' deployments and customers' requirements.



BUSINESS INSIDER

Figure 3.5-1 Scotiabank, BI Intelligence Estimates 2015

LTE Broadcast's one-to-many capabilities (also known as eMBMS, and LTE Multicast) has been used to offload the bandwidth intensive media content like video streaming to achieve spectral efficiency. However, this technology can also be used to communicate messages between vehicles with or without C-V2X capabilities. For example, when a C-V2X enabled vehicle generates safety messages, the messages can be sent to other vehicles in the vicinity with or without C-V2X capabilities. Furthermore, the generated safety messages can be sent via LTE Broadcast to road operators or emergency services to provide the appropriate support if necessary.

It's worth noting that there is another radio efficient broadcast technology called Single-cell Point to Multipoint (SC-PTM). SC-PTM reuses the existing LTE Broadcast architecture, but the multicast area can be dynamic and can be targeted to a single cell. This is important when there is requirement to target appropriate messages to different smaller target areas.



3.6 Functional redundancy and resilience

In general, as a measure of increased reliability, the PC5 interface between vehicles and RSUs and the Uu interface between vehicles and the network can be used as functionally redundant communication channels. Redundancy can be supported on:

- physical communication level using different spectrum/frequencies, protocols, and possibly hardware components
- application level using different application modules linked with the physical levels

The duplication of messages via relatively independent channels can reliably support very critical safety use cases. The use of the Uu interface benefits also from the inherent broadcast mechanisms leading to a more efficient use of spectrum. In addition, the use of edge computing can also be considered as a concept of increasing local resilience. The seamless access to the edge cloud and the local applications running on it would also be possible if elements of the core network or links to the central clouds via external gateways failed.

3.7 Ease of Upgrading Existing Network Technologies

3GPP based Cellular-V2X technology can address all known use cases and can also address future ITS use cases offering full flexibility for different business models. LTE is a globally deployed technology and therefore meets the requirements of a globally organized automotive industry. When augmented with Multi-access Edge Computing (MEC), LTE advanced, LTE-Advanced Pro, NB-IoT and LTE vehicle-to-everything (V2X), it provides a viable and cost-effective solution that can accelerate the adoption of V2X communications by transport authorities and the automotive industry. LTE is continuously evolving and 3GPP continues to standardize the building blocks for this evolution path towards 5G (Rel. 15 onwards) bringing great enhancements in radio performance. In particular, starting with LTE Advanced Pro, multi-Gbps data rates, higher spectral efficiency and latency in the order of a few milliseconds are supported, enabling a number of new application scenarios for vehicular connectivity.

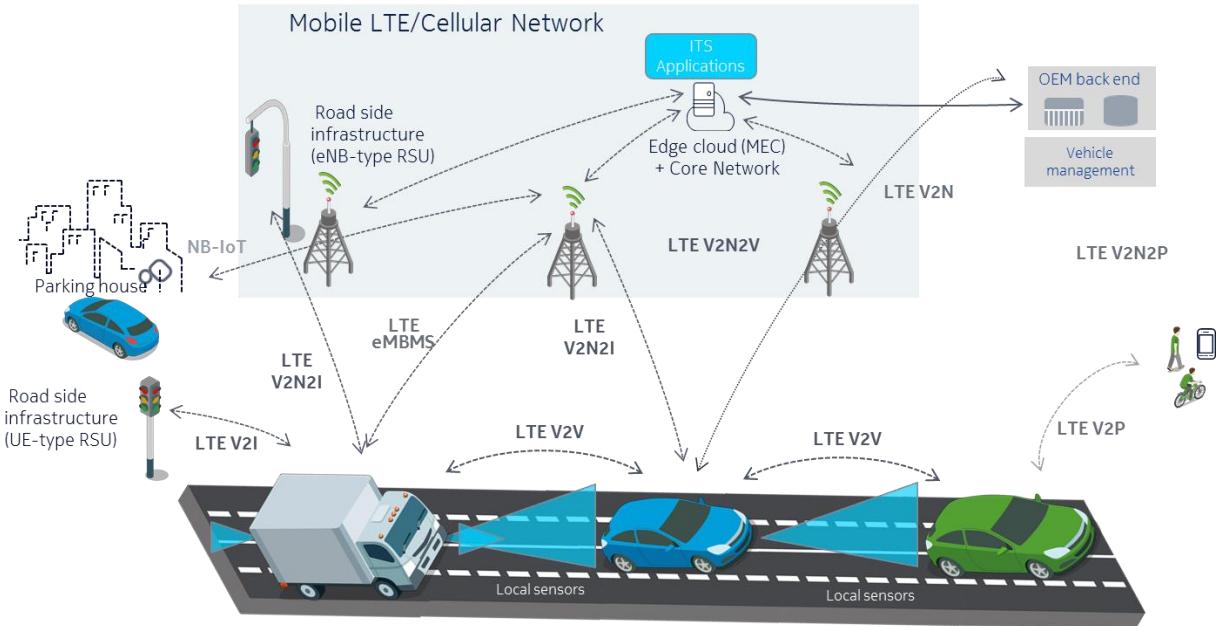


Figure 3.7-1 The hybrid use of the LTE technology to support ITS

The hybrid use of the LTE portfolio will meet automotive industry needs on the way to 5G. It supports automated driving, increases comfort and improves the infotainment experience. It also increases road safety and traffic efficiency while optimizing infrastructure investments. MEC rapidly processes content at the very edge of the mobile network cloud. It can support several use cases with low latency and distributed functionalities, such as distributed analytics, predictive algorithms and distributed self-learning with an inherent and consistent high level of security.

3.7.1 Evolving existing LTE network to deploy C-V2X

According to the GSMA, as of July 2017, LTE networks have been launched by 613 operators in 195 countries, reaching 70% of the population [13]. LTE-based V2X can leverage the existing customer base and ecosystem from device/chipsets manufacturers to infrastructure builders, to site/tower companies, to application/services providers. By utilizing nation-wide deployments of LTE, some C-V2X applications can be supported instantaneously with network software feature upgrades. As more vehicles and roads support C-V2X, network expansion would be required to support additional traffic and improve the coverage areas. This would be achieved by densifying the network by adding new eNBs/small cells and their associated backbone and core networks, possibly in colocation with traffic RSUs.

C-V2X deployments for mode 3 operation potentially require only software upgrades for the radio access network nodes to support Radio Resource Management features for the initial C-V2X deployments. These include support of sidelink communication (system information broadcasts, link adaptation, interference mitigation, scheduling, and QoS differentiation, etc.); other potential software upgrades can include features to support high-speed mobility;

optimized control signaling, and features to partition radio resources such as frame configuration and carrier assignments.

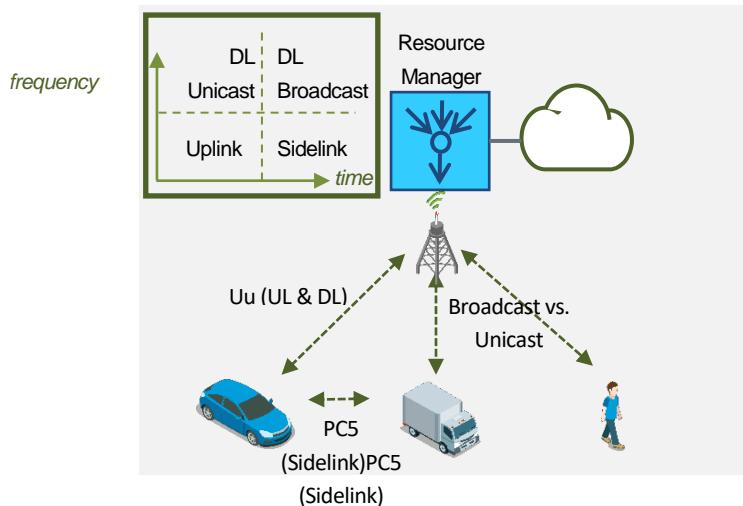


Figure 3.7-2 Example of Radio Resource Partition between Unicast/Broadcast, and Uplink/Sidelink

New Network Elements = New and Improved V2X Services

The LTE ecosystem currently includes a host of additional network elements and functionalities providing an evolution path to better and more sophisticated network support of C-V2X through several domains. They will enable and improve new V2X services leveraging the huge investment which has gone into providing high quality networks. And network operators continue expanding coverage and capacity of their networks.

Multi-access Edge Computing

Cloudification is a key trend in mobile networks and provides greater efficiency and flexibility. Multi-access Edge Computing (MEC) uses the mobile operators' networks to complement centralized clouds with distributed edge clouds hosted by the mobile network. MEC is located at the edge of the network typically at network aggregation points allowing direct LTE communication from vehicle to vehicle, infrastructure and pedestrians. In addition, MEC can host data aggregation and analysis services processing data before sending it into the central cloud. From a backend point of view MEC extends the cloud with cloudlets and introduces micro data centres at the edge of the network.

MEC can be used to reduce latencies to approximately 20ms which is particularly important for traffic safety applications. It can also support distributed computing of localized data. MEC also contributes to guarantee reliable latency and to increase general reliability of communication services, in particular, local communication. These functionalities form a comprehensive communications infrastructure on the way to improved traffic safety and autonomous driving.

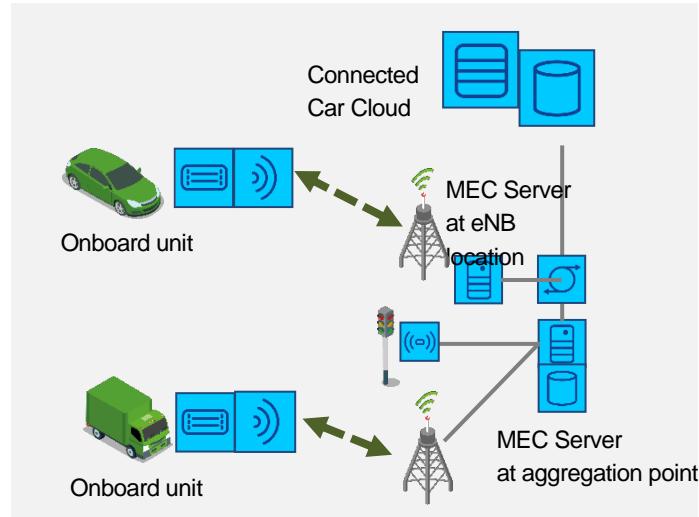


Figure 3.7-3: Multi-Access Edge Computing Diagram

For example, multi-access edge computing (MEC) nodes will make low-latency or location based V2X services possible such as hyper-local HD roadmaps, optimized sidelink congestion control, low-latency V2V relays, location-based analytics, etc.

By incorporating Big Data and local analytics engines, V2X network operations would be improved and new services to businesses, the government, and consumers can be offered by the network operators.

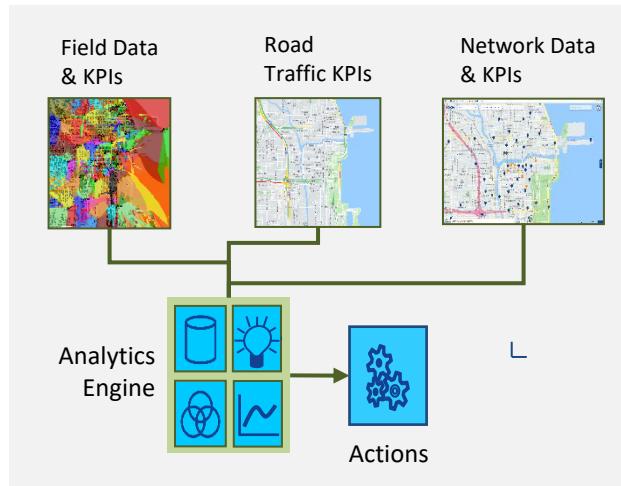


Figure 3.7-4 Big Data and Analytics Engine for C-V2X

In addition, the Enhanced Multimedia Broadcast Multicast Service (eMBMS) and Single Cell Point-to-Multipoint (SC-PTM) will allow for efficient transmission of V2X information such as traffic and road hazard warnings to applicable vehicles --- sending the right data to the right vehicle at the right time and location. It can be used to avoid network traffic congestion.

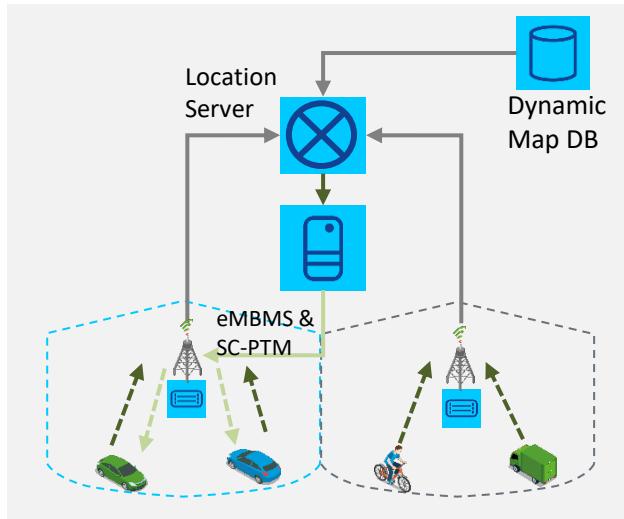


Figure 3.7-5: Location-based Broadcast and Monitoring

Narrow-Band Internet of Things (NB – IoT)

IoT support through eMTC and NB-IoT is another capability LTE networks can provide. It will expand coverage to deep indoor areas such as underground parking spaces. It can also provide telemetry for traffic infrastructure like parking spaces, construction work indicators, traffic signs, etc.. IoT changes the requirements for connectivity significantly, mainly with regards to long battery life, low device costs, low deployment costs, extended coverage and support for a massive number of devices. Based on these requirements, several different non-cellular Low-Power Wide Area Network (LPWA) connectivity solutions are emerging and are competing for IoT business and the overall connectivity market. While operators and vendors are reviewing their connectivity roadmaps against the IoT requirements and the potential threats from new entrants and start-ups, NGMN's view is that LTE-M, NB-IoT, are the superior solutions to satisfy the connectivity profiles and requirements for IoT. This is because cellular IoT provides an easy software upgrade of existing networks while providing optimized device KPIs, battery life, coverage and cost.

The LTE evolution for LTE-M and NB-IoT will enable cellular IoT for low cost, low power and wide area deployments that provide:

- Long battery life through power saving mode and eDRX
- Low device cost by using simpler devices
- Low network deployment cost by enabling shared carrier capacity
- Full coverage via new coding, repetition and boosting power spectral density
- Optimized core network for IoT.

Cloud-Ready Evolution

Cloudification affects not only the edge but the entire mobile network. By introducing Cloud RAN operators can effectively re-use their existing distributed or centralized radio architectures while enabling new benefits. This means the roll out of capacity can continue in parallel with establishing and executing a Cloud RAN strategy that aims to improve TCO and network performance compared to that of today. Operators can migrate to the new architecture by deploying multi-layer Cloud RAN in steps triggered by business needs such as:

- To save costs when deploying heterogeneous network features (e.g. LTE-LTE or LTE-Wi-Fi)
- To save costs while increasing device and user capacity for M2M and IoT
- To save costs by deploying new ultra-reliable or low latency services
- To save costs by deploying 5G technology

End-to-end Security

Paramount to the viability of C-V2X is end-to-end security which is a natural element of the 3GPP standards and their evolution. C-V2X deployments must consider physical security of network elements including road-side installations, as well as the cyber security of the access, transport, core, platform, and application nodes and their interfaces. Applications can benefit from the proven high level of security provided by the lower levels of LTE communications as well as the use of virtual identities in the access network. Additional V2X security can be developed on top of these already incorporated security infrastructures (see Section 4.5).

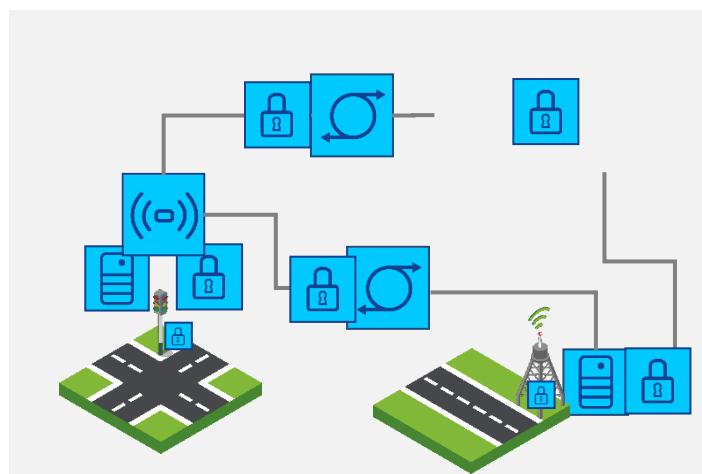


Figure 3.7-6 Security of access, transport, and core V2X network elements

3.7.2 Evolution to RSUs and support of V2I

Some road operators and publicly funded projects consider the investment into new RSUs and other road side infrastructure with the objective to increase traffic safety and efficiency however it is very costly to build and maintain a parallel network for exclusive use for traffic safety because the ITS spectrum is restricted to be used for

traffic safety only. Eventual deployments would likely be limited to major road traffic areas where the investment could be justified. The 3GPP Rel. 14 standard describes two possible examples of RSUs: UE-type RSU or RSU collocated with eNB. UE-type RSU combines a UE with the V2X application logic accessible via PC5. For example, UE-type RSUs intelligently control traffic lights or other road side infrastructure. Alternatively, RSUs could be combined with an eNB or small cell, as a collocated local gateway, and a V2X Application Server. These collocated RSU with eNB would also provide network coverage, higher reliability, and more versatile application functionality. For this deployment case, the conventional approach would be to co-locate the base station and application function within the RSU.

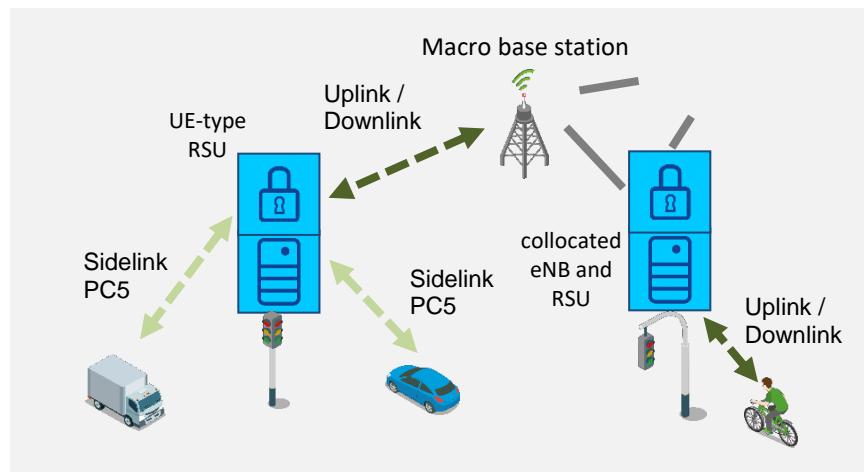


Figure 3.7 7: UE-type and collocated eNB/RSU deployment

The deployment of a collocated eNB and RSUs extends the coverage of the mobile networks, which is an attractive opportunity for road operators interested in investing into future-proof technology with immediate benefits since:

- V2N technology is already built into millions of cars with the possibility to communicate with each other as well as the road infrastructure, and therefore increasing road safety and traffic efficiency immediately
- by collocating eNBs with RSUs, the existing mobile network is extended in an easy and cost-efficient way
- The combination of RSU-ITS functionality with eNB/small cells is a very efficient use of real estate which is heavily required for rollouts due to the smaller network cells
- V2N has also a clear path to 5G, therefore it's protecting the investments into public infrastructure

3.7.3 3GPP Evolution to 5G

3GPP has shown strong innovation while moving through four generations of mobile network technologies. The ecosystem has been extended continuously and it is now approaching the next generation of technology – 5G networks. For the first time two generations, 4G and 5G, will coexist and intensively interwork with each other. It is expected that 4G and 5G access networks will provide continuous access to services for a long period and will eventually be managed by 5G core networks.

One major advantage of 3GPP Rel. 14 technology is the clear migration path from LTE-V2X Phase I to Rel. 15 Phase II [16] and Rel. 16 NR Phase III (in planning). The technology evolution path makes sure that 4G LTE will co-exist with 5G NR and Rel. 14 V2X will be compatible with Rel. 15 Phase II (eV2X).

This means, vehicles equipped with Rel. 14 will benefit from vehicles equipped with Rel. 15. Vehicles equipped with Rel. 16 are able to communicate for the Rel. 14 use cases with the Rel. 14 vehicles, and enhanced use cases will be handled via Rel. 16/NR capabilities.

5G technologies that are being standardized within 3GPP Rel. 15 and beyond include multi-connectivity (multiple RATs collaborating as one system), control and user plane separation, massive MIMO, support of millimetre-wave frequencies and support of ultra-low-latency transmission. These technologies will enable V2X applications with very strict requirements for higher throughput, lower latency, and higher reliability. Furthermore, key to achieving the various demands of 5G-enabled applications would be the support of network slicing which facilitates a personalized network and services with super quality of experience for all users. Along with providing tailor-fit networks, 5G technologies will improve the energy efficiency, security, and manageability of networks.

Assuming the introduction of a radio access based on IEEE 802.11p in a significant amount of vehicles, these vehicles can communicate only with other vehicles equipped with 802.11p. If the new and upcoming services for automated driving will need a 5G-V2X technology because of their advanced requirements, these vehicles have to be equipped also with 802.11p radio access because of backward compatibility. Furthermore, those vehicles equipped with C-V2X only, cannot communicate to 802.11p equipped vehicles. One option to overcome this interworking problem is to use the mobile network as a mediator: Both vehicle types, either equipped with 802.11p or equipped with C-V2X, can send their messages via V2N/Uu (and/or via 802.11.p or PC5 respectively) to an application logic in the network (e.g. operated on a MEC), which then translates and distributes the messages to other vehicles. Therefore, the introduction of a “dead-end” technology like 802.11p would create the need for a costly and inefficient interworking of the two different technology stacks.

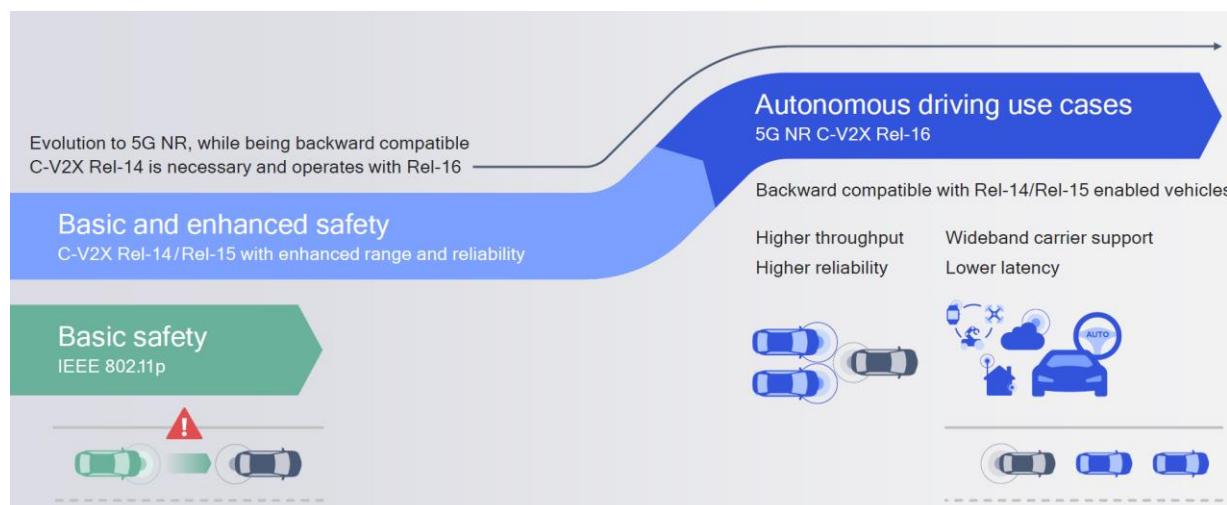




Figure 3.7 8 Evolution of C-V2X direct communication to 5G NR (new radio)⁶

5G NR will allow the deployment of new use cases important for the implementation of cooperative, highly and fully automated driving going far beyond the basic and enhanced safety and traffic efficiency applications. Examples of those use cases are shown in the following Table 3.7 1:

The new mobile transport needs to carry more traffic volumes and more traffic types including low latency as well as perennial needs for synchronization, reliability and security. It consists of a programmable, multi-layer and multi-technology fabric that supports SDN workflow automation and agile network services instantiation. It supports multiple RAN technologies, including LTE and LTE-Advanced Pro, processing models and sites, and distributed cloud infrastructure for virtualized RAN and packet core functions.

The success in 5G networks is no longer related exclusively to equipment optimization and utilization but rather to overall experience, fulfilment of a complex use case requirement and meeting the service defined quality.

Table 3.7 1 Examples of use cases which will be supported by 5G NR

<i>High density Platooning</i>	<i>enables vehicles to dynamically form a group travelling together. reducing the distance between vehicles substantially.</i>
<i>Real time situation awareness and high- definition local maps</i>	<i>comprehensive exchange of information on hazards in the local environment of the vehicle and update of dynamic local HD maps.</i>
<i>Extended real time sensors</i>	<i>enables the exchange of raw or processed data gathered through local sensors or live video data amongst vehicles, RSUs, pedestrian devices and V2X application servers as well as sharing of intentions and trajectories of vehicles to support safe and coordinated driving.</i>
<i>Tele-operated Driving</i>	<i>enables a remote driver in an operations centre or a V2X application to operate a remote vehicle for those passengers who cannot drive themselves or a remote vehicle located in dangerous environments</i>

Obviously, it is not precluded that the above-mentioned scenarios as well as the general features are also supported by Rel. 14/15 (LTE-A-Pro) systems, especially from the radio access perspective. 5G will however provide a more optimal platform for the scenarios due to the more stringent support of some requirements such as ultra-low latency, optimized support of a scalable number of vehicle devices edge connectivity, and optimized radio technology and network architecture from 5G inception. A key and sole advantage of 5G is the support of network slicing which will provide an optimal support for C-V2X as a distinct slice or as a “sub-slice”. The optimal support by a 5G slice of enhanced MBB, massive IoT and critical communications will enable the support of all types of applications for C-V2X.

⁶ Qualcomm webinar,
<https://d3v6gwebjc7bm7.cloudfront.net/event/15/87/87/1/rt/1/documents/resourceList1518453045031/5gnrbasedcv2xwebinardeckfinal1518453060732.pdf>

5G and functionalities like slicing will offer operators unique opportunities to create new sustainable business models.

3.8 Opportunities to include additional traffic participants like vulnerable road users

Although this paper has a focus on vehicle communication, additionally “Vulnerable Road Users” (VRU) can benefit from C-V2X PC5 communication. It is assumed that this technology will be integrated into smart phones or consumer electronics, such as bicycles/electric bicycles, motor bikes, wheel chairs and other devices.

The main requirements for a consumer device, which have V2X use cases implemented, are the following:

- High position accuracy, to determine the position of the VRU as accurate as possible. If position accuracy would be low, CAM/DENM or BSM type messages would be created, which lead to more confusion than transparency about the movement behaviour of the VRU and the resulting collision probability. High position accuracy is therefore needed to avoid an overflow of misleading information.
 - ➔ With reference to ongoing 3GPP standardization efforts (WI-750063⁷), as well as latest publications from chipset vendors, it can be noted that a lot of effort is spent to increase position accuracy in the consumer device. Position accuracy can be significantly increased by the analysis of higher bandwidth signal transmission [14], or with the support of GNSS correction signals like net-RTK (Real Time Kinematic), PPP (Precise Point Positioning), and others. It is expected that such technologies will be incorporated into consumer devices soon.
- Smart algorithms and machine learning techniques can detect and predict the movement behaviour of the VRU. Smart intelligence is needed to filter relevant information, both on sender side (VRU) as well on receiver side (vehicle). This includes also the individualization of the algorithms, because movement behaviour is highly individual due to the characteristics of the VRU.
 - ➔ On the Smartphone side, continuous efforts are spent to improve movement detection characteristics. Based on the sensors (gyrometer, accelerometer ...), algorithms are detecting steps, staircase movements, and others, to produce results for sports, healthcare, and other applications. On the receiver/vehicle side, continuous improvements are made to produce an environmental model of the surroundings of the vehicle, using all available sensorial information in a data fusion process. Within this process, the relevant information is continuously filtered out of the data stream of sensorial data. It can be expected that advanced intelligence will even improve already today's available movement detection components.
- Up to date high definition maps are needed to determine whether the VRU is located in a “safe” area (safe in terms of collision probability with a vehicle), or whether the VRU is on the road or close by.
 - ➔ High definition maps (HD-maps) are the next step when it comes to automated driving. Huge efforts are undertaken to produce and continuously update high-definition maps. Additional

⁷ 3GPP work item no 750063 “UE Positioning Accuracy Enhancements for LTE”

information which is especially important for VRU's, e.g. footpath, bike lanes, etc. are part of the HD-maps, because it sets restrictions to the driving possibilities of the vehicle. It can be expected that such kind of information within HD-maps will be available in near future.

- PC5 enabled C-V2X modem, together with a 5.9 GHz antenna.
 - ➔ If the PC5 will be integrated into the standard LTE- or 5G modem, this capability would be part of the standard cellular modem in consumer devices [15]. Regarding the antenna, the standard WiFi frequencies includes the 5.8 GHz spectrum, so designing an antenna able to receive data also in 5.9 GHz band is not a huge effort from a technical perspective.
- Battery consumption of the modules, which are involved to make sure, that a C-V2X application does not drain the battery.
 - ➔ Battery/power consumption is a critical topic in consumer devices, but this highly depends on the use case. Power consumption might not be so essential, if the VRU sits on a (electric) bicycle, because power is not a limited resource in this case, or can easily be harvested by the consumer device itself.

With a V2N connection, the VRUs could also be made visible to cars via a server, e.g. a MEC server of the network.

In general, incorporating VRU's into the C-V2X eco-system is seen as big challenge but also a great opportunity to improve safety and efficiency on the road. It's not seen in the first go to market phase but as an opportunity for later stages.

3.9 Future proof and support of automated driving

Expected performances with 4G V2X (and tomorrow 5G V2X) will enable a sharp decrease in latency which will translate into additional use cases with real-time automation characteristics; Moreover, thanks to the very low latency and high bandwidth it will be possible set up new trade-offs between embedded intelligence (and sensors) versus intelligence in the cloud with probably less costly UEs.

Autonomous driving in a broader scale will be accepted only by customers as well as by society in general, if cooperative behaviours between the vehicles as such and between vehicles and other traffic participants exist. Use case examples are cooperative lane merge, cooperative strategic traffic distribution, cooperative passing on rural roads, etc. Cooperation has very high requirements in terms of real-time characteristics of communication between the various parties and high throughput of information exchange.

Autonomous vehicles will therefore be excellent candidates to benefit from this V2X technology. Advanced use cases usually associated with Level 4/5 autonomous cars such as cooperative or even synchronized cooperative driving will be more efficiently implemented.

Moreover, it will be possible to safely and remotely control/pilot autonomous vehicles for security reasons or in very specific environments, thus paving the way for much wider use cases (smart agriculture, robotics, Industry 4.0,etc.).

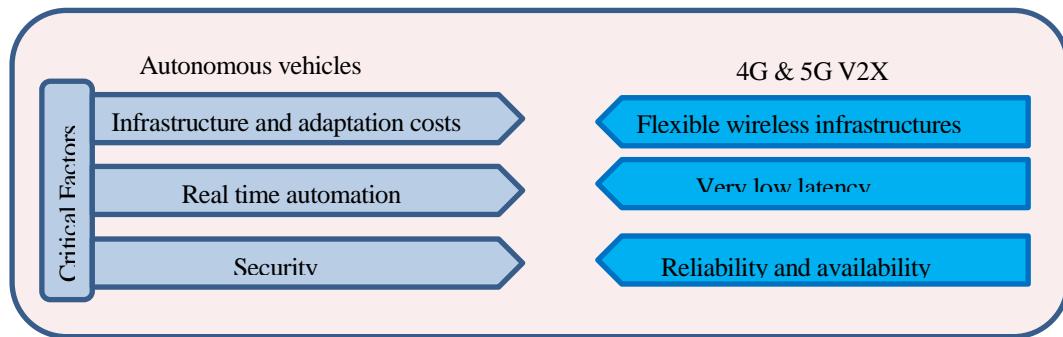


Figure 3.9-1 C-V2X provides enablers for future proof and support of automated driving and other real-time applications

Especially when it comes to automated driving, NGMN values the V2V capabilities as highly relevant. With a clear technology evolution path, automated driving will therefore benefit from a harmonized technology stack based on 3GPP technologies.

3.10 Comparison of Cost Aspects

For a comparison of the cost factors between a C-V2X sidelink (PC5) solution and a DSRC/802.11p solution, as a basic assumption it should be stated, that antenna, cabling and application stack is the same, regardless what technology is used. Therefore, a comparison of the costs can focus on the communication chipsets itself and the integration efforts for a certain technology.

As already described in Section 3.3, the ability of C-V2X for higher integration of the communication module is seen as the major cost benefit relative to a DSRC/802.11p solution. These cost benefits are not only associated with the bill of material, but also the savings in terms of reduced supplier complexity, less effort in the supply chain and logistics, and savings for maintenance.

It is expected, that even with higher integration the C-V2X sidelink (PC5) technology will be integrated also in consumer chipsets for VRU-use cases, such as bicycles, wearables, bags, and others. This will accelerate even more the economies of scale of C-V2X/PC5 because the technology will become a standard feature in consumer devices.

The same effect is expected for traffic RSU's: The additional control units needed for traffic roadside equipment, e.g. a SPAT/MAP controller unit, are already equipped with a cellular modem. The purpose of the cellular modem is to connect the RSU with a cellular network for security functions, such as renewal of



certificates and also for e.g. remote maintenance purposes. The higher integration of C-V2X sidelink (PC5) with the Uu part in a modem will also reduce the costs in traffic roadside units, from a chipset perspective. Of course, the costs for antenna (for ITS services the 5.9 GHz band) as well for cabling will remain more or less the same, regardless of technologies.

4 C-V2X Operation

4.1 C-V2X Operation Modes

4.1.1 PC5 Operating Scenarios

In this part, the two scenarios of V2X communications through PC5-based interface are explained in more detail, which are PC5 with no direct operator involvement (mode 4 and mode 4 operators assisted) and PC5 with operator's resource scheduling (mode 3). Both scenarios can support V2V, V2I and V2P. For V2I either transmitter UE or receiver UE(s) are UE-type RSU. For V2P, either transmitter UE or receiver UE(s) are pedestrian UE.

Scenario1 (PC5 with no direct operators' involvement or via operators' assistance):PC5/ Mode 4

In this scenario, a UE transmits a V2X message to multiple UEs at a local area using the PC5 interface. The transmitter UE autonomously selects resources and transmission schemes. There two possible cases for this scenario:

- The OBU (UE) only supports communication of PC5 without the availability of the Uu interface. In this case, the UE will communicate with other UEs without operator's support. A pre-configuration of the module will be needed.
- the OBU (UE) supports both PC5 and Uu communications. An operator can send and update configuration parameters if necessary through the Uu interface however the operators are not involved directly in the communication.

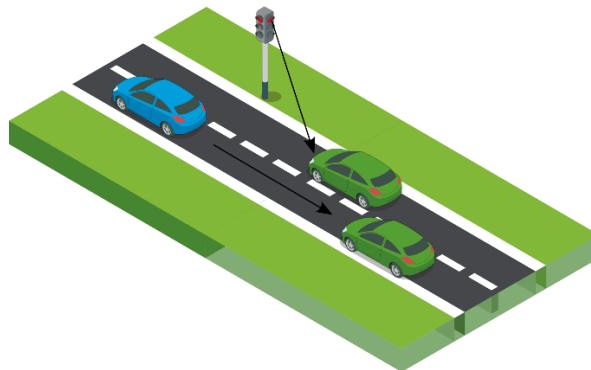


Figure 4.1-1 Scenario 1: C-V2X/PC5 / Mode 4

V2V/V2I/V2P communication is carried out without necessarily relying on network involvement for scheduling and it does not necessarily require any network infrastructure. It even does not necessarily need a valid subscription (SIM/eSIM) of the UE, so it is able to work also completely out of control of a network operator.

Scenario 2 (PC5 with Operators' resource scheduling)

In this scenario, the transmitter UE sends V2X messages to the receiver UEs via the PC5 interface; the eNB sends control signalling (e.g., resource management, MCS, etc.) to the transmitter UE over the downlink of the Uu

interface. Mobile Network Operators' spectrum can be used for transmitting the resource allocation and signalling in this mode of operation independent from the PC5 spectrum that is used for data transmission.

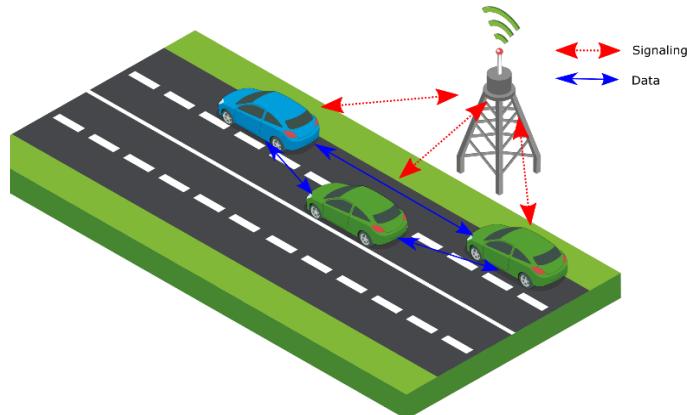


Figure 4.1-2 Scenario 2: C-V2X/PC5 / Mode 3

When the UEs are within coverage, both scenarios can be chosen for C-V2X communications. When the UEs are off coverage, UEs can only choose the first scenario to communicate with each other. Both in and off coverage scenarios are relevant in real life automotive communications.

It is expected that the first deployments of PC5 communication will be operated in mode 4. Since the penetration of PC5 enabled cars will grow gradually the available spectrum will provide sufficient capacity and its resource management is initially not required.

4.1.2 LTE-V2X Uu based Operating Scenario with DL Broadcast

In this scenario, a V2X capable UE transmits a V2X message (V2V, V2P and V2I) to the network in uplink and the network transmits it to multiple UEs at a local area over the downlink (Figure 4.1-3). For V2I the receiver can be either a normal eNB or a collocated eNB with a RSU. In this the latter case the eNB transmits a I2V downlink message to multiple UEs in a local area. The system supports semi-persistent scheduling in the uplink and broadcast or unicast in the downlink. This operation is carried out in conjunction with the application server which organizes the distribution of the information.

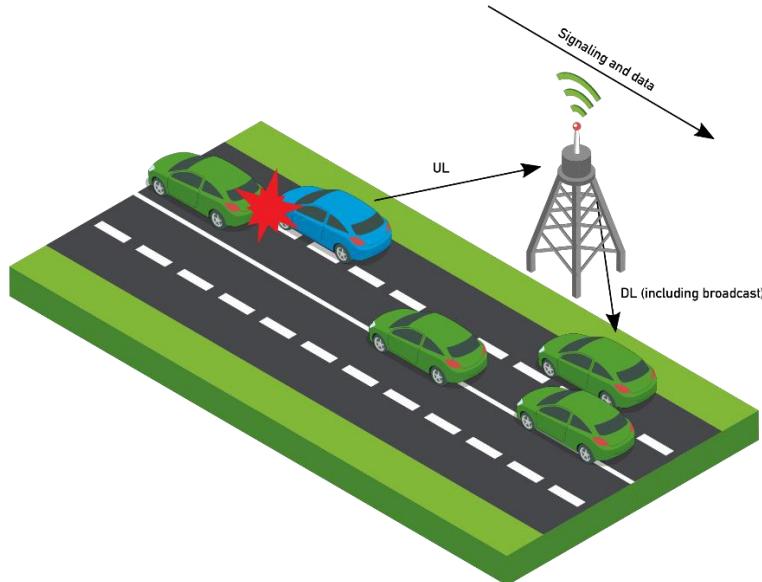


Figure 4.1-3 LTE-V2X Uu based Operating Scenario with DL Broadcast

4.2 Multi-Operator Scenarios

4.2.1 Inter-PLMN for V2X communication over PC5 (direct V2V link)

As C-V2X has been defined as a tool box in 3GPP, several deployment scenarios are possible. As discussed in Section 4.1, initially, C-V2X mode 4 i.e. autonomous V2V direct mode, is expected to be the first mode implemented and deployed thus leading to a fully decentralized radio resources allocation on the 5.9 GHz band (see also Section 4.4).

In the future however, with the increase of C-V2X supported cars' penetration rate, a coordinated radio resource management, i.e. V2V mode 3, is expected to be deployed, especially for specific use cases in selected bands (e.g. high density truck platooning). Although mode 3 is more efficient than the decentralized mode 4 (see simulation results of Figure 3.1-1, Figure 3.1-2 and Figure 3.1-3) its operation requires some level of coordination between MNOs.

Generally, there are 3 options on how different MNOs can share the resource pools on the same spectrum band, e.g. 5.9 GHz (Band LTE 47) for V2X communication over PC5 with mode 3:

- 1 Divide radio resources between MNOs in the Frequency domain:
 - a. **Each MNO uses a different 10MHz or 20MHz channel** on the 5.9GHz band
 - b. **All MNOs use the same channel with some coordination between them:**

Example: MNO1 vehicles transmit in the lower part of a 10 MHz channel. MNO2 vehicles transmit in the higher part of the same channel. Both MNO1 and MNO2 vehicles receive on the full 10 MHz channel.

- 2 Divide radio resources between MNOs in the **Time domain**:
 - All MNO vehicles transmit and receive on the same full 10 MHz channel
 - All eNBs (from all MNOs) have to be synchronized e.g. to GNSS
 - Coordination needed between MNOs (positioning and scheduling)

- 3 Divide radio resources in different geographical areas for different MNOs (**Space domain**):
 - Along borders between geographical areas, either coordination between MNOs needs to be established, otherwise the use of mode 4 will be a fall-back solution.

It is also worth noting that contrary to IEEE technologies, 3GPP standardizes both RAN and Core architectures for any new technology such as C-V2X including interworking between PLMNs and roaming architectures. As an example in

Figure 4.2-1, UE A belonging to PLMN A is roaming into PLMN B and can communicate with UE B, which is belonging to PLMN B, via PC5 or via Uu interface.

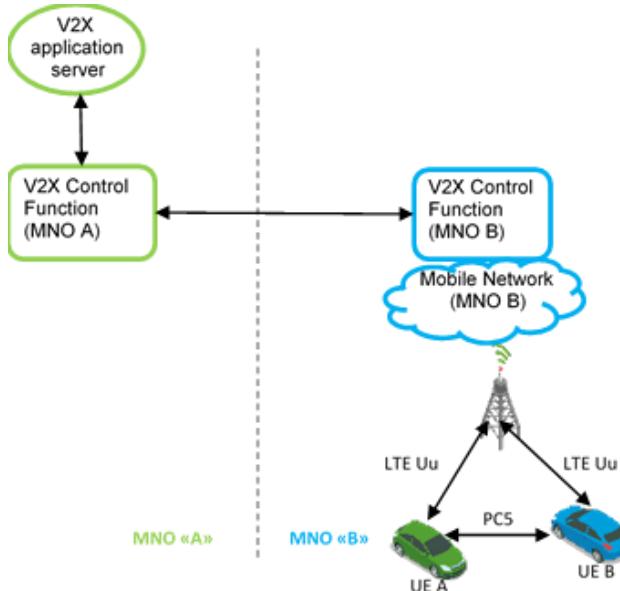


Figure 4.2-1 UE A (from MNO A) roaming into MNO B thanks to functional architecture enabling a standardized 3GPP C-V2X interworking between MNOs A & B

4.2.2 Inter-PLMN for V2X communication over Uu

V2X services can be supported over the Uu interface by Mobile Network Operators using their own licensed spectrum as a complementary service to PC5 operation. Although one MNO can only directly reach its subscribed UEs, additional V2X roaming functionality over Uu between two MNOs will be needed. Example of MNO roaming strategies are:

- Exchange between different V2X Application servers hosted by different MNOs
- An MNO could allow UEs to listen to broadcast in Read Only mode for those UEs which belong to other MNOs not deploying eMBMS. UEs are then receiving a V2X service on a frequency of one single MNO.

4.3 Duration of existence of LTE in the networks

Cellular networks have been deployed in licensed spectrum that are auctioned by regulators for each country. Usually the spectrum is licensed to an MNO for more than 10 years and this licensing is often renewable. MNOs have obligations in the terms of licenses to reach some KPIs (covered populations, geographical footprint, etc.) which lead to incremental but overall significant investment to reach the committed QoS. In other words, the technology of choice for the roll out of a network is carried out for the longer term. This is particularly the case for LTE as it clearly outperforms previous 2G and 3G systems. Note that in Europe and US most of 2G and 3G systems are still up and running (first deployments dating back to the early 90s). It is expected that LTE networks deployed by MNOs will exist for at least the next two decades. It is also important to stress that LTE Advanced is a core element of the new 5G system.

Moreover, today 2G/3G/4G technologies are operated within the same network (and tomorrow 5G as well) thanks to a full radio and core network standardization especially from SDOs such as ETSI & 3GPP leading to a smooth and progressive integration of a new technology whilst taking full benefit of coverage/capacity and thus investments made on previous generation systems.

4.4 Spectrum and Regulations

C-V2X supports V2N communications using existing mobile frequency bands (e.g., 800, 1800, 2600 MHz), and V2X communications (V2V, V2I, V2P) use the core 5.9 GHz ITS band (5 855 – 5 925 MHz). Discussions on harmonization of this ITS band is expected in WRC-19 especially for APT countries where the frequency bands 5770 - 5850 MHz and 5855 - 5925 MHz (or portion of the band) are being used in some APT member countries[17].

In Europe, Intelligent Transport Systems (ITS) are specified in the ETSI Harmonized Standards between 5855 – 5925 MHz as shown in the figure below. This frequency band is designated for road safety ITS on a non-exclusive and license exempt (unlicensed) basis. The European Directives define the spectrum usage conditions of this band

in a technology neutral way[18][19] . Any technology fulfilling the ITS requirements in the harmonized standards should have access to the band [HS EN 302 57]. These spectrum usages of this band are described as follows:

Frequency band	Frequency range	Usage	Regulation
ITS-G5B	5855 MHz to 5875 MHz	ITS non-safety applications	ECC Recommendation (08)01[19]
ITS-G5A	5875 MHz to 5905 MHz	ITS road safety	Commission Decision 2008/671/EC[18], ECC Decision (08)01[19]
ITS-G5D	5905 MHz to 5925 MHz	Future ITS applications	ECC Decision (08)01[19]

The transmitter maximum RF output power in this band shall not exceed 33 dBm and the maximum power spectral density shall not exceed 23 dBm/MHz. The maximum channel BW is 10MHz. For an operating 10MHz channel, RF parameters such as spectrum masks, out of band (OOB) emissions, receiver spurious emissions, and receiver sensitivity are all defined in ETSI harmonized standards EN 302 571[20].

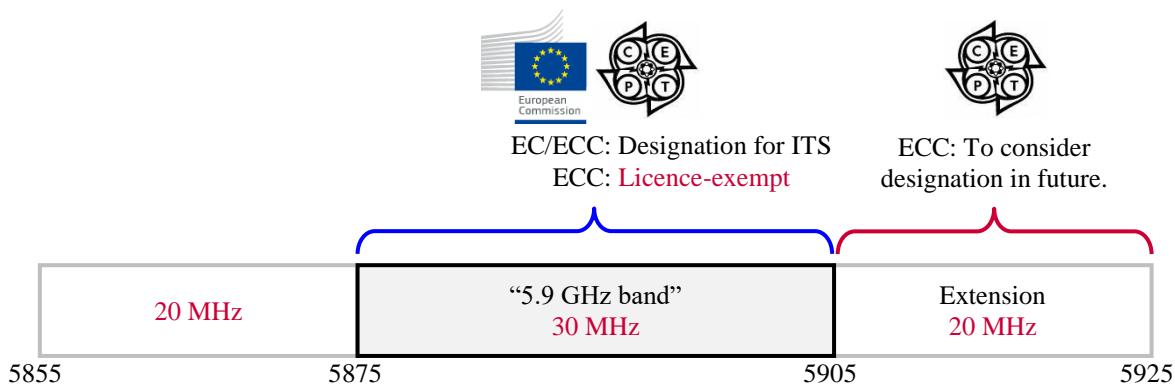


Figure 4.4-1 Europe Channel allocation in 5.9GHz for V2X services

The EU harmonized 30 MHz (5875-5905) for safety-related ITS is suitable for C-V2X. There is a need for some form of coexistence between C-V2X and its competitor IEEE 802.11p at the 5875-5905 MHz unlicensed band. The required sharing mechanisms however will degrade the performance of both C-V2X and IEEE 802.11p which is bad for road safety therefore, NGMN encourages the EU and Member States to

- consider– at least temporarily and for the initial phase – if different channels at 5.9 GHz can be allocated to C-V2X and 801.11p respectively, and
- consider– at least temporarily for the initial phase - if already dedicated spectrum for ITS services in the 5905-5925 MHz band could be allocated for ITS applications based on C-V2X

In the US the FCC has already allocated the frequency band 5850 – 5925 MHz for a non-exclusive and licensed basis V2X services 16 years ago. FCC regulations make normative references to IEEE 802.11p with one channel allocated for control while other channels are allocated for shared channel V2X services. As shown in Figure 4.4-2

below, channel 172 is for V2V safety applications for accident avoidance and mitigation, safety of life and property. Channel 184 is for high-power, longer distance communications to be used for public safety applications involving safety of life and property, including road intersection collision mitigation.

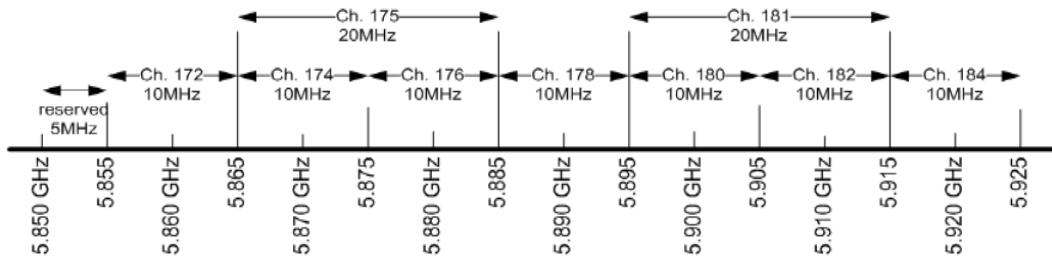


Figure 4.4-2 FCC channel allocation in 5.9GHz for V2X services

As for region three⁸, harmonization of frequencies in supports of the evolving Intelligent Transport Systems within the frequency range of 5 850-5 925 MHz is expected to be discussed in WRC-19 by APT Members. The Japanese Regulator has allocated the band of 755.5 – 764.5 MHz (Digital Dividend) on an exclusive and license exempt basis for ITS but it's likely that more spectrum will be needed in the 5.8GHz band for future C-V2X.

Regarding China, in November of 2016, the Ministry of Industry and Information Technology of the People's Republic of China (MIIT) has allocated the frequency band of 5905 - 5925 MHz for C-V2X trials in Shanghai, Chongqing and Hangzhou etc. China is currently studying how to allocate the spectrum for full C-V2X deployment.

4.5 Security Aspects of LTE-V2X / PC5

Security and privacy for V2X applications requires (a) security and privacy functions, as well as (b) provisioning and management of the keys and certificates for those functions.

(a) Security and privacy functions: In LTE- V2X / PC5, the security and privacy functions themselves are mostly standardized at layers above 3GPP (either ETSI ITS or IEEE/SAE). There is only marginal differentiation here between LTE-V2X and DSRC/WAVE; also, because this is standardized, there is very little opportunity for vehicle manufacturers to differentiate in this area. Section 4.5.1 points out a high-level description of basic security and privacy requirements for V2X. Sections 4.5.2 to 4.5.4 outline the security and privacy functions, whereas Section 4.5.5 addresses future enhancements of V2X security in 3GPP.

(b) Provisioning and management of the certificates: the central certification authorities involved in V2X security provisioning (such as the highest level Certification Authority for V2X services) will also be fixed,

⁸ which contains most of non-FSU Asia east of and including Iran, and most of Oceania

typically by governments. But, there are some aspects of provisioning and management that can be facilitated by cellular, using the wide area connectivity which is inherently available, and in some cases more specifically using 3GPP's Generic Bootstrapping Architecture (GBA) based on the pre-shared key (PSK) infrastructure in LTE. There are some advantages of LTE over DSRC/WAVE here and there is some scope for vehicle manufacturers to differentiate. Section 4.5.6 explains where these advantages arise.

4.5.1 High-level Description of Security Requirements for V2X

The majority of V2X messages are safety-related broadcast, with no restriction on which vehicles within range are allowed to read them. This includes V2V Cooperative Awareness Messages (CAMs) and I2V/V2I Decentralized Environmental Notification Messages (DENMs), as well as the BSMs respectively. These messages are, naturally, not confidentiality protected. They are signed however, to ensure that they come from a genuine, authorized sender, and have not been tampered with. In addition, they are also anti-replay protected, to ensure that the time of transmission is also authentic.

Other, non-safety messages have a pre-determined audience. These are unicast or multicast messages and can be encrypted for confidentiality, as well as being signed for integrity and authenticity as explained above. Another security-related requirement, especially for safety-related messages, is that the senders should be trustworthy and accountable and, hence, the removal/revocation of detected misbehaving participants from the V2X system is essential. This should be supported by appropriate technical measures and certification procedures for the underlying software and hardware.

Availability is yet another security requirement, especially for safety-related messages, which may be complicated by the scalability issues in some environments. Denial of service (DoS) attacks therefore need to be considered with respect to both illegitimate and legitimate entities. This includes detection and, where possible, mitigation of crude, localized radio jamming. It also includes prevention and/or early detection of more efficient DoS attacks, e.g., based on spoofed signalling messages that disable service for an extended time, or on spoofed safety messages being “amplified” by being replayed multiple times by legitimate entities and hence flooding the airwaves. In particular, it should not be possible for an attacker from the Internet to cause messages to be broadcast that are disruptive by their nature or their frequency; this is most naturally achieved in the system by clear authorization and authentication of parties that can trigger message broadcast at all. As for spoofed messages from vehicles, the system includes the ability to revoke misbehaving vehicles, as discussed elsewhere in this section. Timely and efficient revocation of such vehicles is a challenge, which may be addressed in real time and/or periodically, as well as at the start of each ride.

4.5.2 High-level Description of IEEE 802.11p and LTE-V2X PC5 Communications Security

IEEE 802.11p standard [21] for DSRC/WAVE (broadcast) communications does not include security features, mainly to enable efficient short-lived and dense communications links involving high-speed vehicles in metropolitan

environment. The needed security features are introduced by higher-layer standards, to be described in Section 4.5.4.

For the two modes of operation of the V2X communications system based on LTE (LTE-V2X), namely over PC5 (LTE PC5) and over LTE-Uu (LTE Uu), several security mechanisms exist. V2V/V2I/V2P can communicate either directly over PC5 interface or through the LTE network over the LTE-Uu interface. V2X communication over the PC5 interface is supported both when the UE is "served by E-UTRAN" and when the UE is "not served by E-UTRAN", as specified in 3GPP TS 23.285[22]. LTE-V2X security is specified in 3GPP TS 33.185[23], which does not specify security features for LTE PC5 not served by the network, but rather delegates such features to higher-layer standards, to be described in Section 4.5.4. Similarly, essentially the same is the case for LTE PC5 served by the network, except for the uplink/downlink from UE to E-UTRAN over the LTE-Uu interface for exchanging the signalling messages, which inherits the security features of LTE. Accordingly, in LTE PC5, data messages exchanged by wireless broadcast do not include security at the communications (3GPP) layer.

It should be noted that PC5 messages for proximity-based services (ProSe) have the data format specified in 3GPP TS 33.303 [24], including the headers that contain predefined fields for multicast group keys which can be used to secure PC5 multicast messages, with data integrity, scrambling, and confidentiality. This feature is not used in the existing 3GPP standards for LTE PC5, 3GPP TS 33.185[23], but may possibly be interesting for future use cases.

Neither IEEE 802.11p nor LTE PC5 prevent UEs from establishing ad-hoc security associations for protecting the mutual communications (unicast, multicast or broadcast), which may also be useful for some use cases, but this is not standardised. In particular, point-to-point security associations may be formed between two vehicles using well-defined mechanisms at the layers above that of IEEE 802.11p and LTE PC5, e.g., a TLS session establishment based on certificates provisioned for V2V communications.

4.5.3 High-level description of LTE Uu Communications Security

V2X communications over the LTE-Uu interface are based on eMBMS for broadcast/multicast of V2X messages in LTE network. Namely, LTE-Uu is used for UL/DL unicast, while eMBMS is used for DL broadcast/multicast.

LTE-Uu unicast messages between mobile devices (e.g., vehicle) and E-UTRAN, can benefit from regular LTE air interface security, without modification of the LTE security architecture. eMBMS broadcast/multicast messages can be protected as specified in 3GPP TS 33.246[25] however, if eMBMS broadcast messages target arbitrary vehicles in a given area, then such messages are not secured on radio links and, as such, require protection at application layer. Unicast messages between a vehicle and the V2X Application Server or the V2X Control Function are likely to be end-to-end protected. The air interface encryption is then just an additional layer of confidentiality protection and may not be applied as such for the sake of rapid communications.

LTE-V2X specifies a mechanism to provision security for the communication channel between the vehicle and the V2X Control Function or the V2X Application Server, respectively, using the PSK TLS protocols based on LTE pre-



shared keys[22][23], according to the Generic Bootstrapping Architecture (GBA) specified in 3GPP TS 33.220[26]. This mechanism necessarily involves LTE-Uu.

It should be noted that LTE Uu (over eMBMS) and LTE PC5 can be used by a given UE independently for transmission and reception.

4.5.4 High-level description of Application-layer Security in IEEE 802.11p and LTE-V2X

At present, there are two main choices for these higher-layer security standards: either the IEEE/SAE standards (IEEE 1609.2 [27], with some aspects further defined in SAE J2945/1[28]) or the ETSI ITS standards (primarily TS 102.731[29], TS 102.940[30], TS 102.941[31], TS 102.942[32], TS 102.943[33], and TS 103.097[37]). Both can be used for protecting V2X applications and services running over either IEEE 802.11p or LTE-V2X(PC5 based or LTE-Uu based). In current practice, IEEE/SAE standards use IEEE 802.11p as a bearer, whereas ETSI ITS standards consider using both IEEE 802.11p and LTE-V2X.

At a high level, there is little difference between the IEEE/SAE and ETSI security architectures and functions. The same messages are protected in essentially the same way, although there are some differences in the cryptographic details, and some different efficiency optimizations in the two sets of standards. The security functions essentially deal with enrolment, registration, authentication, authorization, revocation, security associations, and standard security functions providing confidentiality and integrity as well as anti-replay and accountability. Both approaches relate to digital signatures and PKI for handling the certificates and credentials needed for implementing the security functions. (Note that a public-key credential essentially consists of the public-key certificate and the corresponding secret/private key.) Both approaches address privacy as an important requirement and use temporary identifiers with a limited lifecycle for this scope.

In the US, IEEE 1609.2 is typically instantiated by the Security Credential and Management System (SCMS) [35][37] , which specifies the security architecture and elements of a concrete system for secure V2V communications. It focuses on provisioning and management of the certificates and credentials in a way compliant with IEEE 1609.2. SCMS seems likely (although not yet certain) to be adopted.

More significant differences between the IEEE/SAE and ETSI ITS approaches can be seen in the way that credentials or certificates are provisioned and managed:

- The SCMS scheme, designed for use with IEEE/SAE, uses vehicle public-key credentials (locally generated) for signing the messages coupled with the corresponding public-key certificates issued by a Pseudonym CA (PCA), and each vehicle is provisioned with a large quantity of them to last for several years. There is also the ability to revoke the certificates if a device is detected as misbehaving (with a carefully designed mechanism to allow the “unmasking” of a misbehaving device only if multiple authorities agree to do so); a Certificate Revocation List (CRL) is then distributed to devices periodically. Because revocation is possible, these could in principle be long-lived certificates.

However, for privacy reasons, the lifetime of a pseudonym certificate is kept short (see Section 4.6 below).

- ETSI ITS approach may in general support both symmetric-key and public-key credentials and certificates (ETSI TS 102 731[29]). However, it appears to be focused on the latter. Again, the certificates are issued by a PCA. The main difference is that there is no explicit revocation of the certificates. This is enabled by the certificates being issued one or just a few at a time by the PCA. Namely, if a device is detected as misbehaving, its certificates are then just not renewed. Due to the absence of explicit certificate revocation, it follows that the lifecycle of the certificates needs to be very short. Also, the number of certificates issued by the PCA at a time then determines how fast the misbehaving device can be put out of the V2X system.

In particular, the V2X security architecture defined by the EU project PRESERVE[37], which was adopted by the Car2Car communication consortium (C2C-CC), was designed to be compliant with the ETSI ITS standards. It uses long-term certificates issued by a Long-term CA (LTCA) for the enrolment and revocation and short-term operational certificates issued by a PCA for signing the messages. The short-term certificates need to be issued online, in real time, maybe on a daily basis, and are suggested to last for only a few minutes. Note that the PRESERVE V2X security architecture was designed to be compliant with the IEEE/SAE standards too.

4.5.5 Enhancements Planned for V2X Security in 3GPP

3GPP is considering continuing V2X standardization work to support advanced use cases and services (e.g., platooning, cruise control, advanced/remote driving) and to align with development of the 5G standard. At present, it is unclear whether this will have any impact on the existing LTE-V2X, especially given that most security for V2V over PC5 interface is left to the application layer. This implies that the security and privacy features depend on how various applications are designed and implemented, which may possibly raise practical security concerns with a growing number of applications in the future. Accordingly, a generic protection of signalling and application data at the communications (3GPP) layer, even in broadcasting, may possibly be considered in the future, although there is no current plan for that.

4.5.6 Summary of advantages of LTE- V2X Security

3GPP chose to place most V2X security at the application layer, as explained above. One particular advantage of this approach is that it allows a single national (or even multinational) central certification authority. If, instead, security had been dealt with mainly by 3GPP-specific mechanisms, then this would have required much more reliance on inter-operator roaming relationships, as well as multicast/broadcast security on a far larger scale than ProSe.

Thus, most aspects of security for LTE-V2X are handled by higher-layer standards. In this respect, LTE-V2X security and IEEE 802.11p security are broadly similar. However, LTE-V2X does have some particular security benefits, because of ways that it can facilitate the provisioning and management of security for V2X applications.

At present, there is considerable flexibility (one might say uncertainty) about how certificates will be delivered. ETSI TS 102 941[31] gives the following non-exhaustive list of examples:

- An ITS G5 communication via an RSU.
- A WLAN consumer network using IEEE 802.11 protocol (via a public or private hotspot or a home network).
- A Cellular network connection by a mobile network operator (3G, 4G or LTE).
- A wired or wireless connection at EV Charging station.
- Using the Vehicle On-Board Diagnostic (OBD) port and a diagnostic system at the Service Garage or inspection workshop.

So, what advantages does LTE-V2X offer? Firstly, with C-V2X (LTE or 5G), a wide area connection can be expected almost all of the time. This allows either certificates or revocation lists to be updated regularly and promptly. The ETSI ITS approach to pseudonym certificate management requires frequent issuance of new certificates to vehicles, while the IEEE/SAE approach requires regular updates to certificate revocation lists at the vehicle; thus both approaches need wide area connectivity. IEEE 802.11p does not itself provide this, whereas LTE does (although vehicles using IEEE 802.11p for safety messages may have wide area connectivity anyway).

Wide area connectivity also facilitates software/firmware updates, including security patches. Note that ensuring the software integrity (e.g., at the start of each ride) is important for the V2X system to function properly. Also, it seems that the scalability issue in the V2X system can be better resolved with the support of network infrastructure in LTE-V2X than in IEEE 802.11p.

Secondly, possibly the main security advantage of LTE-V2X relates to the security of V2X management and provisioning messages, between the vehicle and the V2X Control Function or V2X Application Server. LTE-V2X specifies a mechanism to provision security for these communication channels, using the Pre-Shared key (PSK) TLS protocols based on LTE pre-shared keys[22][23], according to the Generic Bootstrapping Architecture (GBA) specified in 3GPP TS 33.220[26]. This ability to use GBA for provisioning the initial cryptographic session/service keys at the transport or application layer is specific to cellular, due to the existing pre-shared key (PSK) infrastructure. Being based on symmetric keys pre-shared with the network, GBA thus relies on the trustworthiness of the mobile operator. There may be some further scope to use GBA to facilitate the creation of secure connections over which other management messages, including certificates or certificate revocation lists, could be sent. There may also be scope for manufacturers or operators to offer services based on this.

Thirdly, the LTE subscription identifiers and credentials can natively be used in the enrolment and/or registration phase of both ETSI ITS and IEEE/SAE (with SCMS) approaches when built upon LTE-V2X. Also, the PSK infrastructure provided by mobile operators can natively support symmetric-key credentials and certificates, which can also be used within the ETSI ITS approach, possibly for some use cases in the multicast scenario (resembling the ProSe functionality).



Finally, especially for public-safety use cases, having a liable trustworthy mobile operator (at least on the national level) playing a role in the V2X system appears to be yet another advantage of LTE-V2X with respect to both security and privacy.

In summary, wide area connectivity, PSK infrastructure with GBA, as well as trustworthiness of mobile operators appear to be unique leverages offered by LTE-V2X, which result in a number of advantages related to enrolment, scalability, provisioning and management of credentials, certificates, and certificate revocation lists, provisioning of signalling messages, software updates, enforcing privacy regulation and best practices, as well as support of future use cases. The well-established trustworthiness of mobile operators here relates to the mobile network functionality, pre-shared key infrastructure, tracking based on cellular/network identity, traffic monitoring, and to lawful interception.

4.6 Privacy

To prevent privacy-related abuses and encourage voluntary participation in the V2X system, it is important to minimize the risk of tracking the vehicles by monitoring the messages transmitted in the system, especially because they are broadcasted. To this end, the requirements of untraceability and unlinkability should be respected. Recall that untraceability means that, except for authorised entities, it should be hard to derive the vehicle long-term identifier from temporary identifier(s), and that unlinkability means that, except for authorised entities, it should be hard to track the movement of the same vehicle on the basis of (temporary) identifier(s) used in the system.

Privacy is thus conditioned on the correct behaviour in the system. To minimize the risk of abuses, the conditions under which privacy can be revoked should be clearly specified and made known to the user (e.g., vehicle owner), and should preferably involve at least two independent authorised entities accountable for their actions.

Privacy-related requirements (in line with GDPR [38]) also include the minimality principle with respect to data disclosure and data retention. Namely, the data regarding the user can be disclosed outside the V2X system (including vehicles) only with the user's consent and retained in the V2X system no longer than necessary.

4.6.1 Tracking

To alleviate possible consumer or regulatory concerns, there is a clearly established requirement that third parties (outside the V2X system) should not be able to use V2X messages to track a user over an extended period. Some local or regional regulations may contain explicit requirements on the prevention of vehicle tracking.

For communications over the PC5 interface, both ETSI ITS and IEEE/SAE (with SCMS) standards include comprehensive mechanisms for issuing pseudonym certificates to vehicles. As described in Section 4.5.3 above, there are differences in how these certificates are issued, and how they are revoked for a misbehaving device.

It is clear that repeatedly used pseudonym certificates can be directly used for vehicle tracking. So, their lifecycle, as being critical for linkability, should be defined by regulation authorities. In particular, it should not be too long. For example, the US NHTSA Notice of Proposed Rulemaking [40], which is applicable in the US only, suggests a change of the pseudonym certificate every five minutes, but each certificate is allowed to be reused on different days within a period of two weeks. If a pseudonym certificate does not change during a ride, then tracking would be straightforward for each ride, possibly all the way from the starting location to the destination location. If such a certificate is allowed to be reused on different days, then further linking would be possible, which implies that a frequent change of reusable [40] pseudonym certificates (e.g., every five minutes) would then be required for privacy. Of course, a very frequent change of pseudonym certificates would require an increased computation and bandwidth load on the PCA, and might also increase the risk of service interruption, if the PCA is not scaled correctly. Accordingly, a trade-off between privacy and efficiency is necessary.

Even if the pseudonym certificates change with every V2X message, passive tracking of vehicles may still be feasible in some usage scenarios, by using only radio receivers for data collection. For example, if for public safety, each enrolled vehicle is frequently broadcasting its location together with the time stamp in a beacon message, then, as demonstrated in[40], vehicles may be effectively tracked by exploiting the very nature of the beacon information, that is, location and time. For this to be performed, it is necessary that the space resolution is high (on the order of few meters) and that the beaconing frequency is at least about 1 Hz (that is, one beacon message per second). It is shown in[40] that the known technique of multi-hypothesis tracking together with Kalman filtering can then successfully track vehicles even in reasonably dense traffic (on the other of several hundred vehicles). In essence, the success of the technique is based on the continuity of individual vehicle movements. Naturally, repeatedly used pseudonym certificates only facilitate tracking. For illustration, vehicles can be tracked with almost perfect accuracy if they broadcast their location once per second, but change pseudonyms less than once per ten seconds, even in busy traffic in metropolitan environments.

Consequently, a very frequent change of pseudonym certificates is not sufficient to prevent vehicle tracking based on radio signals in the beaconing scenario. From the experimental data reported in [40] it follows that the effectiveness of tracking by signal processing rapidly decreases if the beaconing frequency goes below 0.5 Hz. A lower frequency therefore, possibly depending on the expected or even actual vehicle speed, is better for privacy. Furthermore, beaconing at irregular intervals, possibly randomized and occasionally interrupted, appear to be effective countermeasures against illegitimate tracking. A lower frequency however may be in conflict with road safety requirements, as there may be good reasons for sending beacon messages at high frequencies. Accordingly, if a higher frequency turns out to be necessary for a road safety service to be provided, then the V2X system users should be made aware of the privacy implications and the V2X system providers should be held accountable.

It is important to note that any kind of passive vehicle tracking based on radio signals assumes a practically very demanding condition that the radio receivers collecting the data must be placed alongside the roadways in order to systematically cover a given relatively wide area by listening to the cars passing by. Since this clearly relates to the V2X system providers, they should be trusted not to abuse the collected data, especially when efficient tracking based on signal processing and/or unchanging pseudonym certificates (or other temporary identifiers) is possible. The needed trust may possibly be alleviated by technical measures aiming at an early detection of suspicious behaviour as well as by an appropriate regulation.

Privacy concerns thus need to be carefully addressed by the standardization organizations, respecting the data minimality principle for various usage scenarios. In accordance with the GDPR [38], the data collected in the V2X system should be used only for the specified purpose and by the authorised and accountable entities.

Academic and industrial research has looked for ways in which the individual signed messages from a vehicle could be cryptographically unlinkable. One such approach is based on group signatures, but schemes identified so far do not seem practical (see [41]). Another avenue of research is based on the use of privacy-preserving attribute-based credentials or Privacy-ABCs, originally proposed in [37] and also known as anonymous credentials. More practical details can be found in [43]. Namely, in principle, an anonymous credential can repeatedly be used for signing and yet be perfectly unlinkable at the application layer. This is achieved by unlinkable presentation tokens derived from the same credential, which can be verified by any receiver by using efficient non-interactive zero-knowledge proof techniques. A recent theoretical and experimental assessment of selected ABC techniques for vehicular ad hoc networks is given in [43]. It remains to be seen whether this approach will lead to a mechanism that could be sufficiently practical for vehicle safety messages.

4.6.2 Trusted Parties

For LTE Uu, one question that has caused some debate is whether mobile operators should be able to track the location of vehicles (i.e., whether mobile operators are considered as “third parties” in the sense of the previous requirement). Vehicles (and their drivers and passengers, too) will have regular wide-area cellular coverage anyway, and a mobile operator will know the whereabouts (at least on a cellular level) of any mobile device that it is serving – this is standard mobile network operation, to be able to deliver incoming communications to the device. Of course, this relates only to the vehicles that effectively use cell-phones. No privacy mechanism has yet been standardised to prevent tracking a UE on the basis of its cellular/network identity while attached to the network. (The pseudonym certificate mechanisms can prevent mobile operators from tracking vehicles purely using PC5 messages, as discussed above.) This tracking ability continues to be important for criminal investigation, when properly regulated. Needless to say that, more generally, mobile operators and telcos need to be trusted not to violate privacy by abusing their (legitimate) technical ability to perform data traffic monitoring and lawful interception anyway.

It is at the very least a good practice to inform V2X users about the location privacy implications when they agree to use V2X services, and to seek their consent; indeed, this may be required by some legislation such as the GDPR

in Europe. Note that this applies even if V2V services themselves are only on the PC5 interface, because some configuration and management (signalling) messages will use the Uu interface, provided that the network is available (as pointed out in Section 4.5.2). Including location privacy in the user information and consent, as mentioned in the previous paragraph, may be sufficient to address regulatory concern about tracking by mobile operators. This means that the mobile operators participating in the V2X system may be considered as trusted parties subject to appropriate regulation constraints. On the other hand, some believe that a fuller technical solution will be needed, blinding trackable identities even from a mobile operator. It is shown above however that in some important use cases, the V2X system providers may inherently be able to track vehicles regardless of the identities used.

Note that the issue of tracking is complex and relative to the resources of outsider or insider entities attempting to do the tracking. In practice, the intercepted V2X messages can correspond to the air interface only and can relate to broadcasting only. More generally, intercepted V2X messages over wired connections can also be used for tracking. Different (insider) parties or authorities having various roles in the V2X system (e.g., related to enrolment, authorisation, certificate provisioning etc.) can also possibly collude together to do the tracking. So, they should be trusted not to collude with each other. In this regard, the separation of critical elements in the system such as the enrolment and PCA authorities should be supported by technical means or business contracts or regulations. Having liable trustworthy mobile operators in the V2X system, at least on the national level, may be considered as an advantage of LTE-V2X. This holds also with respect to data disclosure and data retention, and not only tracking.

4.6.3 Other Layers

Pseudonym V2X certificates can be used as (temporary) identifiers at the application layer for tracking vehicles, during their validity period. However, there exists (temporary) identifiers at multiple layers. For example, in case of IP-based V2X, in addition to V2X certificates, there is an IP address and a MAC address. Any of these might be used for tracking; even if they all change periodically, an identifier remaining unchanged at one layer could be used to link identifiers before and after change at another layer. To prevent linkability, it is necessary – or recommended – to change identifiers in V2X messages at multiple layers simultaneously. ETSI ITS provides this capability in[44] (Section 6.3.1), and SAE provides it in[28] (Section 6.3.6.2). LTE-V2X supports the change of identifiers at multiple layers simultaneously, by changing lower-layer identities when informed that the application layer identifier has changed (see[23], Section 6.6.2). Note that for PC5, the routing of packets is done based on the lower-layer destination address, which is source independent and, as such, cannot be used for tracking, even if it is not changed.

As the change of the lower-layer identities may cause some loss of connectivity or unavailability at application/service level, for applications/services that rely on lower-layer identities, the simultaneous change of identifiers can only be performed when the vehicle is in “safe conditions”. These conditions may be difficult to assess/determine at application or network level. Furthermore, these conditions may be subject to rapid change, depending on vehicle use or environment. There is also a risk that the procedure for the change of the lower-layer



identities might fail, hence, mechanisms to prevent identifier linkability must be considered with caution as there are some potential unwanted/undesired effects.

4.7 Certification

The basic technological precondition that has led to the success story of today's mobile communications is open standardization. Technical specifications pave the way for independent companies to develop wireless communications solutions addressing customers' needs around the world in an open market. Global competition in wireless technology fosters ground-breaking communication features. Before selling any products on the mobile communications market, customers and users have to be convinced that the product offered is able to operate properly in existing networks. A certification regime is established by the mobile communications industry to ensure that equipment from different vendors can be smoothly integrated into the network.

It is becoming even more important for cellular vehicle-to-everything (C-V2X) to ensure that products operate in line with technical specifications and achieve the required performance. C-V2X is expected to become an integral part of future automotive functions, increasing driver convenience, traffic efficiency and, in particular, road safety. The GCF (Global Certification Forum) and the PTCRB (PCS⁹ Type Certification Review Board) are widely recognized certification bodies for mobile communications systems. The established voluntary certification process helps to:

- Ensure high quality of mobile communications products
- Make multivendor mobile communications solutions possible
- Shorten time to market

Up to now, certification has focused on the final user device. It has been extended recently to cover vertical applications as well. In terms of vertical applications, mobile communication is an enabling technology that is integrated as a dedicated subsystem to provide connectivity. Conformity assessment in the sense of final product certification is in case of vertical applications no longer applicable within the telecommunications domain. The final product is assembled outside of this industry. In the case of C-V2X, this is done within the automotive domain, leaving advanced test procedures and further conformity assessments to companies related to automotive production.

⁹ PCS: Personal Communication Services

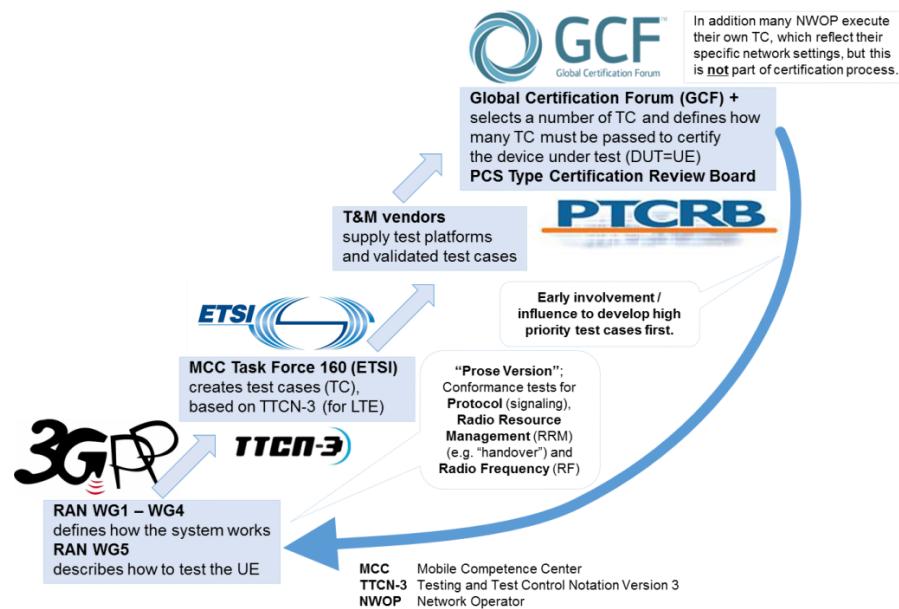


Figure 4.7-1 Certification Process for User Equipment (UE) today

Thanks to the generally accepted voluntary certification framework, the telecommunications industry is well prepared to offer C-V2X vertical-application products that are verifiably:

- In line with radio communications protocol specifications
- Ready for multivendor interoperability
- Able to achieve the required radio performance

Customers can rely on the promise of quality made by the telecommunications industry and connectivity providers.

4.8 Added value of the Mobile Network Operators

V2X use cases are offering a variety of new business opportunities for telco operators. First of all, and as mentioned several times in this white paper, the relevance of the Uu part for V2X communication is without doubt. So, cellular connectivity is and will be installed in nearly every vehicle in the next years for a huge variety of V2N based use cases. If only the sidelink (PC5) based capabilities are considered, the use cases requiring a sidelink communication has to be understood. The major characteristics of these use cases are

- the information exchange between vehicles, and vehicles and infrastructure must be established instantly, with latencies below 100ms,
- the information exchange has only local relevance, so its location based information is in the vicinity of a vehicle within a couple of 100 meters,
- the information exchange must be established agnostic to the vehicle manufacturer or road side unit operator,

- the information exchange must be established regardless of the mobile network operator, the vehicle or traffic roadside unit subscribed to,
- the information exchange must work, regardless whether coverage is provided by the mobile network operator or not.

With the sidelink (PC5) capabilities standardized in the 3GPP, Rel. 14 C-V2X, the 3GPP community is willing make additional major contributions to the mobility and transportation eco-system. That was one reason why NGMN started the V2X-Task Force activity, filing comments to NHTSA's NPRM process¹⁰, and why 5GAA is engaged in various activities such as the go-to-market approach for C-V2X/PC5. This approach is aligned between major car manufacturers, chipset-vendors, as well as mobile network operators and infrastructure suppliers to the operators. Every uncertainty in the market hinders market development and quick penetration of the technology. Significant penetration is needed as it is the major driver for creating customer benefits for a sidelink based communication (peer-to-peer). Even in an unmanaged (mode 4) operation of sidelink communication, the mobile operators are interested to lay a foundation of a highly dynamic, innovation-friendly environment.

Beside the fact that in a mode4 operation there is no need to involve the mobile network operator, the operators can bring in a variety of added value. Also, these value-adds of operators can be best explained by understanding the related uses cases. If a use case, which communicates its data/payload directly between devices, and in which license exempt spectrum such as 5.9 GHz is used, some would argue that there is no need for telco operators. From a very rigid functional perspective, that's true, but from an operational perspective of a customer oriented implementation of a use case, the telco operators are able to deliver a variety of benefits, which at the end delivers the use in a way to be accepted and recognized by the customer:

1. Every sidelink communication needs trust between the communicating partners. The security and privacy concepts (see also Section 4.6) are founded by the implementation and continuous renewal of certificates and certificate revocation lists. To distribute certificates into a vehicle, a couple of technical methods are possible but from a customer convenience point of view the only realistic way to distribute certificates for V2X use cases is cellular connectivity. The telco operators therefore will deliver one major prerequisite to operate V2X sidelink based use cases in a customer friendly way.
2. As mentioned in Section 4.2, the starting scenario of V2X sidelink safety use cases will be most likely a mode 4 operation, so no involvement of telco operators is needed. But the more the eco-system evolves, the greater the need for an efficient use of the 5.9 GHz spectrum. The beneficiaries of efficient spectrum management are primarily the regulators who would see the need for efficient usage of a rare resource. Otherwise, the car manufacturers would request more spectrum from the regulators, most likely more spectrum would be allocated to the use cases, because the use cases are safety related. The telco operators would therefore create benefit for the regulators in using a rare resource as efficient as possible.
3. This will become even more relevant if QoS has to be managed to provide certain KPI's for a specific use case. E.g. truck platooning requires a certain bandwidth and reliability on the sidelink, which can only be provided if

¹⁰ NGMN comment to NHTSA NPRM process, 04/2017:

https://www.ngmn.org/fileadmin/user_upload/170412_NPRM_NGMN_Alliance_v1_0_web.pdf (12.01.2018)



the spectrum, where the information exchange takes place, is managed. Because the truck platoon is initially a commercial use case, the spectrum used as well as the effort to manage the spectrum offers additional business opportunities for telco operators.

In summary, a harmonized communication stack between the mobile network link and sidelink will offer many additional opportunities in the eco-system, which in turn will speed up the development and deployment of new services for connected and automated driving.

4.9 Business Models

As outlined in the preceding sections, cellular communications, as a combination of PC5 and Uu connectivity, are a critical enabling factor in a very broad range of use cases which have widely varying network requirements in terms of latency, throughput, reliability, security, etc. It is also clear that there is a long-term vision roadmap of use cases which will evolve and become technically and commercially viable over a variety of time horizons, which has already been started (Uu), will start soon (PC5), and will continue for several years into the future.

Prominent examples of use cases that combine PC5 and Uu connectivity include the following:

- Video sharing between vehicles
- Information sharing for automated driving
- Cooperative lane change
- Cooperative collision avoidance
- Cooperative driving
- Hazard warning
- Forward collision warning
- Intersection collision warning
- Truck platooning
- Distribution of security certificates

One of the use cases, truck platooning, is analysed in more detail (see Section 4.9.4),

The general market potential of vehicle services (i.e. connectivity-based subscription services) for connected cars (i.e. vehicles with permanent Internet connections based on mobile operator subscriptions) is shown in Statista's Connected Car Market Report, March 2017. Both main service categories (Safety & Security, and Maintenance & Diagnostics including Software Updates OTA) are expected to grow exponentially across the globe in the coming few years.

VEHICLE SERVICES IN MAJOR REGIONS

Market KPI comparison by region



Figure 4.9-1 Vehicle Services in Major Regions (Statista's Connected Car Market Report, March 2017) [45]

According to IDC's Worldwide Semi-annual Internet of Things Spending Guide, May 2017[46], connected vehicle spending in Europe (encompassing Security, Infotainment, Emergency Services and V2V/V2I Advanced Solutions) will represent a multi-billion market, with Germany not only being the biggest market, but also the fastest growing market (CAGR of 22.9% between 2016 and 2021).

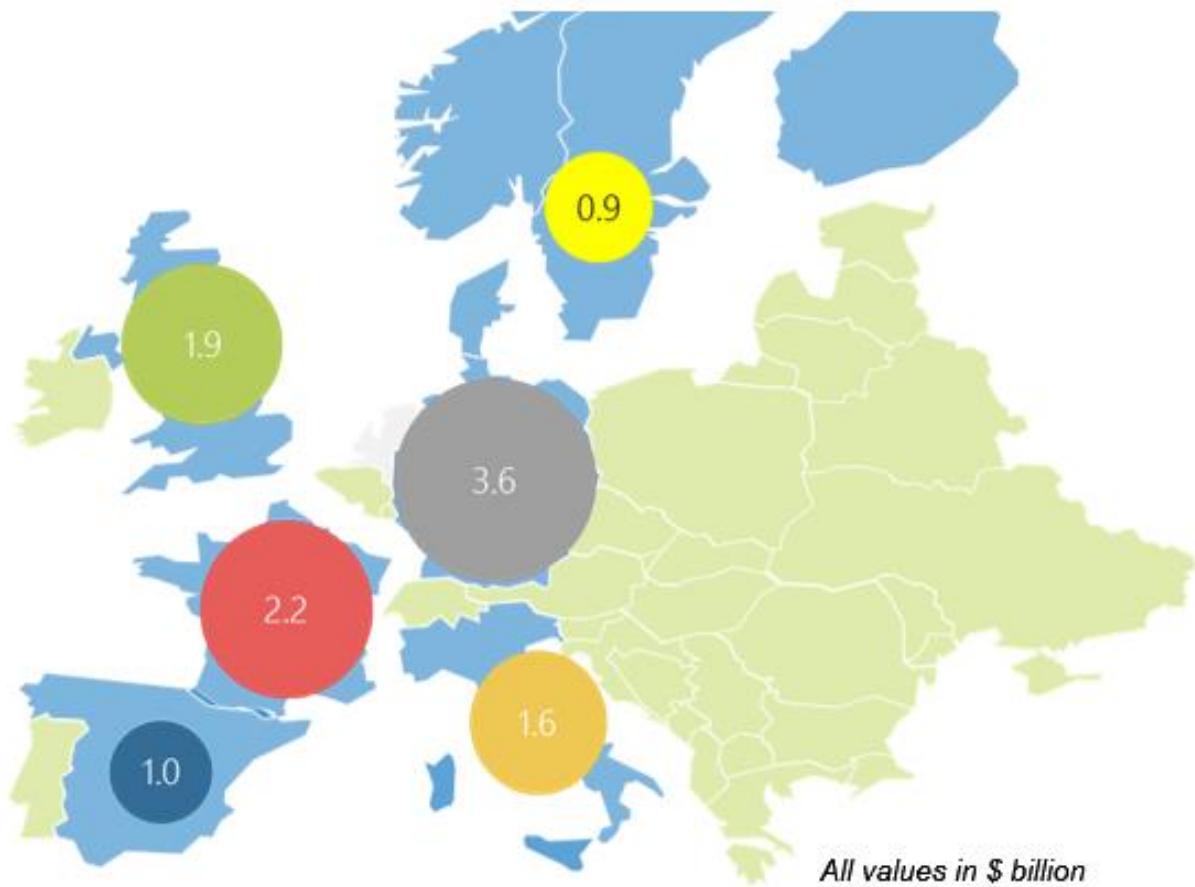


Figure 4.9-2 Connected Vehicles Spending Guide in Europe (IDC's Worldwide Semiannual Internet of Things Spending Guide, May 2017[46])

The widespread adoption of C-V2X across the automotive and telecommunications industries will require investment in development of technical standards, upgrades to the network infrastructure, and the deployment of V2X-capable in-vehicle and roadside user equipment at scale. Whilst the level of investment needed across these domains is not yet accurately estimated, it is clear that a high-level business case for investment will be required. Given that C-V2X will enable an extensive set of use cases, delivering significant benefits for society, commerce and individual consumers, the investment business case must be considered holistically across all potential use cases. The return on investment will ultimately be delivered additively from many use cases, in different forms - including reduced costs, new revenue streams, and tangible and intangible societal benefits.

The full set of use cases enabled by C-V2X technology cannot be known at this point, as innovative new uses for the technology are certain to emerge over time, so this paper does not attempt to exhaustively explore the business model for every use case. It will however give an overview of some of the innovative business models which can be leveraged to maximize the return on C-V2X investment as a whole.

4.9.1 Business model overview

The business model for automotive connectivity has historically been fairly simplistic, with connectivity accessed either through in-built user equipment provided by the OEM or third-party equipment provided by the vehicle user (for example, smartphone); and connectivity data plans paid for by the vehicle purchaser either directly (to the telecoms service provider) or indirectly (bundled with the purchase price of the vehicle).

For example, according to their own announcements, AT&T will have 14 million connected car subscribers in 2017 and Verizon expects that Telematics will generate \$850 million in 2017 from 9.4 million subscribers.

Comparisons with the digital services brought to market via the Internet however suggests that many alternative business models are possible, and may offer significant potential to maximize return on investment.

The business model for a product or service describes how value is **created** for the consumer of that product (the value proposition) and how value is **captured** by the provider of the product or service. In many innovative business models, there are more than two participants and the link between value creation and value capture can be indirect. For example, many successful products and services have been monetized indirectly through advertising and data monetization. From a value creation point of view, the following give some examples of possible mechanisms:

- **Multi-sided markets**: The solution creates an environment where suppliers and consumers of various services can transact in a way that matches supply with demand efficiently, and creates surplus value that benefits all with the processing of transaction data (example: Amazon).
- **Freemium**: A service whose basic form is offered free, but whose continuous or more advanced usage is charged (example: Dropbox).
- **Metered usage**: A service whose usage is charged in proportion to its actual consumption (example: AT&T)
- **Advertising**: A mechanism that allows advertisers to target messages to a service's users, which are matching their expressed or inferred profile, interests, wants or preferences (example: Google).
- **Data & Analytics**: Systems and capabilities that allow the creation of products and services based on insights gleaned from the processing and analysis of data collected during the use of a digital service or device by its customer base (example: Premise).
- **Bundling**: Charging a flat fee for a bundle of service units, regardless of the actual service consumption. Alternatively, provision of more than one service bundles collectively for a single fee (example: Jet).
- **Vertical Integration**: Combination of capabilities, processes and assets from multiple companies for the provision of a single service (example: Tesla).

Value capture mechanisms might be:

- **Licensing**: Paying a license fee to acquire the right to use a solution (Example: Microsoft Office)
- **Premium Service**: A service commanding premium price thanks to its differentiated, non-commoditized, benefits (example: Spotify).

- In-App Purchase: Keeping a share of revenues generated from in-app purchases (example: Clash of Clans)
- Software Subscription: Paying a recurring subscription fee to use a service (example: AVG)
- Razorblade: Subsidizing the bought-once part of a solution and charging for a recurring complement (example: Xbox)
- Outcome-Based Pricing: Charging for a service on the basis of achieved agreed results (example: Google AdWords).
- Membership: Paying a recurring membership fee to use a service or resource (example: Birchbox)
- Price Discrimination: Change price dynamically to optimize the yield of a service (example: Uber)
- Transaction Fees: Pay a service with a fee imposed for every transaction with it (example: Ebay).

In this paper a methodology is used whereby the participants in a use case can be mapped out, so that the flows of value and monetization can be understood. This then allows the potential business models for the use case to be explored and evaluated.

4.9.2 Business Models for use cases that combine PC5 and Uu connectivity

Examining closely the use cases that we identified as characteristic of combined PC5 and Uu connectivity, we can group them in two categories depending on their main benefit but which share common monetization mechanisms.

Safety, Convenience, and Security & Maintenance: Services of this type are critical for the life and comfort of vehicle passengers and vulnerable road users (VRUs), and must come with a strong SLA.

ADAS and Autonomy-related, including Software Updates OTA: Cellular connectivity-dependent ADAS and autonomy capabilities are premium offerings, given the strong SLA they need to carry.

Given these premises:

- VRUs should enjoy safety-critical services targeting them for free, and as soon as they are available
- Vehicles that incorporate the necessary capabilities would carry a premium to cover the cost of the strong SLA
- Services, such as those related to convenience and security, would similarly be premium-priced

Based on the nature of these offerings, they can be monetized in many ways:

- Cost absorbed in vehicle price
- A la carte (incremental pricing per feature), as a bundle of features, or as a basic service complemented with optional add-ons
- One-off payment or subscription-based
- Pay As You Go, or rolling contract
- Bundled with other services (e.g. financing, insurance)

- Using price discrimination per segment as profit maximization mechanism

4.9.3 Ecosystem and Value Networks for C-V2X

The ecosystem surrounding connectivity in automotive is rich and complex, with long value chains between providers of various parts of the solution and the end-consumers. Broadly the ecosystem breaks down into a number of layers as shown in the Table 4.9.3-1. The flow of value and money between players in this ecosystem dictates the essential elements of the business model for a specific use case.

Table 4.9.3-1: Players in the automotive eco-system

Automotive OEMs	<ul style="list-style-type: none"> • Cars • Trucks
Suppliers	<ul style="list-style-type: none"> • Tier 1 & 2 (System Integrators) • Wireless Module Vendors • Chipset Vendors • Software/Solutions • Middleware • Connectivity/Bluetooth • Graphics HMI • Databases
Connectivity Players	<ul style="list-style-type: none"> • Mobile Network Operators • TSPs • ICT Solution & Cloud Platform Providers • ITS
App platforms	<ul style="list-style-type: none"> • Unconnected • Software-based • Fleet / Commercial • Autonomous Driving • Smartphone Platforms
Apps	<ul style="list-style-type: none"> • Telematics / Tracking • Safety & Maintenance • Media & Entertainment • Communications • Productivity • Maps & Navigation • Mobility as a Service
Business Users	<ul style="list-style-type: none"> • Freight • Company Fleets • Car Rental • Taxi Fleets • Delivery • Public Transport • Emergency Response
Consumers	<ul style="list-style-type: none"> • Consumers • Families • SoHo
Additional stakeholders	<ul style="list-style-type: none"> • Insurance • Dealers • Auto Repair • Regulatory Bodies • Local Authorities (Government, Law Enforcement, Smart City, Road Operators) • Location-based commerce players

- Security infrastructure and services providers

4.9.4 Example C-V2X use case: Truck Platooning

Truck Platooning offers an exemplary use case leveraging C-V2X to deliver significant commercial and societal value. The basic proposition is straightforward, making use of autonomous driving capabilities to allow commercial heavy good vehicles to safely maintain shorter separation distances at higher speeds, with reduced driver involvement, thus delivering savings in fuel consumption and driver costs.

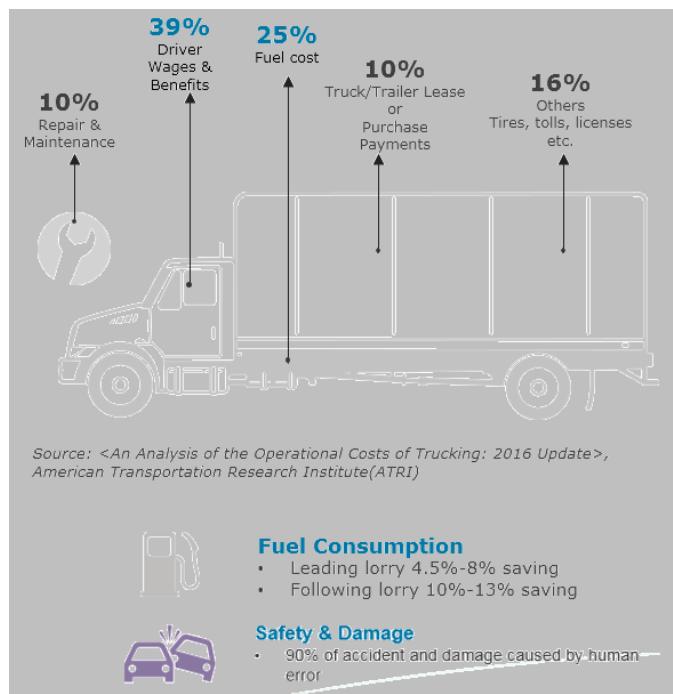


Figure 4.9-3 Driver wages/benefits is the greatest cost in US trucking

The core value of truck platoons for truck operators arise from cost reductions. As shown in Figure 4.9-3 (source: An Analysis of the Operational Costs of Trucking: 2016 Update, American Transportation Research Institute-ATRI,[47]) , the two largest operating costs associated with a truck are the driver and fuel costs, both of which can be potentially reduced through platooning.

In a platoon, two or more trucks drive closely together using sensors, communication and automation to safely narrow the driving gap between them. This brings aerodynamic advantages, reducing overall drag for both trucks thus reducing the amount of fuel required (and hence CO₂ emitted), by approximately 10%. In a platoon, the lead truck is (initially at least) controlled by a human driver; however the drivers in following trucks are not continuously in control since the automation system controls acceleration and braking. This opens up an opportunity for the drivers in following trucks to take rest breaks whilst in the platoon, increasing the overall time the truck can be moving without a rest break being required. As an additional benefit, it is anticipated that the incidence of accidents involving trucks will be reduced through the automation in a platoon which reduces costs for fleet operators, insurers and society in general.

C-V2X technology has an instrumental role to play in truck platooning, as connectivity will be required between trucks in the platoon and from the platoon to the wider environment within which it operates. Within the platoon there is an obvious need for reliable low-latency V2V communications from truck to truck, so that the following trucks can react quickly and safely to (for example) braking of the lead truck. But, there is also a requirement for V2I communications for exchanging information with the local road network, and V2N communications to receive updates about the wider road network and to ensure that appropriate systems are kept updated about the platoon – for example, smart city and road operations systems.

A value network for C-V2X enabled platooning is shown in Figure 4.9-4 (partially based on “Truck Platooning: Driving The Future Of Transportation”, TNO, February 2015, [48]).

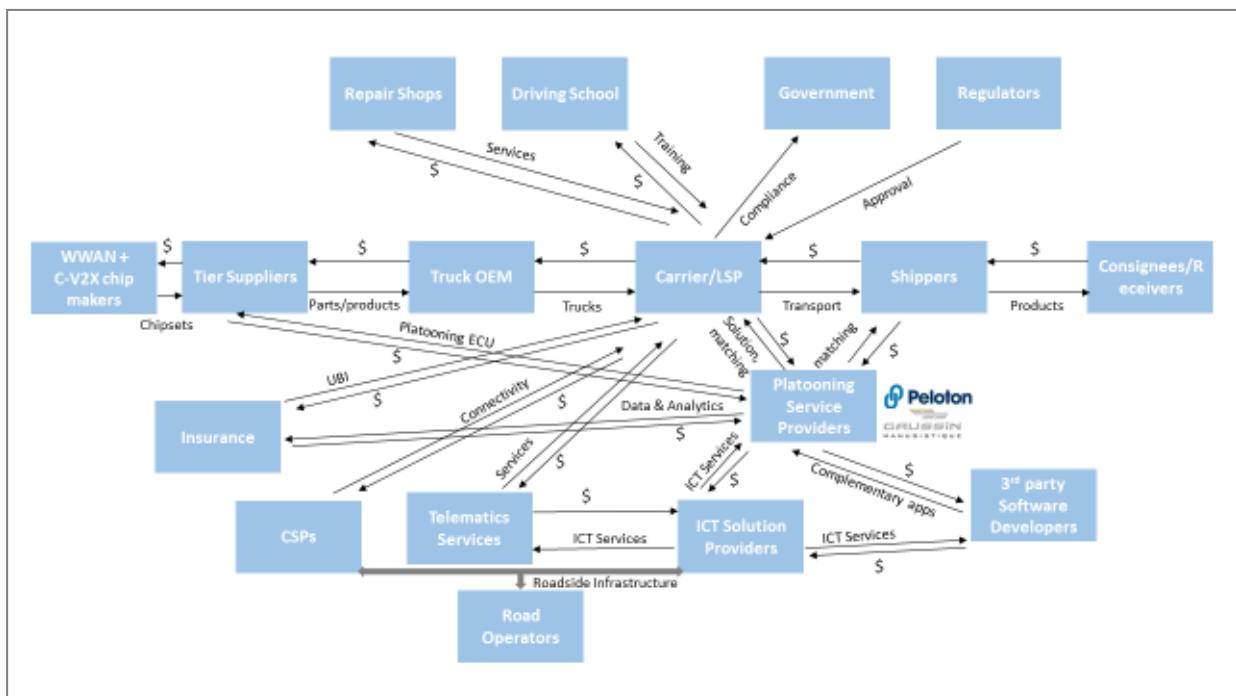


Figure 4.9-4 Value network showing integrated platooning and services exchanged

In this platooning example, it is assumed that the hardware and software capability within the truck is provided by the OEM, sourced from one or more suppliers. It is further assumed that there will be a centralized control of platoons, operated by a platooning service provider. This provides a way for different truck operators using different brand trucks to schedule and form platoons, as well as being a central point for data collection and exchange with other systems such as road operators and fleet management systems.

A number of potential business models exist for this platooning scenario – elements of which might include subscription or pay-as-you-go fees from truck operators for access to the platooning service, sales of derived data to road operators or insurance companies, fees paid by the platooning service operator to high-definition specialist

map providers etc. Some of the potential value creation and value capture mechanisms are captured in the table in Figure 4.9-5.

Offerings		Core Telco Services	Advanced Connectivity	Ecosystem Tech. Enablement	Ecosystem Business Enablement	Apps & Platform	Data Monetization
Customers		<ul style="list-style-type: none"> Seamless Global Connectivity 	<ul style="list-style-type: none"> 5G, C-V2X, Slicing NFV/SDN, MEC 	<ul style="list-style-type: none"> API's, ID, Device, Location OBD-II 	<ul style="list-style-type: none"> Distribution, Tech & Cust. Support, Payments, Billing 	<ul style="list-style-type: none"> App Dev, Promotion, Discovery, Monetization 	<ul style="list-style-type: none"> Advertis., Dyn. Pricing, eCommerce, Analytics
Business Users	<ul style="list-style-type: none"> Freight Distribution Haulage Logistics Other Company Fleets 	<ul style="list-style-type: none"> Global Connectivity and ICT for P2P and telematics applications Bundled Connectivity for Platooning C-V2X Contract for P2P/telematics connectivity & ICT 	<ul style="list-style-type: none"> Bundled C-V2X incl. V2V 	<ul style="list-style-type: none"> Bundled Positioning 	<ul style="list-style-type: none"> Customer support and billing bundled 	<ul style="list-style-type: none"> Platooning hardware & software Cloud NOC Bundled apps Premium apps (e.g. see through) Managed service fees Subscription/Membership In-App Purchase % 	<ul style="list-style-type: none"> Data & Analytics Subscription/Membership Outcomes-based Pricing
Apps	<ul style="list-style-type: none"> Telematics / Tracking Safety & Maintenance Media & Entertainment Comms & Productivity Maps & Navigation Mobility as a Service 					<ul style="list-style-type: none"> Application development environment Access to user base Promotion, discovery, monetization In-App Purchase % 	<ul style="list-style-type: none"> Data & Analytics Subscription/Membership Outcomes-based Pricing
Automotive OEMs	<ul style="list-style-type: none"> Trucks 	<ul style="list-style-type: none"> Global Connectivity and ICT for P2P and telematics applications Bundled Connectivity for Platooning C-V2X Contract for P2P/telematics connectivity & ICT 	<ul style="list-style-type: none"> Bundled C-V2X incl. V2V 	<ul style="list-style-type: none"> Bundled Positioning 	<ul style="list-style-type: none"> Customer support and billing bundled 	<ul style="list-style-type: none"> Platooning hardware & software Cloud NOC Bundled apps Premium apps (e.g. see through) Managed service fees In-App Purchase % 	<ul style="list-style-type: none"> Data & Analytics Subscription/Membership Outcomes-based Pricing

Value Creation

Value Capture

Figure 4.9-5 Platooning Business Models – ICT Offering Stack Value Creation & Capture

4.9.5 Business Model Summary

The Truck Platooning use case example shows that there are multiple ways to monetize services that relying on C-V2X technology. On top of the value capture methods presented, potential secondary monetization mechanisms from the deployment of C-V2X (especially for OEMs) include:

- Enjoying increased demand for C-V2X-equipped vehicles as additional segments enter the market thanks to enhanced autonomy
- Bringing in younger customers
- Boosting customer retention
- Having more options and features to sell
- Monetizing the increased vehicle-miles travelled, and the higher per-vehicle service because of proactive servicing and as vehicles are more sophisticated and run harder
- Modernizing public and private transportation systems

To conclude, it is highly likely that a combination of use cases can generate a sufficient return on investment for the main players (primarily automotive OEMs and telecom service providers) to justify the investment in technology development and rollout.

5 Way forward

5.1 Roadmap

With the finalization of the 3GPP Rel. 14 in March 2017, C-V2X is seen as a key step for the market introduction of V2V and V2I use cases. As the members of 5GAA have announced [49], they will test and validate the C-V2X technology to make it commercially available for vehicles beginning in 2021.

Because in this point in time, nearly every new produced vehicle will be production wise equipped with cellular technology for their V2N communications, and because of the C-V2X functionality can and will be included as part of the cellular chipsets, nearly every new produced vehicle will be equipped with C-V2X technology[50].

Deployment of LTE-V2X (V2V / V2I)

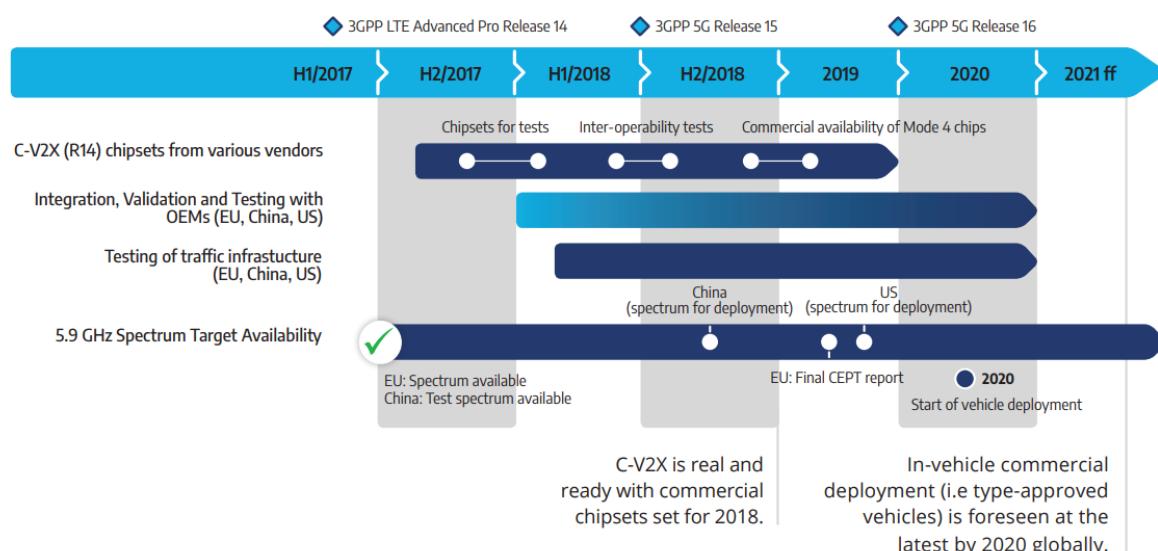


Figure 5.1-1 timeline for the deployment of C-V2X technology in vehicles and in traffic infrastructure components from 5GAA

Four contributors in the NGMN, which are the chipset vendors CATT, Huawei, Intel, Qualcomm, and a 5th chipset vendor Samsung are committed to provide C-V2X chipsets. These vendors provide nearly all communication chipsets used in connected cars for V2N purposes on our roads today.

Various vehicle manufacturers (Audi, Ford, SAIC, BMW), and automotive suppliers (Continental) including supportive vendors, CATT, Qualcomm have already announced intensive further testing including interoperability tests among chipset manufacturers and across vehicle manufacturers targeted to be conducted by mid-2018[51][52][53][54]. Announcements made by Qualcomm [55] and Rohde&Schwarz [56] indicate the successful launch of the first commercial chipsets in the second half of 2018. The vehicle manufacturers organised in the

5GAA forecast starting production tests with the C-V2X V2V commercial chipsets and communication modules in 2019 for commercial deployments beginning of 2021.

To ensure that also the V2I and I2V use cases are enabled the 5GAA expects parallel testing for the deployment of traffic related roadside units (RSUs) in Q1 2018. With reference to the benefits of V2N communication, the road operators are recognizing that most of the planned V2I use cases could be realized with a much quicker effect to a broader customer group, if the safety information would be distributed via cellular networks. Examples were given in Section 3.4.

These benefits could be created for all traffic participants using cellular infrastructure, regardless of whether they use fixed installations in the vehicle, or via smartphones, or use aftermarket devices.

In terms of regional deployments, see Section 5.3.

5.2 NGMN Role and Activities

NGMNs general view on V2X is maintained by continuously updating an overview on the relevant stakeholders of the automotive eco-system, namely

- Car manufacturers/1st tiers
- Fleet operators
- Insurance, maintenance, and other service providers
- Road operators, traffic infrastructure providers (parking operators, , ...)
- Public transportation
- Infotainment, media
- Tolling operators
- Public safety organisations

According to the market needs of the various stakeholders NGMN members will continually spend effort in developing and standardizing capabilities the mobile network can provide. Examples are

- QoS/Predictability/Network Slicing,
- Low latency/ultra reliability/local context/edge compute
- Direct communication/C-V2X
- Precise positioning and position integrity/precise positioning as mobile network service
- Multiple contracts (vehicle/customer)/dual eSIM approaches

With regard to go-to-market strategies, NGMN carefully monitors possible barriers to a quick market introduction and will derive counter measures when needed. This addresses for example

- Positioning of C-V2X against 802.11, market introduction, spectrum sharing in 5.9 GHz,
- C-V2X/PC5 in licensed spectrum, truck platooning, what spectrum, multi-PLMN operation,
- E2E QoS (incl. predictability) cross PLMN's
- Multi-PLMN edge compute

V2X needs collaboration amongst a variety of stakeholders represented by various organisations, therefore NGMN and their members collaborates with the relevant stakeholder organisations, e.g.

- 5GAA
- 3GPP
- ETSI

- GSMA
- ITU
- IETF
- AECC
- SAE
- EATA
- ASECAP and IBTTA

6 Conclusions

This white paper presents a summary of the findings of the NGMN V2X task force. NGMN concludes with the following key points:

- To date, NGMN members have provided cellular connectivity to more than 30 million vehicles worldwide which are used for a variety of safety related use cases (e.g. distribution of end of traffic jam warning, black ice warnings, etc.). It is expected, that in the near future, every vehicle will be equipped with cellular connectivity. This is a good and market driven basis for further deployment of further C-V2X technology and services.
- With the finalization of 3GPP Rel. 14 specifications at the beginning of 2017, NGMN members now have a 3GPP standardized solution, which supports both long range as well short range communication, and which fulfils all the requirements of a C-ITS eco-system.
- After already ongoing tests, the technology will be deployed by 2020.
- NGMN believes that C-V2X is not only able to enhance safety features for vehicles, but also supports use cases for other traffic participants, such as pedestrians and cyclists.
- NGMN has investigated and concluded that C-V2X technology is superior to IEEE 802.11p standards, technically, economically, and eco-system wise, and can well satisfy basic safety applications.
- NGMN studies found the following technical advantages of C-V2X:
 - It has better performance than IEEE 802.11p, e.g. in communication range, latency and scalability;
 - It can be harmonized with cellular technology and easily utilize the benefits of cellular technology, such as improving the penetration of C-V2X based on high penetration of cellular vehicle terminals and mobile phones, disseminating information using cellular broadcast and decrease the investment in infrastructure by reusing already deployed cellular networks.
 - It has a natural evolution path to future advanced applications by updating current networks to 5G.
- NGMN supports the go to market statements from major industry stakeholders, such as car manufacturers and chip-set suppliers, and collaborates with the relevant industry associations, such as 3GPP, ETSI, and 5GAA.
- NGMN members are engaged with other partners of the eco-system in ongoing tests in various trials worldwide; NGMN fully supports the timeline of go to market for C-V2X technology using chipsets commercially available from major chipset vendors by Q3/2018 for deployment in vehicles at the beginning of 2020.



- There are solutions for major topics for C-V2X market introduction, such security, spectrum, multi operator deployments, and others, which are described in detail in this white paper. There are of course also some open issues, which are also described in this paper.

This paper recommends to the players in the C-V2X eco-system to take note of the NGMN V2X Task Force studies and findings. NGMN expects that related SDOs and stakeholder organisations will take the content of this White Paper and the recommendations into account in their future work.

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Annex A Typical use cases and requirements

A.1 Road safety application

A.1.1 Forward Collision Warning (V2V communication)

The vehicle equipped with a V2X module periodically broadcasts the message named BSM in SAE standard or CAM in ETSI standard, indicating its current location, speed, acceleration and optional estimated trajectory. The adjacent back vehicles equipped with V2X modules receive the broadcasted message and determines whether a risk of forward collision will happen. The adjacent back cars with driver assistance void forward collision.

In[57][58], the communication requirements of this use case is as follow:

Item	Value
maximum absolute velocity	250km/h
communication range	Short range, the range should be sufficient to give driver(s) in adjacent cars ample response time.
maximum latency	100ms
minimum frequency	10messages/s
message payload	50-300Bytes, maximum : 1200bytes

A.1.2 Roadwork Warning (V2I communication)

A road infrastructure with equipped V2X broadcasts the information on current valid roadwork and associated constraints. The adjacent vehicles receiving this information can take immediate action (e.g. change lanes). The remote vehicles receiving this information can also reroute their navigation. This use case can reduce the risk of accident at roadworks and improve traffic efficiency.

In[57][58], the communication requirements of this use case is as follow:

Item	Value
maximum absolute velocity	250km/h
communication range	Short range and long range
maximum latency	100ms
minimum frequency	2 messages/s
message payload	50-300Bytes, maximum : 1200bytes

A.1.3 Vulnerable Road User (VRU) Safety (V2P communication)

A vehicle and a pedestrian are both equipped with V2X modules, periodically broadcast their own current location, speed, acceleration and optional estimated trajectory. Nearby vehicles can receive, decode, and process messages and provide warnings to drivers to avoid collision with the vulnerable road user.

In[57][58], the communication requirements of this use case is as follow:

Item	Value
maximum absolute velocity	vehicle :250km/h depending on Vulnerable road user type, pedestrian(5km/h),bicycle(15km/h)
communication range	Short range
maximum latency	100ms
minimum frequency	1 messages/s
message payload	50-300Bytes, maximum : 1200bytes

A.2 Traffic management and efficiency

A.2.1 Cooperative Adaptive Cruise Control (V2V communication)

A vehicle with V2V capability joins and leaves a group of corporative-adaptive-cruise-control (CACC) vehicles. This provides convenience and safety benefits to participating vehicles and also has societal benefits to improve road congestion and fuel efficiency.

In [57][58], the communication requirements of this use case is as follow:

Item	Value
maximum absolute velocity	250km/h
communication range	Short range
maximum latency	100ms
minimum frequency	1 messages/s
message payload	50-300Bytes , maximum : 1200bytes

A.2.2 Curve Speed Warning (I2V communication)

The curve speed warning application alerts the driver to manage curves at appropriate speeds.

In [57][58], the communication requirements of this use case is as follow:

Item	Value
maximum absolute velocity	250km/h

communication range	Short range
maximum latency	100ms
minimum frequency	1 messages/s
message payload	50-300Bytes , maximum : 1200bytes

A2.3 Traveller Information Alert (V2N2V communication)

When a vehicle's sensors detect important events (e.g. accident, airbag deployed, hazardous road conditions detected), its V2X module sends a Traveller Information Message (TIM) indicating its current location, speed, acceleration, event type, and any other additional information to an application server (AS) over the Uu interface. It may also send the same information over the PC5 interface which is outside the scope of this use case. How the AS handles the message is application specific and is also outside the scope of this use case. The AS will then multi-cast a notification using the Uu interface to vehicles and smartphones that have subscribed to the service within the “area of relevance”. AS will determine what the “area of relevance” is. The devices that receive the notification need not have any V2X capability. The devices can use the information to take action such as updating their navigation systems or to alert the drivers.

Item	Value
maximum absolute velocity	250km/h
communication range	>300 meters
maximum latency	10 sec (V2N2V)
minimum frequency	1 multicast every 30 seconds from N2V
message payload	300-1200 bytes

A.3 Infotainment and others

A.3.1 Automatic access control/parking access (V2I communication)

Upon signalization of an access controlled area (e.g. a private or public parking), a concerned vehicle entitled to access this area will supply its identity to the road side unit to obtain the right to access the area.

In [57][58], the communication requirements of this use case are as follow:

Item	Value
maximum absolute velocity	250km/h
communication range	Short range
maximum latency	100ms
minimum frequency	1 messages/s
message payload	50-300Bytes , maximum : 1200bytes



A.3.2 Security Certificate Revocation List (CRL) Distribution (N2V)

A vehicle's certificate may need to be revoked for a number of reasons such as faulty hardware/software sending erroneous data or the V2X system in the vehicle is hacked. The Security Credential Management System will manage the CRL list and periodically send the list to ALL the vehicles under its jurisdiction via multi-cast over Uu interface. Vehicles that don't receive the CRL via multi-cast can still procure the list via on-demand unicast via Uu interface. CRLs can also be distributed via RSUs with PC5 interface, this is outside the scope of this use case.

Item	Value
maximum absolute velocity	250km/h
communication range	N/A (vehicle within a MNO coverage area should be able to receive CRLs)
maximum latency	Not Critical
minimum frequency	1 multicast every 15 minutes
message payload	Up to 400 KBytes

Annex B Simulation assumptions and parameters

B.1 Evaluation scenarios

Performance results of C-V2X and DSRC are obtained from system level simulations. Assumptions made for the evaluation are derived from 3GPP[59]. System performance is investigated considering two environments:

- Urban: Vehicle velocity 15km/h and 60km/h, vehicles drive on two lanes per direction.
- Freeway: Vehicle velocity 70km/h and 140km/h, vehicles drive on three lanes per direction.

Configuration parameters and values are stated in Table B.1-1.

Table B.1-1: Simulation Parameters

Parameter	Value	
Carrier frequency	PC5 based V2V& DSRC: 5.9GHz	
Bandwidth	PC5 based V2V & DSRC: 10MHz	
Number of carriers	1	
Synchronization	Frequency Error	Two assumptions for DSRC and LTE-V2X PC5 are made <ul style="list-style-type: none"> – Constant frequency error [Reference Annex B.7] – Uniformly distributed frequency error [Reference Annex B.7]
	Time Error	Assumed ideal for LTE-V2X PC5 and DSRC
Vehicle UE	In-band emission	For LTE-V2X defined in [3GPP TR 36.843, A.2.1.5]
	Antenna height	1.5m
	Antenna pattern	Omni 2D
	Antenna gain	3dBi
	Maximum transmit power	23dBm
	Number of antennas	1 TX and 2 RX antennas for LTE-V2X PC5 and DSRC. Baseline is that 2 RX antennas are separated by wavelength/2.
	Noise figure	9dB

B.2 Scenario Setup and Mobility Model

Vehicle UE location in urban and freeway scenarios follow values obtained from a spatial Poisson process. The assumed minimum safety distance between vehicles depends on velocity configured for the specific simulation. Mobility is assumed in both scenarios with an additional parameter to consider the intended direction at intersections in the urban environment. Subsequent probability values are applied:

- Go straight: 0.5
- Turn left: 0.25
- Turn right: 0.25

Details of the vehicle UE drop and mobility model for urban and freeway environments are shown in Table 3.1-2.

Table B.2-1: Scenarios Setup

Parameter	Urban case	Freeway case
Number of lanes	2 in each direction (4 lanes in total in each street)	3 in each direction (6 lanes in total in the freeway)
Lane width	3.5m	4m
Road grid size by the distance between intersections	433m * 250m. Note that 3m is reserved for sidewalk per direction (i.e., no vehicle or building in this reserved space)	N/A
Simulation area size	Minimum [1299m * 750m]	Freeway length >= 2000m. Wrap

		around should be applied to the simulation area.
Vehicle density	Average inter-vehicle distance in the same lane is 2.5m (baseline) or 4s * absolute vehicle speed. Baseline: The same density/speed in all the lanes in one simulation.	
Absolute vehicle speed	15 km/h, 60 km/h	140 km/h, 70 km/h

Figures B.2-1 and Figure B.2-2 illustrate the road configuration of the two environments, urban and freeway respectively.

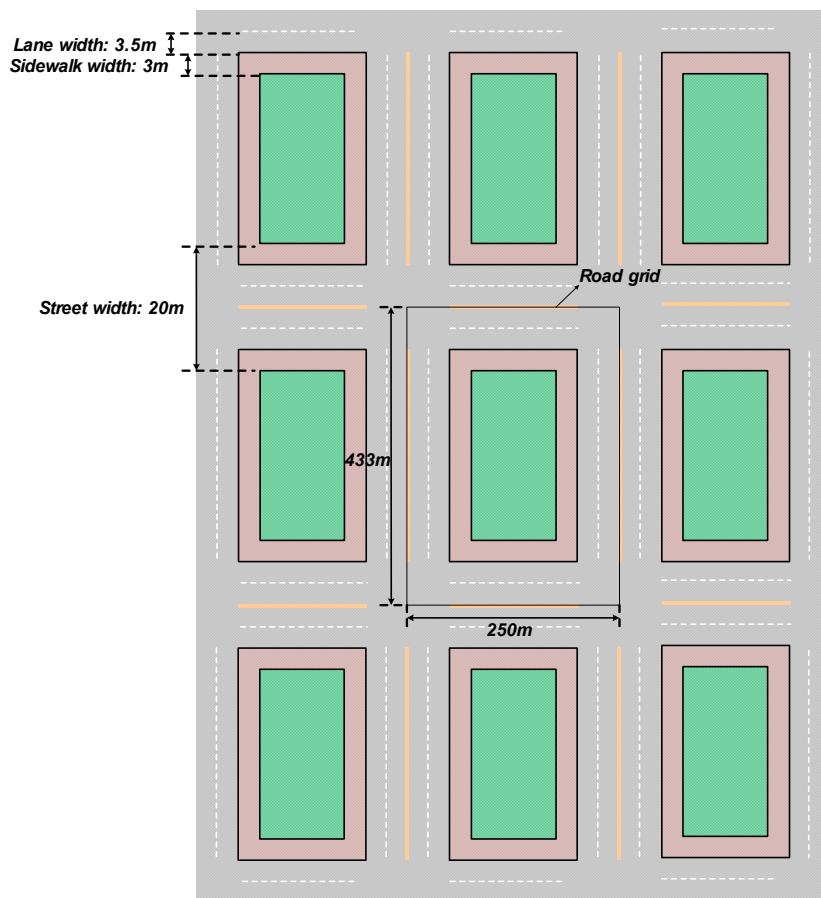


Figure B.2-1: Road configuration for urban environment

Lane width: 4m

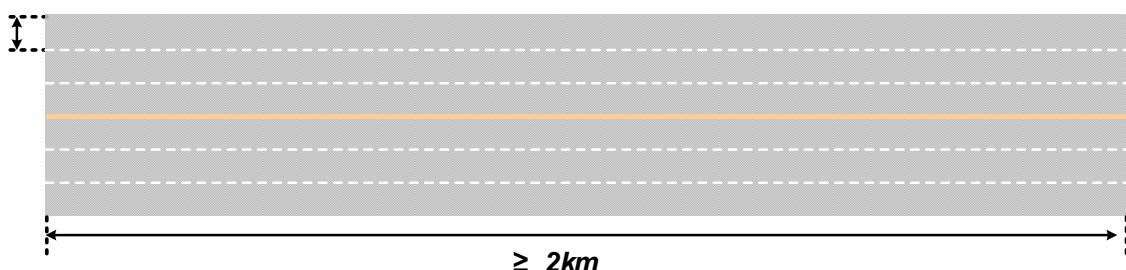


Figure B.2-2: Road configuration for freeway environment

B.3 Channel model

Values stated in Table B.3-1 are assumed for radio channel configuration.

Table B.3-1: Channel Model Configuration for V2V

Parameter		Urban case	Freeway case	
Pathloss model	Description	WINNER+ B1 Manhattan grid layout	LOS in WINNER+ B1	
	Antenna Height	1.5m		
	Pathloss (< 3m)	Pathloss at 3m		
Shadowing distribution		Log-normal		
Shadowing standard deviation		Line of Sight (LOS): 3dB Non-Line of Sight (NLOS): 4dB	3dB	
Decorrelation distance		10m	25m	
Fast fading		NLOS with fixed large-scale parameters during the simulation defined in [TR 36.843, A.2.1.2.1.1 or A.2.1.2.1.2].		

B.4 Traffic model for V2V

Data traffic offered from vehicles in this scenario is either generated recurrently, then periodic or generated after a single event has occurred. The system level simulation distinguishes data traffic generated on the application layer:

- Periodic: 300 byte message followed by four 190 byte messages, time instance to generate 300 byte message is randomized amongst vehicles in the specific scenario. Inter-message arrival time is 100ms in each scenario.
- Event-triggered: Six 800byte messages with inter-message arrival time 100ms, probability that the first message is generated follows from the Poisson process with company specific arrival rate per second and per vehicle.
-

It is mandatory to assess periodic data traffic. However, it is the companies' decision to consider periodic traffic in addition when evaluating optional event-triggered traffic. For each application layer message, the following additional link layer overhead may or need not be taken into account in the evaluation, see Table B-4-1. Other values assumed for protocol related overheads are not precluded.

Table B-4-1: Additional Protocol Control Information

Technology	Layer 2 Protocol Control Information				
	Sublayer	MAC	RLC	LLC	PDCP
LTE-V2X	10 byte	1 byte	—	5 byte	Total: 16 byte
DSRC	30 byte	—	8 byte	—	Total: 38 byte

B.5 Performance Metric: Reliability & Communication range

System performance is evaluated in terms of Packet Reception Ratio (PRR). This metric states the number of UEs having successfully received one transmitted data packet (denoted X) to the total number of UEs (denoted Y) in the distance of interest.

$$PRR[\%] = \frac{X}{Y}$$

Calculation of the Cumulative Distribution Function (CDF) considers distance between transmitter and receiver from range (a, b). Following values stated in Table B.5-1 are applied.



Table B.5-1: Distance between transmitter and receiver in freeway and urban environment

Parameter	Environment	Freeway	Urban	Value Urban, 15km/h (optional)
a [m]		0	0	0
b [m]		320	150	50

The average PRR value is obtained from calculation:

$$PRR [\%] = \frac{X_1 + X_2 + \dots + X_n}{Y_1 + Y_2 + \dots + Y_n}$$

Same introduced parameters X and Y are applied and index n states the number of generated messages during simulation runtime. Distance of interest is in range (a,b) with values:

$$a = i * 20[m], b = (i + 1) * 20[m], \text{with } i = 0, 1, \dots, 25$$

B.6 Channel Model Calculation

Vehicle-to-vehicle channels are updated during the simulation as follows:

- Let N be the number of vehicle UE in system simulation
- Initialization (at time 0)
 - N vehicle locations are generated per agreed drop model
 - PL (0) – NxN matrix generated as per vehicle locations and agreed channel models
 - Shadowing (in log domain): S(0) – NxN i.i.d. (with the exception that shadowing between two vehicles should be the same in the two directions) normal matrix generated as per agreed shadowing model
 - Fading (0) – NxN i.i.d. processes with a common distribution
- Update (at time 100*n ms)
 - Vehicle locations are updated as per agreed update rules
 - PL(n) – N x N matrix generated as per updated vehicle locations
 - S(n) = exp(-D/D_corr) .* S(n-1) +sqrt{ (1-exp(-2*D/D_corr))}.*N_S(n)
 - where N_S(n) is an NxN i.i.d. (with the exception that shadowing between two vehicles should be the same in the two directions) normal matrix generated as per the agreed shadowing model
 - D is the update distance matrix where D(i,j) is change in distance of link i to j from time n -1 to time n
 - Fading process is not impacted due to vehicle location updates – fading is only updated due to time e
 - UE performance should reflect fast fading variation within the subframe

B.7 Frequency error

- Baseline is to evaluate both Case 1 and Case 2.
- Case 1: The extreme case should be assumed, i.e., frequency error between TX and RX is fixed as X PPM.
 - X = 0.3 for LTE-V2X
 - X = 40 for DSRC
- Case 2: Frequency error in each UE is uniformly distributed [-Y, Y] PPM w.r.t. UE's sync reference.
 - Y = 0.1 for LTE-V2X
 - Y = 20 for DSRC



Annex C Comparison Tables for SLS Results

Within the NGMN project on V2X, a number of companies (Datang, Ericsson, Huawei, LGE, Nokia) provided comprehensive simulation results on link level as well as system level for LTE-V2X/PC5 compared to DSRC/802.11p. The simulation considered both mode 4 and mode 3 on system level. The following tables compare simulation results.

Table C-1: Comparison Table of SLS Results – PC 5 Mode 4 vs IEEE 802.11p (Urban)

Urban					
Speed	PRR	3GPP LTE-V2X (distance in m)	IEEE 802.11p (distance in m)	Gain (in m)	Gain (in %)
Average 60 km/h Urban	95%	66 [61, 67]	40 [38, 43]	25 [19, 27]	63 [45, 68]
	90%	82 [77, 84]	59 [55, 60]	22 [20, 25]	37 [33, 42]
	80%	101 [98, 106]	78 [71, 81]	22 [17, 27]	29 [21, 38]

Table C-2: Comparison Table of SLS Results – PC5 Mode 3 vs IEEE 802.11p (Freeway)

Freeway					
Speed	PRR	3GPP LTE-V2X (distance in m)	IEEE 802.11p (distance in m)	Gain (in m)	Gain (in %)
Average 70 km/h Freeway	95%	245 [200, 289]	88 [81, 95]	146 [85, 207]	182 [111, 254]
	90%	306 [280, 331]	150 [142, 157]	157 [139, 174]	106 [97, 114]
	80%	368 [356, 379]	195 [179, 211]	185 [168, 201]	89 [80, 99]
Average 140 km/h Freeway	95%	408 [395, 415]	148 [135, 157]	260 [256, 264]	177 [163, 193]
	90%	444 [440, 451]	186 [170, 196]	258 [245, 270]	139 [124, 159]
	80%	490 [485, 500]	214 [191, 230]	276 [256, 294]	130 [111, 154]

Table C- 3: Comparison Table of SLS Results – Freeway, PC5 Mode 3 vs Mode 4

Freeway					
Speed	PRR	3GPP LTE-V2X Mode 3 (distance in m)	3GPP LTE-V2X Mode 4 (distance in m)	Gain (in m)	Gain (in %)
Average 70 km/h Freeway	95%	245 [200, 289]	139 [112, 165]	106 [88, 124]	77 [75, 79]
	90%	306 [280, 331]	223 [167, 278]	83 [53, 113]	44 [19, 68]
	80%	368 [356, 379]	293 [241, 344]	75 [35, 115]	29 [10, 48]
Average 140 km/h Freeway	95%	408 [395, 415]	264 [220, 312]	143 [103, 175]	57 [33, 80]
	90%	444 [440, 451]	335 [309, 353]	109 [88, 131]	33 [25, 42]
	80%	490 [485, 500]	410 [392, 423]	81 [72, 93]	20 [17, 24]