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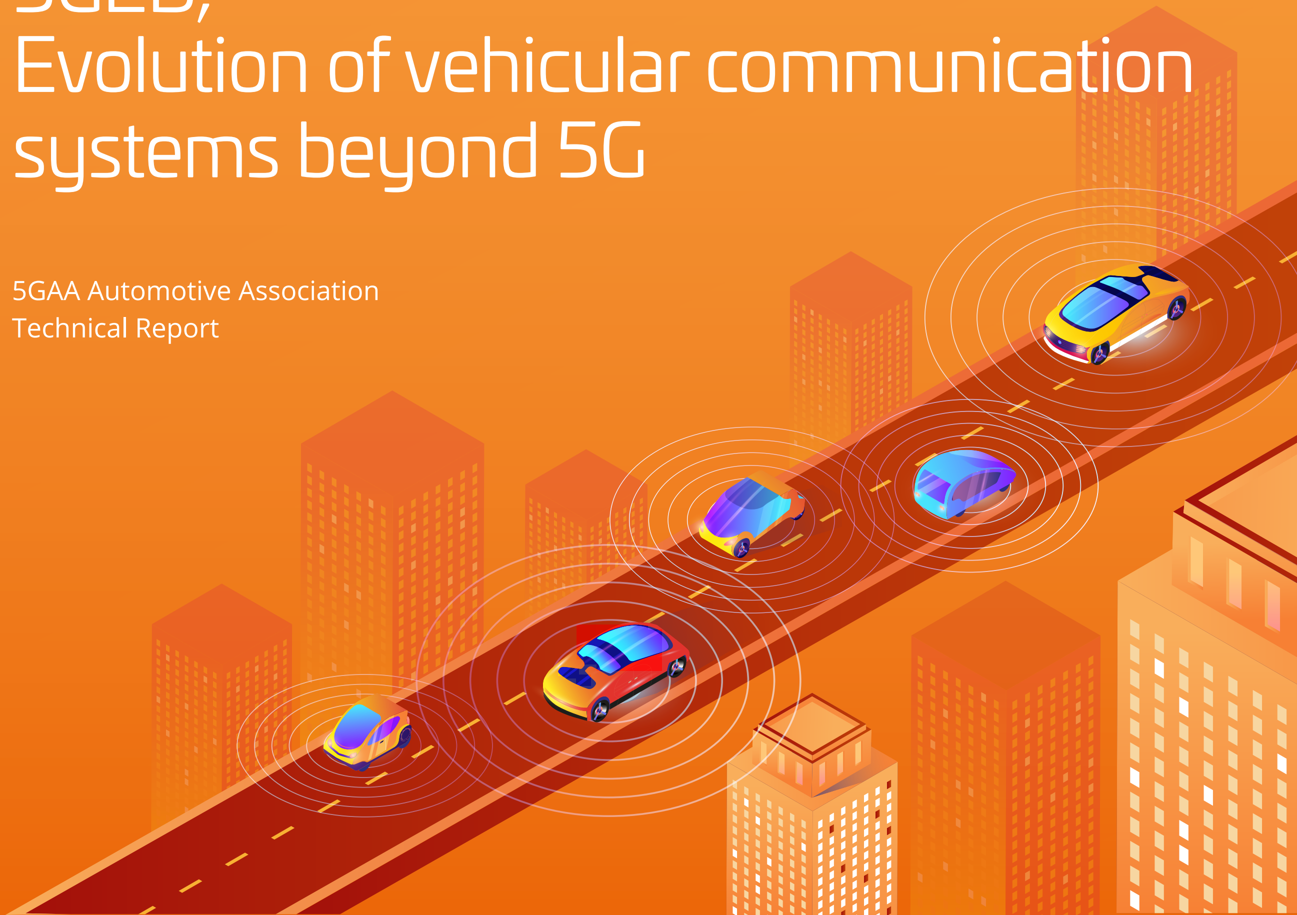
Evolution of vehicular communication systems beyond 5G

5GAA Automotive Association
Technical Report



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Contents

1 Introduction

In recent years, 5G communication standards have started to systematically address the wireless communication requirements of vertical industries such as the automotive sector. Development of 5G communications systems for vehicular use cases, referred to as 5G-V2X, has enabled a number of automotive services that significantly improve the level of safety, efficiency and comfort experienced by traffic participants. In this context, joint efforts from stakeholders in telecommunications and transportation play an essential role in making these services a reality.

The 5G Automotive Association (5GAA), a cross-industry organisation, has over the past five years devoted significant time and effort into better understanding the use cases and requirements for developing technical solutions, carrying out trials, building business models and market strategies, and fostering multi-industry consensus among relevant communication standards organisations. Such an endeavour is bringing end-to-end mobility solutions based on common understanding and setting the stage to support their smooth rollout in several regions.

As the world is starting to embrace the offerings of 5G technology and unleash its potential to support new services, the preparation for ‘beyond 5G’ technologies is gradually being launched in academic and industrial circles. Evolution of wireless communications has enabled more and distinct sets of new services while enhancing existing ones. In the automotive sector, it is generally considered that the lifetime of a typical car with integrated communication modules is around 15-20 years. During this lifetime, the communication technologies, especially those based on 3GPP standards, will undergo several enhancements communicated and made available in the form of releases. These releases can capture advances in communication technologies that are currently being operated or technologies for a new generation of communication systems. If the car is capable of supporting multiple releases of communication standards, these can be exploited to support their services. Thus, it is crucial for the automotive sector to follow the evolution of communication technologies and start contributing towards their development during early stages in order to build suitable systems.

Driven by this motivation, this White Paper presents a holistic analysis of 5G communication systems and beyond. Since the community is at the starting phase of 5G's technological evolution, expectations on future V2X systems are understood based on the knowledge of V2X solutions accumulated from the past years embracing LTE V2X and NR V2X, as well as based on widely observed trends in the transportation sector. Based on the expectations, essential features for future vehicular communication systems are identified. In addition, potential technical developments introduced thanks to the 5G evolution and 6G research efforts are analysed with respect to automotive services.

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3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

3GPP	3rd Generation Partnership Project
5GAA	5G Automotive Association
ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
ASIL	Automotive Safety Integrity Level
CAM	Cooperative Awareness Message
CN	Core Network
CS	Circuit Switched
CSP	Communications Service Provider
CU	Central Unit
C-V2X	Cellular V2X
DAA	Direct Anonymous Attestation
DAS	Distributed Antenna System
DENM	Decentralised Environmental Notification Message
DMRS	Data demodulation reference symbol
DU	Distributed Unit
ECC	Elliptic Curve Cryptography
GDPR	General Data Protection Regulation
GEO	Geostationary Orbit
GPS	Global Positioning System
ICT	Information and Communication Technologies
ISAC	Integrated Sensing and Communication
ISO	International Organisation for Standardisation
ITS	Intelligent Transportation System
ITU-R	ITU Radiocommunication Sector
KPI	Key Performance Indicator
LEO	Low Earth Satellites
LoS	Line-of-Sight
MEC	Mobile Edge Computing
ML	Machine Learning
MNO	Mobile Network Operator
NIST	National Institute of Standards and Technology
NTN	Non-Terrestrial Network
OBU	On-board Unit
OEM	Original Equipment Manufacturer
PCF	Policy and Control Function
PKI	Public Key Infrastructure
PTW	Powered Two Wheelers
QoS	Quality-of-Service
RAN	Radio Access Network
RO	Road Operator
RSU	Road Side Unit
SDU	Service Data Unit

SLA	Service Level Agreement
SLR	Service Level Requirement
SMF	Session Management Function
TC	Trusted Computing
TCG	Trusted Computing Group
TEE	Trusted Execution Environments
TN	Terrestrial Network
TPM	Trusted Platform Module
UE	User Equipment
UPF	User Plane Function
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
VRU	Vulnerable Road User

4 Expectation of future vehicular communication systems

4.1 Requirements perspective

Future developments of 5G are likely to span several years and work has already started. In order to make a credible forecast of the system requirements, both the current developments in vehicular networks and the widely observed trends in the transportation sector are analysed in this study.

The published 5GAA Roadmap [1] offers a unique perspective on current developments in vehicular networks. Given the multi-stakeholder nature of V2X services, it shows an alignment and synchronisation among the stakeholders towards realising truly connected and automated mobility systems. Starting from 2018 and lasting up to 2029, the Roadmap captures what has been accomplished and what is envisioned in terms of mass deployment of services. The envisioned V2X services that are part of the Roadmap include several use cases that are pointing towards the development of automated driving such as cooperative manoeuvres, and sensor sharing [2]. Use cases in the Roadmap address mass-deployment demands and specific requirements in a holistic way, from technical realisation to business models and consumer acceptance. Several studies within the 5GAA and other projects around the world have been working on these aspects. In this White Paper, these studies are considered as the starting point to understand the requirements and features of the future vehicular communication system.

The ongoing V2X developments are certainly a steppingstone towards the future. However, it is also important to look beyond the timeline of the published Roadmap. One such opportunity is to take note of some of the widely observed trends in the transportation sector today. This is motivated by the fact that the digital transformation of the transport sector has only begun. These trends are indicative of how society is and will be using the existing digital services, and what it could possibly expect from the promises of the current services.

In the following pages, five common trends are presented. The ordering of these trends is chosen randomly and does not have any special meaning. Following the description of these trends, their high-level impact on vehicular communication networks is presented. This is used to pave the way towards identifying new or modifying existing requirements for future V2X systems.

Trend 1: *Higher levels of vehicular automation*

The number of driving tasks that are being automated in a vehicle is increasing. Building the technology to increase the levels of vehicular automation is largely driven by the vehicle OEMs. Over the last few years, heavy investments have been made by these OEMs and other supporting organisations towards research and development of the necessary technical components. Given that society has started witnessing the rollout of SAE Level 2 and 3 automation in the personal vehicle segment by multiple vehicle manufacturers, this clearly indicates the interest in moving towards higher levels of vehicular automation over the coming decades. Automated driving is an enabler for services such as driverless taxis, advanced parking functions, charging station locators, entertainment services, etc.

Trend 2: *Availability of relevant travel and traffic information*

Today, several mobile applications are emerging to provide traffic- and travel-relevant information to users before they start their journey. Travel information here refers to information about the available modes of transportation to reach the destination. Traffic information refers to the availability of live traffic conditions along the roads and routes taken. Both public and private organisations are active in this domain. Increasing the convenience of such services will largely depend on efforts towards establishing partnerships between public and private transport systems, and traffic management operators.

Trend 3: *Proliferation of connected devices and services*

Over the years, the number of people, devices and businesses connected to the internet via mobile networks has been continuously increasing. With vehicles joining the connected devices ecosystem, this is bringing along new sets of devices and businesses keen to enter the market. Solutions include, among others, VRU devices, vehicle on-board units (OBU), as well as devices related to traffic signals and signage. Businesses include, among others, operators in traffic management and vehicle maintenance. Increasing the number of connected devices is expected to influence future mobility systems in all three fundamental areas: safety, traffic efficiency, and convenience. Although some of the connected vehicle services already exist today, with increasing proliferation of connected devices, these services and customers are expected to grow further.

Trend 4: *Digital roads*

Road operators and traffic managers are rolling out diverse roadside equipment for better signalling and managing roads [3]. Although these signs are increasingly digital and can be remotely controlled based on traffic situations, wireless connectivity solutions are driving an evolution towards truly *digital roads* [4]. This involves road operators using ICT technologies and data-driven methods to maintain road infrastructure and manage road traffic efficiently, safely, and in timely manner. Additionally, the data available from different road users and sensors installed on the roadways are expected to help develop platforms like *digital twins* that can enable visualisation and simulation of road scenarios, thus allowing both short- and long-term road network planning, better road infrastructure design, and foresight studies on vehicular mobility.

Trend 5: *Diverse mobility services*

Mobility services today are largely dominated by the availability of vehicle sharing services, where customers can conveniently rent any type of vehicle. Vehicle rentals include, cars, bicycles, e-scooters, and vans. These services are offered either directly from vehicle manufacturers or third-party service providers. Customers can usually adopt a mobility plan of their choice, ranging from a short commute within the geo-fenced area of the service provider, or renting a vehicle for longer journeys or time spans, e.g. based on monthly subscriptions, with maintenance and insurance covered. With the emergence of mobile applications and connected vehicles, access to such services is more convenient, which is leading to more and more mobility service providers, particularly in urban areas. Combining mobility services with high levels of vehicular automation, rental vehicles could offer services even without the presence of a human driver. Integrating such vehicles could expand the service offerings to both people and businesses (e.g. logistics).

The table below presents how the previously described high-level trends can potentially impact Cellular-V2X (C-V2X) systems.

Trend	Influence on C-V2X systems
Higher levels of vehicular automation	• Higher number of active users at any point in time. • Increasing demand on infotainment services, which could potentially be high data rate services. • Enable the use of sensing information to improve performance, reliability, and predictability of vehicular communication systems. • Enable the sharing of vehicular 'compute capability', which could potential require low-latency communication support.
Availability of relevant travel and traffic information	• Need wireless connectivity to access and update traffic and travel information. • Need increasing infrastructure-based sensing capability in specific areas like intersections to gather real-time traffic updates. • Enable road infrastructure to share relevant traffic information with desired entities. • Availability of long-range wireless links between road infrastructure and backend traffic systems.
Proliferation of connected devices and services	• Require the network to support more diverse use cases and additional requirements on selected metrics, such as reliability and latency. • Increasing number of connected devices working on different generations of communication technologies, thus requiring considerations for service continuity. • Higher connection density of devices can lead to increased network load resulting from always on services such as VRU protection, basic safety messages. • Require energy-efficient ways to support always on services. • Need to provide accurate positioning services for road users, irrespective of whether they have an active connection with the network or not.
Digital roads	• Enable coordination between different entities; depending on the proximity of the nodes, short- and/or long-range wireless links may need to be established. • Vehicles to play a key role in monitoring and reporting issues along the way; requires reliable uplink connections between the vehicles and a central network entity. • Need sensing capability on the vehicle and infrastructure side in order to support mixed vehicle traffic with different automation levels. • Establishing a connection and preferably low-latency link between certain vehicles, infrastructure, and the central network entity. • Storage and processing capability closer to the roadways, for example at the edge, to facilitate faster data collection and processing.
Diverse mobility services	Some specific influences arising from mobility services include: • Wireless access to vehicles in indoor/underground parking lots. • Support emergency call services at all times. • Wireless link availability that can enable remote driving of vehicles whenever requested.

4.2 Multi-player ecosystem point of view

Meeting the demands and requirements introduced by the above trends requires a stable ecosystem of diverse stakeholders. These stakeholders include different kinds of transportation providers, communication system providers, software application providers, third-party service providers, etc. Several factors play a crucial role in establishing and maintaining stable collaborations among all these actors. Some of them include:

- *Business aspirations/goals:* Despite having a common vision for the overall mobility system, each player needs to have opportunities to satisfy or attain their respective business interests/targets. Furthermore, the ecosystem should bring additional value to each of the players.
- *Customer and society acceptance:* In order for the grand multi-player mobility ecosystem to thrive, it has to focus on society and customer requirements and needs. The primary requirement of the V2X system is understood to be ‘safety’ – ensuring people are safe both inside the vehicle and around it. Trust is a necessary component for societal acceptance of the whole system. With increasing trust and acceptance, a strong customer base could be developed by leveraging the diversity of the different players. A strong customer base is crucial for business sustainability.
- *Ease of collaborations:* Realising the envisioned mobility system requires various kinds of collaborations between players belonging to a certain domain and/or between players who belong to different domains. For example, Communication System Providers may need to establish agreements with other CSPs for roaming or infrastructure-sharing to support the different mobility services.
- *Service evolution:* The collaborations between different parties need to result in the development of a platform that can enable new services based on the evolving or changing needs/requirements. These new services could also leverage the capabilities of existing players in the ecosystem.
- *Stakeholder inclusion:* Creating new services may lead to the identification of new stakeholders who need to be involved in the overall ecosystem. An ecosystem that is capable of continuously evolving yet providing value to customers and stakeholders is necessary – and to attract new players, all of the above aspects will play a significant role.
- *Regulations, investment and commitment:* Beyond the above aspects, clear regulations regarding the functioning of the ecosystem, heavy investments from stakeholders and/or governments, and a strong commitment from all involved parties are decisive factors for successfully realising the long-term vision.

4.3 Service continuity

The typical lifespan of a car today is close to two decades. This can lead to cars being equipped with legacy communication technology even as newer generations or more advanced solutions are rolled out. This puts pressure on future wireless networks to support mandatory (standard) services on legacy cars despite evolutions in the latest technologies.

Today, some sophisticated V2X-based services are already being implemented in mass-produced vehicle models. Telematics Communication Units in connected vehicles provide a high-speed data link capable of a broad range of applications, including services for safety and security, remote monitoring, navigation and entertainment. Some of the services require a voice connection to an operator. In more and more regions, emergency services are also becoming mandatory for all cars, e.g. the EU-eCall or the Russian ERA-GLONASS call. These services also require certification.

The EU-eCall and ERA-GLONASS are currently based on 2G/3G technology and circuit switched (CS)-voice calls. As yet, 4G technology and beyond is not supported by regulation. An IMS-based emergency service, such as the NG-eCall, is not expected to be allowed by an updated regulation before 2025.

As the average lifecycle of a car is about 18 years, cars produced until 2025 are approved according to whether they support 2G/3G eCall services. The same applies to the public telecommunications infrastructure for Public Safety Answering Points (PSAP) whose software is currently based on CS-voice calls and the decoding of a Minimum Set of Data transmitted by the in-band modem.

The 4G/5G technology is not compatible with emergency services designed for 2G/3G as it does not provide any CS domain connectivity. This means that either 2G/3G network have to be kept alive, or all TCUs have to be replaced. Both options could result in extremely high costs.

By 2025, more than 50 million cars are expected to still support EU-eCall as the standard emergency service. This may remain so for several decades. Hence, in the deployment phase of upcoming wireless technologies, the required support of legacy services should be considered from the beginning. Further, it should be taken into consideration that the reframing of 2G/3G spectrum may take place when legacy cars are still utilising these CS services. To avoid mandatory services being disrupted, future communication technologies could well incorporate mechanisms to support legacy services, or at least coexist with them. Furthermore, a notification could be sent to the TCU to inform the user if this service is available, which might also include information where and how the service is provided. In any case, for legacy cars to avail themselves of any service based on prior technology generations, their registration status with the network, such as, “searching”, “registered”, or “denied” needs to be communicated and clarified.

5 Essential features for ubiquitous connected and automated mobility systems

V2X systems have seen various iterations and developments in recent years. With the emergence of new use cases and requirements, these systems have evolved by either enhancing existing features and functionalities or introducing new ones. Some of these features include enhanced resource allocation for direct and network-based communications, power control, network slicing, Quality-of-Service management, and network exposure. Against the background of the existing 5G system and expectations on future V2X systems, the following sub-sections in this White Paper discuss some of the essential features for V2X systems. Apart from technical aspects related to the communication network and device capabilities, essential features from other areas, such as privacy and security, spectrum needs, regulations, policies, and standards, are also presented.

5.1 Network availability and reliability

V2X networks are expected to support many different use cases. In a considerable number of these use cases, the V2X services and applications pose stringent end-to-end requirements on the communication system. Considering the criticality of the V2X applications in those use cases, it is of utmost importance that the required communication service is *available and reliable* from the beginning to the end of the communication chain. Therefore, a communication network that supports automotive services requires specific adjustments on multiple layers and interactions among several network functions and components. These adjustments put an extremely high burden on the Mobile Network Operator’s service implementation, which may manifest in cost-inefficiency, or reveal gaps in the current 3GPP solution, and may not be implementable from a technical point of view for the MNO and/or OEM.

Automotive service-centric evaluation of end-to-end reliability and availability of such a composite system is a task spanning multi-layers and multi-subsystems (e.g. RAN, CN, MEC, Cloud, etc). To start the analysis of either reliability or availability, it is first necessary to understand what reliability refers to in the context of the overall V2X system. 3GPP defines ‘reliability’ for V2X as follows [5]:

Reliability is the success probability of transmitting X bytes within a certain delay, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface.

This definition is limited when considering the specificities of multi-layered V2X communication systems. In the case of ‘availability’, 3GPP offers the following definition [6]:

Availability is the percentage value of the amount of time the end-to-end communication *service is delivered according to a specified QoS, divided by the amount of time the system is expected to deliver the end-to-end service.*

From these definitions of reliability and availability, it can be noted that communication service availability is an overarching requirement that could comprise reliability as well. In the remainder of this section, we discuss some aspects that could be relevant to enable reliable and available communication services.

Starting with the radio access networks, the foremost requirement is the availability of radio coverage along all kinds of roads to provide a defined minimum level of QoS. This is particularly important to support services such as emergency call at all times. In order to ensure service continuity and reachability in unserved/underserved areas, recently 3GPP has been discussing the integration of satellite and mobile access networks, in addition to other enhancements. Interworking with various combinations of access technologies is a topic that is widely discussed [7]. One of the main requirements for V2X services in integrated systems relates to mobility support between the different access technologies. Since V2X services have diverse requirements and considering the range of services, it is important to identify what services need to be supported within the integrated system.

Apart from integrated communication systems, another noteworthy requirement is the increasing demand on uplink traffic (conventional mobile services predominantly focus on supporting downlink traffic). With the evolution of V2X use cases exhibiting, for example, growing dependence on data and an increasing number of stakeholders, some additional communication constraints [2] on interoperability, vehicular positioning accuracy, privacy and security aspects, etc. have been observed.

Assuming network coverage is 'available', the received signal strength may vary depending on the radio propagation environment (e.g. due to fading, blockages, underserved areas) in vehicular networks. To maintain a reliable offer in dynamic environments, stable and deterministic connection for certain V2X services could be explored. When vehicles move around they can end up leaving the coverage area of one base station to another, or one distributed unit to another, or one frequency band to another, which could lead to service interruptions or increased latency – caused by factors such as unsuccessful handover or handover to the wrong target cells. Thus mechanisms, procedures, and RF requirements to minimise disruptions to V2X services (reliability) are necessary. Similar service interruptions could occur when road participants move from one MNO to another. In such scenarios, agreed roaming contracts or functional measures to enable service continuity is desirable.

Beyond these issues, several other network aspects, such as network slicing, service differentiation, application design, radio interface selection (e.g. PC5, Uu, and non-terrestrial network links), play a significant role in achieving the desired end-to-end reliability.

As discussed, mechanisms addressing reliability and availability span multiple layers of the protocol stack, starting from the physical layer up to the application layer, such as resource allocation, congestion control, etc. While each mechanism is designed to achieve specific goals/objectives, exploiting synergies, and enabling coordination among the different mechanisms is crucial. It could be beneficial to notify vehicle applications in advance – i.e. mechanisms involved in addressing the end-to-end service requirements of potential 'lower system' reliability or availability – for example by issuing a prior QoS notification [8]. Such prior notification would also help when there are multiple radio access technologies operating simultaneously and in multi-vendor environments.

Beyond the communication link performance, communication infrastructure nodes themselves play an important role. Failures in the components can affect the services and their downtime, particularly delay-critical services in V2X. Having an efficient and cost-effective redundant infrastructure architecture can help in developing robust overall V2X communication systems. Despite robust infrastructure based on redundancy, it would be necessary to look at how to protect the network from complete blackout in the event of major disruption or disaster.

5.2 Predictability

For their normal operation, V2X applications depend on requirements laid out in Service Level Agreements agreed by the network. The information in the SLA is used by the MNOs to define the properties that should be supported in the network or in the network slice for a specific automotive industry customer. Deviation from any of the parameters described in the SLA may result in severe consequences affecting the V2X application (e.g. service unavailability or malfunctioning) and financial loss for the MNO, including penalties applied under the agreed SLA. Typically, fulfilling an SLA is based on a set of end-to-end Key Performance Indicators covering QoS and other performance measures monitored by the network. If any deviation from these KPIs is observed, the following should happen: the application should be notified, the network and/or application-level modification procedures should be triggered, and, compensation for the deviation is awarded under the SLA. Such procedures may be either reactive (triggered when the deviation happens) or proactive (triggered before the deviation happens, based on prediction).

As already discussed in [8], many V2X applications can implement adaptive behaviour in relation to QoS issues and continue operating in a 'degraded' capacity – so-called degraded network performance – providing that the change or adaptation can be triggered fast enough [8][9][10]. In other words, an adaptive application has several operational modes or states allowing it to continue meeting QoS expectations.

Transition to the 'adapted state' can take some time to implement, so it is crucial that upcoming QoS changes are predicted by the network well ahead of time so the application can be notified proactively. 'Proactive adaptation' such as this enables the application to remain 'available' but operate under temporarily degraded QoS conditions. Transition thus depends on the network's ability to provide reliable and accurate predictions to the application or help it acquire them. Bad or late predictions can lead to poor user experience, especially when the system is down – thus forced to enter 'service unavailability' state.

In this regard, new metrics such as *predictability* can be defined in order to be monitored within the SLA for services supporting automotive industry customers. Predictability can be based in determining the time intervals during which the system behaves as predicted (or indeed differently than expected). To calculate predictability, first a set of *a posteriori* observations are made over a period of time and, after sufficient data (analytics) have been collected, the E2E metric is calculated according to a mathematical formula.

Another characteristic of predictability is that it must be considered in relation to the specific service that benefits from the prediction. Different KPIs may attribute different importance (weight) to each specific application, because the application may be more sensitive to some KPIs and less sensitive to others. For example, tele-operated driving depends on latency predictions as well as the data rate of the uplink path, while software upgrading may depend only on the data rate of the downlink path. Since the operation and availability of different automotive use cases depend on the prediction of different KPIs, and also on the support of specific requirements for the prediction service (e.g. accuracy, notice period, etc.), the value of 5G System (5GS) predictability depends on the specific application. Only actionable predictions (which means that they can trigger an adapted state in the application) improve the predictability. 'Bad predictions' (those that are not accurate enough, or do not come on time, etc.) are not sufficient to trigger adaptation, or – even worse – may trigger adaptation that does not increase the service availability.

An example of the *predictability* metric for an application over a certain time window is shown below:

$$\mathit{predictability} = \frac{\begin{array}{c}\sum \mathit{Time\ during\ which\ performance\ degradation\ or\ service\ unavailability\ events\ occured,} \\ \mathit{which\ were\ predicted\ in\ advance}\end{array}}{\sum \mathit{Time\ during\ which\ performance\ degradation\ or\ service\ unavailability\ events\ occured}}$$

The value of the predictability can be directly connected to or associated with application availability. The higher the predictability, the lower the application unavailability, since a higher portion of performance degradation may be compensated by triggering adapted modes instead of rendering the service unavailable.

5.3 Harmonised QoS and policy framework

The integration of different wireless technologies can allow operations of vehicular use cases in different frequency bands (and hence support different transmission ranges and communication performances), enable service continuity based on network availability, and efficiently manage network load. However, to make such an integration transparent to third-party applications, it would be beneficial to have a harmonised QoS and policy framework over the integrated network.

Currently, the QoS for service data flows is primarily managed by network functions within the mobile core network, and focuses on UL and DL traffic within the mobile network. The Policy Control Function (PCF) (i.e. network functions responsible for policy and charging) provides QoS policy rules to the QoS enforcement entities (e.g. Session Management Function (SMF), User Plane Function (UPF), RAN, UE) in order to deliver the connectivity and services according to the agreed/subscribed KPIs. However, within the integrated system, V2X services may be transported over different channels, such as direct communication links between the vehicles as well as satellite links, in addition to the traditional cellular network links. This will require enhancements of existing QoS management mechanisms. These enhancements could cover, for example, availability of QoS parameters for all available types of wireless links, enabling flexibility in selecting the appropriate links or combination of links for the V2X services.

Furthermore, providing the desired end-to-end connectivity service in an integrated system involves QoS management over components from multiple communication service providers and technologies. This would require the QoS management framework to be able to expand beyond a certain communication service provider's domain, enabling the inclusion of new players like satellite operators into the QoS management framework, roaming between terrestrial and non-terrestrial networks, and room for negotiating end-to-end QoS for fulfilling the V2X service requirements, among other examples. From an administrative perspective, it is worth mentioning that OEMs currently need to deal with a large number of contracts from various CSPs in order to provide global connectivity services for their vehicles. Thus, from a third-party service provider's point of view, it would be highly desirable to have a single communication service provider and hence a single contract, despite actually having the integration of multiple CSP networks.

Furthermore, the dynamic nature of road networks can lead to quick changes in the services that need to be supported. For example, an accident on a highway may require to simultaneously trigger local hazard messages as well as cooperative manoeuvres to avoid any collision. Translating and transmitting this scenario to integrated wireless networks would mean that the networks need to quickly adapt to address the end-to-end QoS requirements of the arising services. Supporting the required QoS also requires that the harmonised QoS and policy framework of the integrated network is able to quickly respond to these changes and authorise the QoS updates in the communication service requests.

5.4 Enhanced network exposure

In order to enable the safe operation of connected vehicle applications they need to be aware of wireless network capabilities and services. Efforts in this direction have already been started within 5G standardisation, enabled via 'network exposure' functionality. In the context of vehicular networks, discussions related to network exposure have mainly focused on analytics reporting capability. Analytics related to QoS changes in the Uu interface are communicated to the vehicular applications so they can make the necessary adaptations as early as possible. As future networks are expected to offer more capabilities and services, exposing these to third-party service providers could enable more efficient and safer operation of connected driving use cases. We discuss a few of these exposure capabilities below.

Exposure of available communication links

The introduction of higher frequency bands within wireless networks could result in vehicles having the possibility to access links carrying very high data rate. Informing the vehicular applications about the availability or potential availability of such links could help to speed up certain services, such as HD map downloads. Beyond speeding up services, knowledge about the availability or non-availability of multiple communication links as well as their QoS can allow a third-party application server to effectively manage the resources and services that can be delivered to vehicles.

Exposure of network resource utilisation and availability

Apart from the availability of communication links and resources, information about network resource utilisation and availability for specific third-party application providers could be shared. This network resource information does not need to be constrained to communication resources, but may also include ‘compute’ and ‘storage’ resources. As the demand on network resources is primarily generated by the applications, information related to available communication and compute capabilities could help determine which applications are triggered so that they can be successfully accomplished.

Exposure of positioning services

Assuming high-resolution sensing and localisation will become an inherent capability of future networks, wireless networks can ‘expose’ these services, enabling applications to benefit from developments such as determining the mobility patterns of road users or predicting their trajectories.

5.5 Device capability

Within the V2X ecosystem, there are different kinds of devices capable of communicating with one another. The V2X-enabled devices considered today, such as vehicle on-board devices and VRU devices are particularly unique due to their design constraints resulting primarily from their shape and form factor. Below we discuss some of the essential features of these devices.

- **Support for multiple communication technologies in devices:** It is expected that vehicles would communicate with network entities, such as base stations, other vehicles, pedestrians, and roadside units, to name a few. In order to enable such communication demands, different technologies could be used. More communication technologies imply more communication-related components on devices. In a vehicle, for example, this means more antenna units, cables and processing units for multiple protocol stacks. However, increasing the number of communication components on devices is challenging, as there are a limited number of positions and mounting spaces for antennas and communication modules in a vehicle [11]. This challenge is further exacerbated when vehicles need to simultaneously support radio access technologies in multiple frequency bands, such as cm- and mm-wave bands.

- **Vehicular Distributed Antenna System (V-DAS):** Within a vehicle, distributed antenna systems enable modularised implementations of communication functionalities by splitting or distinguishing the Vehicular Central Unit (Vehicular-CU) and Vehicular Distributed Unit (Vehicular-DU). Several functional split design options for Vehicular-DAS are analysed in [11]. It is stated therein that moving towards a digital interface between the Vehicular-CU and Vehicular-DUs may help to cope with some of the existing challenges, such as cabling losses. However, this also results in an increase of functionalities within the DUs. Data rates beyond 15 or even 20 Gbps in a timeframe of ten years (depending on the number of antennas per distributed antenna unit and bandwidth) can be expected to be supported via the CU-DU interface [11]. In order to support such high data rates, enhancements to existing automotive solutions based on Ethernet developments may be necessary.

- **Vulnerable Road User (VRU) device requirements:** VRUs are taken to include pedestrians, road workers, cyclists, e-bikes, mopeds, e-scooters, and other more powerful Powered Two Wheelers (PTW), but also persons with limited mobility (e.g. wheelchairs and any other road users who are particularly vulnerable to the consequences of traffic accidents [12]. These users may be equipped with different types of devices capable of operating communication services and ultimately carrying out additional sensing and data-analytic functions. Due to the limitations of device size, portability and battery capacity, the device manufacturers have to overcome several design challenges. Among them, device power consumption is the most critical issue in current research and standardisation activities. However, other issues such as flexible antenna design for different deployment options are also worthy of further study.

- **Precise positioning:** V2X use cases rely heavily on precise positioning information but have different accuracy requirements. Ensuring stable, long-term high-accuracy positioning of a vehicle in all scenarios is identified as a great challenge in [13]. In order to cope with this, enhancing vehicular devices with more precise positioning capabilities, or assisting other devices and the network for that purpose, may be beneficial.

5.6 Privacy and security

In today's V2X systems, the integrity and authenticity of PC5-based broadcast messages, such as CAM and DENM, are ensured by using digital signatures and certificates. These certificates are typically issued by entities part of a given trust domain e.g. managed using a Public Key Infrastructure (PKI). The work in [14] has identified the key privacy requirements for C-V2X direct communication systems. Several identified challenges for incorporating these privacy requirements are discussed below.

If cellular communication is used and information is filtered, anonymised and potentially aggregated (for anonymity and quality of data purposes) by trusted back-end systems before being shared with other actors, the privacy risks can potentially be mitigated.

- **Pseudonym certificates:** These need to be unique, have limited validity and should *always* be available in large-scale V2X deployments. The pseudonym certificate provisioning system must be able to operate in diverse scenarios considering different aspects, such as vehicular mobility, vehicular applications, and available communication infrastructure along the road (e.g. multi-vendor, multi-operator scenario). The pseudonym changing strategies, which are widely considered to avoid tracking, need to be robust against any kind of re-identification mechanisms and attacks. Furthermore, the procedures to revoke the pseudonym certificates of 'misbehaving' V2X participants also need to be executed in a scalable and timely manner.

- **Encryption of CAM and DENM:** Encryption of messages for many-to-many communication needs to address the security-delay trade-off in designing the decryption keys. Depending on the service provided, V2X messages can be disseminated in different ways. For example, if the messages are relayed via a roadside unit to vehicles in the vicinity, the collected, processed and relayed information needs to be anonymised to avoid any risk of re-identification. Such anonymising algorithms have still not been demonstrated for highly complex data yet.

- **Privacy preserving PKI system:** PKI provisioning systems need to be designed such that the different parts and involved parties/organisations cannot collude with one another to compromise the privacy of the users. This results in the requirement that different parts of the PKI provisioning system should not have enough information nor any means to independently link the certificates to the vehicles/users. It is necessary to take measures for reinforcing trust within the system in a scalable way.

- **Service-based privacy protection policies:** It is widely known that the C-V2X system can support different categories of services with varying communication requirements such as safety, traffic efficiency, and infotainment. Each of these services can be realised in multiple ways based on the available infrastructure, message dissemination mode, etc. This implies that potential privacy protection policies for C-V2X systems need to take into account both for the service itself and its type of realisation (e.g. centralised or decentralised). Depending on the type of realisation, appropriate models related to *internal* and *external* tracking need to be analysed to identify suitable countermeasures and devise scalable privacy protection policies.

- **Compliance with regulatory frameworks:** This area of data privacy and protection is gaining significant attention from regional and national legislative bodies, resulting in the development of several regulatory frameworks for systems that process personal data. One such prominent framework within Europe is the EU General Data Protection Regulation, or GDPR as it is known. There is still some level of uncertainty regarding the interpretation and practical implementation of such rules. Going forward, it is vital for C-V2X systems to comply with relevant data privacy and protection regulations in order to remain operational in any or all geographical regions.

- **Evaluation of message correctness:** It is essential that the content of C-V2X messages themselves represent the true physical reality. Incorrect or manipulated message exchanges between vehicles can compromise C-V2X systems. Incorrect messages could arise, for example, due to faulty measuring devices on the vehicles. Manipulated messages could be a result of external attacks on the system. Thus, it is necessary for the system to identify such messages irrespective of their source of error and take appropriate action to ensure the correctness of those messages.

5.7 Spectrum demands

Radio spectrum is a fundamental resource for wireless communications. Depending on the use case, C-V2X uses two different types of spectrum. Use cases involving direct communications between or among road users and ITS roadside infrastructure (so-called V2V, V2I, V2P) are supported by the C-V2X PC5 interface and today use the 5.9 GHz band.The 5.9 GHz band is harmonised globally by the ITU-R for ITS, although different portions of this band are available for use in different regions and countries. Use cases that involve network-based communications between road users and mobile network base stations (so-called V2N) are supported by the C-V2X Uu interface and use bands designated and licensed for use by public land mobile communication networks. These bands are also harmonised by the ITU-R on a global or regional basis.

Considering the envisioned growth in the number of connected vehicles, a careful analysis of the spectrum needs for advanced V2X services is vital. Such an analysis can help in gauging whether the available spectrum in the 5.9 GHz ITS band, as well as the various IMT bands, will be sufficient to meet the demands of the V2X services as of today and in the near future. 5GAA has studied the spectrum needs for Day-1 and advanced V2X use cases [15]. These studies provide broad indications of the spectrum requirements based on V2V/I/P and V2N communications. For completeness, we re-state the relevant conclusions below.

- **More spectrum in V2V bands:** Delivery of Day-1 use cases via LTE-V2X for the support of basic safety ITS services requires up to 20 MHz of spectrum at 5.9 GHz for V2V/I communications. Delivery of advanced use cases via LTE-V2X and NR-V2X for the support of advanced driving services will require an additional 40 MHz or more of spectrum at 5.9 GHz for V2V/I/P communications.
- **More spectrum in V2N bands:** At least 50 MHz of additional service-agnostic low-band (< 1 GHz) spectrum would be required for mobile operators to provide advanced automotive V2N services in rural environments with affordable deployment costs. At least 500 MHz of additional service-agnostic mid-band (1 to 7 GHz) spectrum would be required for mobile operators to provide high-capacity citywide for advanced automotive V2N services.
- **Availability of large blocks of contiguous spectrum:** As stated in [15] in the context of V2N use cases, contiguous allocations of large bandwidth in IMT bands would allow the mobile network to schedule the available radio resource dynamically and efficiently by exploiting time, frequency and spatial domains. Fragmented spectrum creates odd allocations that lead to inefficiency as well as increased deployment and device costs.

5.8 Regulations, policies, and standards

Regulatory and certification organisations play a vital role in enabling the proliferation of innovative technical solutions. This relates to establishing regulations and policies that not only drive their acceptance in society, but also allow for efficient, wide-spread deployment of new technologies.

Mobile network deployment policies: To deal with the challenge of rolling out extensive mobile network coverage along routes, irrespective of their type, road-specific coverage demands need to be formulated in mobile deployment auctions [4]. Furthermore, in continents like Europe, it can be common for vehicles to encounter national border crossings and hence switch from one mobile operator to another. To support 'service continuity' for vehicular use cases in such scenarios, both cross-border behaviour within the cellular spectrum licence auctions and incentivised cross-border network reselection strategies need to be considered.

Infrastructure reuse policies: In order to expedite the deployment of C-V2X systems while leveraging the existing infrastructure, it is wise to establish regulations related to infrastructure reuse among different stakeholders in the C-V2X ecosystem [4]. With wireless networks envisioned to operate at higher frequencies, dense deployments are expected. Thus, exploiting synergies between road operators and cellular network operators can lead to cost-effective deployments of C-V2X systems. With the development of regulations related to the sharing of public buildings and infrastructure with mobile network operators, experience has revealed [4] that early awareness campaigns are necessary to inform the public about the benefits that the new services are expected to offer as a boost to public acceptance of the change.

Wireless communication standards: There are several ongoing activities related to the standardisation of wireless communication technologies for C-V2X services. These include the 3rd Generation Partnership Project (3GPP), and European Telecommunications Standards Institute (ETSI). Refer to [1] for further details on the communication technology standards covering current advancements of C-V2X.

Functional safety standards: Safety standards for vehicles have largely been the responsibility of OEMs, limited to the components within a vehicle and based on ISO 26262 standard [9]. However, with the integration of C-V2X systems, the operation of vehicles depends on components that are not necessarily inside the vehicle and thus not directly under the control of OEMs, e.g. the quality of wireless links between vehicles. Furthermore, the 'new' C-V2X components do not necessarily have to fail to create safety risks – even a deviation in their performance (e.g. wireless link performance) needs to be taken into account in the safety design of the overall system including the C-V2X components (i.e. safely monitoring systems or parts, such as radio connections, that cannot be developed in direct accordance with a safety standard). Thus, there is a need to address the challenge of developing functionally safe overall systems including C-V2X components despite relying on connectivity and other parts (such as telecommunications network, road infrastructure, etc.). Since the safe operation of a vehicle also depends on other vehicles or infrastructure components in the vicinity, there is also a need to establish common agreement on functional safety rules and guidelines for C-V2X systems from multiple OEMs. These new safety solutions should further consider the overall system in terms of aspects such as safety, availability, security, and wireless performance requirements.

6 Overview of potential technology enablers for C-V2X services

Every generation of communication technology has identified a set of enablers to fulfil the requirements of new services and improve existing ones. New technologies not only allow operators and C-V2X stakeholders to realise what is currently envisioned, but also open up pathways for new innovations, possibly not yet imagined. In pursuit of these new-generation technologies, a global brainstorming is already underway in academia and industry. This is resulting in several proposals for technical enablers for future communication systems.

From the list of widely discussed proposals, a subset of them is analysed in this paper. The selection is primarily based on their relevance for V2X systems. The discussed technology enablers are listed below:

- Integrated sensing and communication
- Integrated terrestrial and non-terrestrial networks
- Distributed on-broad communication systems
- Refractive meta-surfaces
- Data-driven networks and distributed computing
- New spectrum
- Privacy and security mechanisms

The goal of the analysis is to understand what these technology enablers can offer in terms of V2X service. It also helps to understand the challenges that need to be addressed in case they are adopted in the future.

While technology research is the starting point, other aspects such as standardisation, testing, and commercialisation of technologies are equally important to realise them. The timeline of technology research towards products in the communication industry can take several years – up to a decade if the experience commercialising previous generations of communication systems can be used as a guideline. When communication systems are slowly being integrated into vertical industries, such as the automotive sector, the timelines of different products and services cannot be treated in an isolated way.

6.1 Integrated sensing and communication

Until recently, vehicles have largely relied on sophisticated sensors to improve safety and traffic efficiency via Advanced Driver Assistance Systems, or ADAS. These sensors include different types of radars (radio detection and ranging), lidars (light detection and ranging) and cameras. Such sensors can, among others, detect objects and measure their distance and relative speeds. When appropriately installed on different parts of the vehicle, they can sufficiently perceive the surroundings and support various driver assistance functions. Long-range radars, supporting distances of about 250 m, installed in the front of the vehicles, can enable adaptive cruise control. Likewise, short-range front radars with a wider field of view can support emergency braking. Different sensor technologies have their own strengths and weaknesses. For instance, radars can be operated under diverse weather conditions where lidars and cameras may be more limited. Similarly, cameras can allow image-based detection, while the other technologies may not. Since there is no single sensor technology that can support the wide range of assistance systems, fusing information from different sensors becomes crucial to allow vehicles to robustly perceive their environment.

With the introduction of vehicular communication systems, ADAS are enhanced with wireless communication capabilities. Vehicles are now capable of communicating, becoming aware of environments much beyond the view of their sensors, and cooperating to enable safe and efficient driving scenarios. Incorporating communication capability in the vehicles can be regarded as an extension of the sensor system. It can improve the long-range sensing capabilities of an autonomous vehicle. Sensor fusion combining technologies that can detect objects with high resolution in all-weather scenarios and can, separately, identify objects triggering an appropriate response (e.g. emergency braking) could also enhance the behaviour of autonomous vehicles leveraging short-range sensory inputs.

Since the next generation of wireless communication systems are expected to operate at higher frequencies, this transition is also expected to spread to different verticals, including the automotive industry. Utilising higher frequencies for V2X communications is expected to further complement the existing sensing capabilities of the vehicles. Higher frequency bands and wider bandwidths can enable high-resolution sensing, localisation, imaging, and capabilities for environment reconstruction in communication systems.

In order for the sensing information to be beneficial, it needs to fulfil certain requirements that can, in turn, vary based on the applications. Typically, these requirements are considered in terms of metrics that capture detection accuracy, localisation accuracy, tracking capability, classification of road participants, maximum and minimum detection range, maximum and minimum velocity estimation, and their resolution. To clarify with a simple example, the detection range requirement for a parking assistance system could be much lower (in the range of a few metres) compared to an adaptive cruise-control system (a few hundred metres). For higher range and velocity resolution, it is important to differentiate between road users or objects that are close to each other.

Incorporating sensing systems in vehicles based on sensors and V2X communications and following the traditional way may lead to the existence of two separate sensing subsystems. Having such disjointed systems influences several aspects, such as power consumption, space occupied by the sensors, overall weight of the sensing system, number of required antennas, and cabling requirements. The growing number of sensing/communication devices, limited mounting spaces, and vehicle design constraints all pose significant challenges.

Another well-known problem is radar interference. If multiple radars that are close to each other operate simultaneously (transmitting at the same time and frequency), their fields of view may overlap. This could result in interference and hence affect the overall detection performance. Furthermore, with two separate sensing systems the spectrum would need to be doubled.

The foreseen convergence of radar and wireless communication operating frequencies is resulting in a new design paradigm. This is captured in what is called Integrated Sensing and Communication, or ISAC, see the figure below.

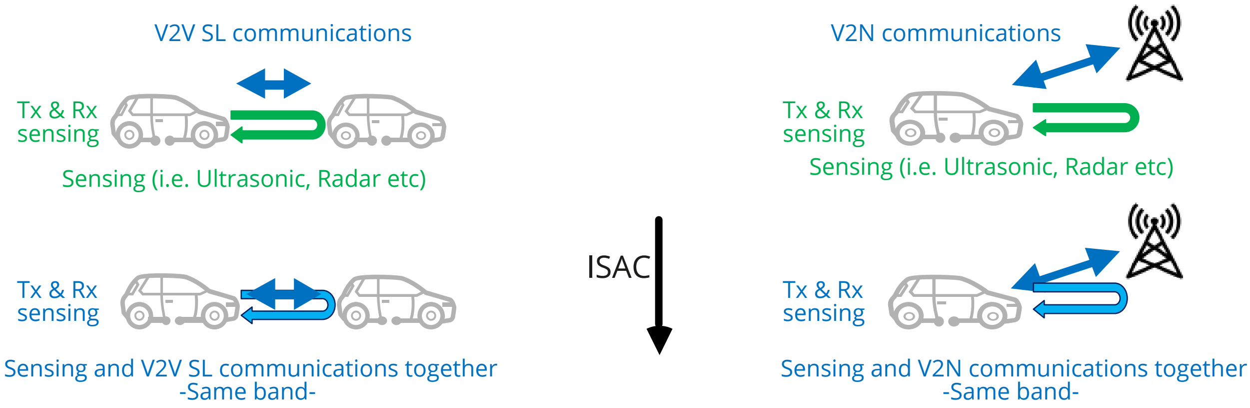

Figure illustrating ISAC for automotive applications

The goal has been to integrate disjointed communication and sensing systems into one system. The fusion of these two systems may be realised at various levels, from loose coupling to tight integration. In broad terms and from a systems point of view, this could have several implications on the multiplexing of spectrum and partial hardware reuse, as well as on joint signal processing and a unified protocol stack.

Benefits and challenges of ISAC

A unified radio signal (as a result of tight integration), which can simultaneously transmit data and perceive the environment, can bring several potential advantages covering multiple aspects, such as hardware size, number of required antennas, cost, latency, and spectral and energy efficiencies. These point to a direction that could address the previously mentioned challenges in disjointed systems. Furthermore, a tightly integrated system design could reduce the isolation between both communication and sensing systems. This offers opportunities to further enable efficient information- and resource-sharing between the two operations. The issue of radar interference when multiple radars in close proximity are simultaneously operating could also be mitigated due to the inherent multi-user access schemes in communication systems. New mechanisms can be investigated to enable efficient radar and V2X interference management.

From users' perspective, maintenance and upgrades of vehicular sensing and communication systems can be done remotely and in a harmonised way. For vehicular applications that rely heavily on precise locations, combining localisation information based on short-range sensing and long-range V2X communication can result in more robust estimates. In order to determine the success and capabilities of an ISAC system, the combined performance of long- and short-range sensing as well as the resultant vehicular behaviour must be benchmarked against actual performance levels – and under similar conditions to a vehicle without electronic assistance driven by a human.

Although the co-design of sensing and communication systems seems promising in many ways, there are several challenges that need to be addressed. Firstly, the radar waveform is not intended for communication, and similarly, the communication waveform is not intended for sensing. Thus, it is necessary to understand the performance limits when utilising one waveform for a purpose that it is not originally intended for. Furthermore, it might be critical to achieve high accuracy ranging capability (distance and/or direction measurement) via the integrated system. The co-existence of radar and cellular systems in the same frequency bands, for example at 77 GHz, could mean that a vehicle transmitting data can potentially interfere with a radar receiver. Similarly, a radar transmission can potentially interfere with a vehicle or base station. This calls for technical solutions with respect to, among others, spectrum sharing, waveforms, resource allocation, and artificial intelligence methods that can efficiently deal with interference in the integrated systems. Additionally, ISAC devices from multiple manufacturers should be able to coordinate with each other, particularly in regard to interference management. The coordination schemes can also potentially be covered by standard specifications and regulations.

An analysis of achievable gains with respect to aspects such as spectral efficiency and reliability based on real-world scenarios is a valuable tool to understand the performance capabilities of the combined system. Besides the gains, knowledge of costs associated with deploying and maintaining such a system needs to be studied for insights about viable implementation options. The major implementation aspect is the placement of integrated antennas, such that both radar and communication requirements can be simultaneously fulfilled.

Apart from technology related challenges, regulatory aspects are another crucial consideration for this enabler. The usage extension of the frequency bands – originally exclusively allocated to radar, ITS communications, or licensed bands for mobile/V2N communication networks – needs to be clarified (e.g. to determine whether usage of the band for both purposes will face regulatory issues). Besides this, the potential re-allocation of the spectrum for ISAC may affect the life cycle of on-board ISAC devices. Furthermore, since radar sensing is a safety critical function, ASIL compliance for the ISAC solution will also need to be considered.

Sensing to assist communication systems (perspective wireless)

As vehicles are moving towards higher levels of autonomy, they are utilising a multitude of sensors (e.g. radars, lidars, and cameras) to achieve greater situational awareness for autonomous driving decisions. The vehicles have precise knowledge of their positioning and orientation, map information, the dynamic street-level environment, and may also be aware of the planned vehicle trajectory. Environmental awareness can be utilised to improve the performance of the vehicle communication systems. Examples of on-board ‘sensing’ to assist the vehicular communication system’s performance include predictive beam management, blockage prediction, Channel State Information compression, transmission adaptation (e.g. Data demodulation reference symbol (DMRS) adaption) for improved spectral efficiency, handover prediction, predictive rate adaptation, and robust RF fingerprinting in dynamic environments.

Utilising the sensing information to improve the performance of the vehicular communication systems would help to improve performance thanks to greater reliability and predictability. There are several challenges that need to be addressed. Current environmental sensing for the purpose of ADAS is directed towards making driving decisions and may not include other purposes, such as detecting objects (i.e. buildings, walls, or base stations) that influence the communication channel. In addition to vehicles and transportation infrastructure identification, enhancing the ability to sense the environment would be needed to detect these features that adversely affect the communication channel. Such information can be added with three-dimensional maps available on the vehicle side. Furthermore, an analysis of the achievable gains in different use cases developed to exploit the 'sensing' information would be necessary. However, there are challenges related to such cases in real-world scenarios due to the complexities of simultaneously modelling the physical and radio frequency characteristics of the environment.

6.2 Integrated terrestrial and non-terrestrial networks

Ubiquitous wireless network coverage satisfying diverse communication requirements is essential to support next generation connected vehicle solutions. To enable the broadest range of envisioned connected vehicle services, this demands higher availability of wireless connectivity, extending it to areas and roadways that were previously underserved, had limited capacity, or simply difficult to connect.

Given the cellular infrastructure being widely deployed today, a wireless communication network comprising of Terrestrial Networks (TN) as well as Non-Terrestrial Networks (NTN) can be a potential enabler for truly ubiquitous connected vehicle services, realised by seamless coverage. NTN specify radio access networks where the access nodes (in particular base stations) are carried on platforms hovering above the terrestrial surface thanks to high-altitude platforms, such as balloons, or via satellites in space. A communication network combining TN and NTN may become an efficient and complementary way to support envisioned vehicular services. For instance, in scenarios where coverage by TN is limited, the coverage and capacity requirements of vehicular services could be addressed by establishing links via NTN. Examples of such scenarios include rural areas or tracks along roadways in suburban areas. Likewise, TN could also complement NTN coverage gaps in areas such as tunnels or under bridges. Efforts towards such a co-existence have already started in standardisation bodies such as 3rd Generation Partnership Project (3GPP), where the first solutions have been issued in Release 17.

Meanwhile, satellite-based services have been used in vehicles for several decades now. By equipping vehicles with either satellite antennas, typically moulded onto the roof or using existing GNSS antennas, for example, vehicles are able to receive GPS signals for localisation and navigation support. However, with the megatrend in the automotive industry towards connected and automated driving, the influence of satellites is foreseen to be far beyond today's prominent navigation services. The availability of satellite constellations, together with antenna development and data management platforms, can open a wide range of possible connectivity solutions and new services, going beyond traditional emergency applications.

Satellite communication for V2X is thus an important development and draws attention to the growing capabilities of satellite-based vehicular networks. The coverage range of a satellite depends largely on its type. For satellites in the Low-Earth Orbit, or LEO, the beam radius can vary between 20 to500 km, whereas for satellites in the Geostationary Orbit (GEO), the beam radius can vary between 200 to 1000 km. This is significantly larger than the cell radius of any TN. Such wide-area coverage can enable services such as the collection and monitoring of continuous performance parameters, especially when the connected vehicles are in underserved areas (i.e. outside the coverage of terrestrial networks).

From an operation point of view, supporting global coverage for vehicles while easing the maintenance of service contracts is desirable for OEMs. Establishing agreements between MNOs and NTN service providers could be a potential option due to OEMs' reliance on MNOs for automotive connectivity solutions today. Ideally, having a single global 'connectivity' provider to manage the roaming and charging policies and contracts of different communication service providers could relieve OEMs of a great burden.

In order to build a unified wireless network that allows both TN and NTN to work harmoniously, their seamless integration is essential. Several aspects may need to be considered to make that work in practice. Beyond stable network coverage everywhere and at all times, smooth handovers and/or good network reselection strategies between the two networks are vital to ensure service continuity among connected vehicle use cases. Since mobility is a highly relevant aspect of vehicular networks, roaming mechanisms should be designed taking into account the integration of both network types. A unified network architecture should enable applications to meet their service requirements in a transparent manner with a single framework for aspects such as QoS management and charging policies, among others.

Regarding utilising satellite-based links for vehicular communications, several challenges need to be addressed. The performance of satellite-based links with respect to metrics such as data rate cannot match today's mobile networks. The data rate requirements for satellite uplink and downlink for vehicular connectivity outlined in the 3GPP 5G system is around 25 Mbps and 50 Mbps respectively [16]. This is notably lower than the data rates achievable over 5G terrestrial networks. Varying link capacities could directly influence the V2X services being offered. However, typical use cases that rely on ubiquitous network coverage today are built around services such as emergency call and online traffic update. These low data rate services could be well served via satellite links. Going forward and considering the applicability of satellite communications, one can expect that the performance of satellite links could be enhanced to support high data rate services in the future.

As for QoS achievable for vehicular communications, satellite-based links can be expected to provide the desired performance over wider areas, even for fast driving/moving vehicles. Thus, mobility management among satellites could become essential, including fast handovers between different satellites. This could require current technologies for inter-satellite links to be further enhanced. In addition to improving handover performance, mechanisms to adjust satellite beams could become relevant. Based on different aspects, such as services offered or vehicle handover rates, the adjustment of satellite beams could vary. Another crucial challenge with respect to the direct connection between vehicle and satellites is the uplink, particularly the link budget and the antenna size. Due to the wide coverage of satellite beams, communication technologies need to evolve to support distances over several hundreds of kilometres.

Another factor is finding ways to improve the efficiency – in terms of size and power consumption in both up- and downlink – of vehicular satellite antenna. This is necessary due to limited options for antenna placement and the availability of power in a vehicle. Furthermore, when antennas are combined with a glass roof, they need to be able to withstand high temperature ranges. Apart from antenna design, additional hardware will be necessary within the vehicles to support satellite-based communications.

6.3 Distributed on-board communications system

Considering that a diverse range of services will be developed to serve both the vehicles themselves as well as passengers, they are expected to generate widely varying requirements on wireless communication networks. To fulfil such a broad and evolving range of requirements in dynamic vehicular scenarios, advances in wireless communication technologies play a crucial role.

Although the evolution of wireless communication technologies tries to address the requirements of potential future services, their real-world implementation can significantly influence their performance. Focusing on the implementation of communication systems in today's vehicles, it has largely relied on incorporating a single communication module within the car. This module is connected via coaxial cables to one or more co-located antennas. The co-location of antennas at a single place will restrict the radio link performance, which may lead to performance degradation of the envisioned services. Losses over coaxial cables also increase with frequency and reduce the overall system performance. Hence, cable length is subject to limitation.

In order to support new services efficiently, given vehicle design constraints, adopting a distributed architecture for communication systems may lead to a series of attractive benefits. It allows the splitting of communication functionalities between the Vehicular-CU and Vehicular-DUs (thus more than antenna functionality only). The Vehicular-CU can be considered as a larger unit with high processing power and higher power consumption, while the Vehicular-DUs are designed as small units able to resist higher temperatures. Based on the considered functional split, gains could be achieved through joint processing of signals from multiple Vehicular-DUs. Furthermore, a distributed architecture allows more flexibility in the placement of vehicular-DUs; more freedom to place them in/on vehicles can lead to improved radio link performance around the vehicle regardless of its design.

In a distributed communication architecture, the interface between the Vehicular-CU and DUs significantly impacts the overall performance of the communication system. The data rate requirements to be fulfilled by the interface could vary from the order of a few Gbps to several tens of Gbps. In addition to the interface requirements, other challenges could arise from aspects such as cost-intensive wiring between the Vehicular-CU and multiple Vehicular-DUs, and requirements on the level of interaction

(CU-DU and DU-DU), which affects the communication system's overall efficiency. Additionally, each of these units may have their own positioning constraints to achieve acceptable performance levels.

Alongside communication systems, the vehicle design philosophy is also evolving. For instance, more and more cars are likely to be released with glass rooftops. Such design changes may challenge the existing implementation methods. For example, it will limit the possibility of mounting antennas or Vehicular-DUs on the rooftop, which is widely practiced today. This design philosophy also hinders the co-location of antennas and Vehicular-CU on the roof.

In order to cope with the complexities of distributed architectures together with evolving communication technologies, automotive service requirements, vehicle designs, and approaches to implement communication systems in vehicles might be worth revisiting.

A distributed architecture complemented by a wireless interface between the Vehicular-CU and Vehicular-DUs could offer a highly adaptable architecture. Such a design would mean Vehicular-DUs can be placed in a variety of different positions, such as on mirrors, bumpers, or spoilers, without the need to extensively redesign the implementation or for expensive (re)wiring. Furthermore, it could ease the process of integrating new and/or updating current antennas and Vehicular-DUs when changes in technology or service requirements are issued. Adopting a wireless interface could also enable certain components of the communication system to behave as plug-and-play units. This could also simplify the maintenance of such units.

Like other potential enablers of future automotive solutions, several challenges need to be addressed before introducing wireless components inside a vehicle. Mechanisms to enable reliable wireless communication between a Vehicular-CU and Vehicular-DUs need to be investigated. The placement of Vehicular-CUs and Vehicular-DUs in different types of vehicles requires detailed analysis with respect to the performance of the wireless interface. When multiple vehicular-DUs try to communicate with the same Vehicular-CU, schemes that allow coordination among the different DUs are necessary to enable efficient and joint processing of signals. Furthermore, coordination mechanisms between Vehicular-DUs that host different sets of functions and communicate with different Vehicular-CUs are essential to avoid performance degradations of the wireless interface.

The distributed approach could also incur additional costs due to the increasing number of components needed, which may also need to operate under different conditions. For instance, Vehicular-DUs that are mounted close to or integrated into a glass roof will need to withstand higher temperature ranges.

Looking into the future, communication between vehicles is envisioned to take place using multiple communication technologies supporting the diverse set of automotive services. These technologies could rely on different kinds of wireless connectivity such as uplink/downlink, sidelink, and satellite link. These links could also communicate over multiple frequency bands and ranges (FR1, FR2, etc.). Hosting such a wide array of communication technologies in the traditional way could, among others, impact the deployment cost, pose further challenges to antenna placement, and require mechanisms that enable their coexistence in an efficient manner. The path towards developing a distributed communication architecture that includes wireless components and a combination of the above features needs to be further explored and studied.

6.4 Refractive meta-surfaces

The demand on C-V2X system to provide ubiquitous service with high reliability and predictability would require the support of multiple communication technologies (terrestrial and non-terrestrial) and multiple spectrum bands. As discussed previously, the antennas for wide-area networks are generally external to the vehicle (e.g. roof mounted), while the modem resides inside the vehicle. High cabling cost from antenna to the baseband modem is one of the key challenges for communication system implementation in current vehicles. This challenge can be considered a prohibitive factor to support multiple technologies and spectrums.

In addition to solutions discussed in Section 6.3, the technology of refractive meta-surfaces could be considered. Meta-surfaces mounted on the exterior (e.g. on windows of the vehicle) would mean the antennas can be moved inside the vehicle, which potentially cuts down on the cabling costs. Refractive meta-surfaces can change the refraction angle to direct the energy towards antennas placed inside the vehicle, as shown in the figure below. Several challenges remain, including the varying angle of incidence of radio waves as the vehicle moves, passive or active refractive meta-surfaces, and support for multiple spectrums.

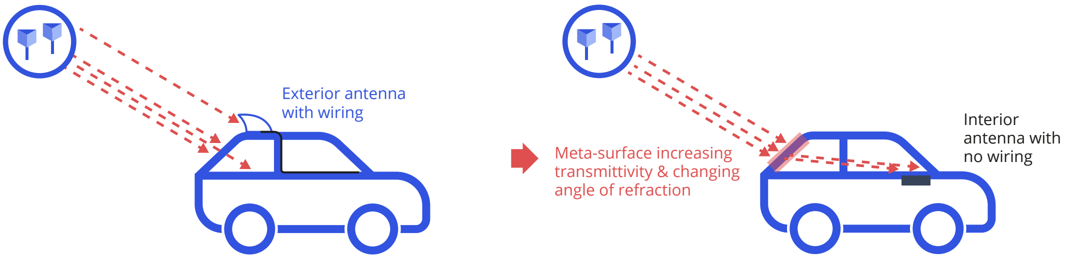

Figure illustrating refractive meta-surface for vehicles to reduce cabling costs

6.5 Data-driven networks and distributed computing

Data-driven networks, or those utilising data to make network and application management decisions, are considered to be a fundamental brick in developing long-term adaptable networks. Regarding the V2X network in particular, there are two types of data under consideration, namely the data collected or created by V2X applications (e.g. sensor data and road traffic information) and data measured or produced by the network entities (e.g. radio link quality and cell load information, etc.). In terms of use, these data serve two main purposes, namely as input to V2X application decisions, such as those made by automated driving control functions, or as a basis for network management and optimisation.

With respect to network management, today's 5G networks have started incorporating capabilities to collect data (such as that discussed above) in a standardised way to perform data analytics. The existing data analytics functionality allows monitoring, prediction and optimisation of certain network aspects, such as those related to network slicing, QoS, and user equipment mobility, which are particularly relevant for V2X services.

The data analytics functionalities are considered to rely on artificial intelligence- and machine learning-based methods, among others. These methods, such as reinforcement learning, supervised learning, and federated learning, are widely discussed to help solve complex wireless optimisation problems and develop data-driven algorithms for complex scenarios. In the context of V2X networks, with increasing levels of vehicular automation and their reliance on wireless connectivity, the scope of data analytics is increasing but also becoming more complex. Significant challenges are arising from the abundant amount of data generated (via sensors, V2X applications, and the network), and their requirements for timely processing.

V2X networks, in addition to addressing the QoS requirements, are expected to be capable of exposing their functionalities to third-party service providers and supporting requirements such as pre-notifying QoS changes to ensure V2X applications adapt in timely way [8]. This requires more accurate measurement and prediction of aspects such as the network status, together with exposure of network information.

One way for the networks to cope with the increasing demands (such as those discussed above) of V2X services is the development of adaptable and flexible networks. Adaptable in the sense of coping with unknown and unforeseen situations; flexible in the sense of efficiently extending functions, algorithms and protocols based on additional network features or requirements. Such networks could, for instance, optimise or foster new resource allocation algorithms, or enhance existing protocols to better suit the new communication scenarios. Enabling such capability would need to endow each network entity with some intelligence. Embedding intelligence refers to adding methods and tools that allow each network entity to carry out certain functions or tasks based on reasoned inputs and an ability to learn from data. Such networks could quickly become accustom to the dynamic nature of vehicular networks with lower design overhead and less human intervention. Greater flexibility could also make integrating and operating new network features and capabilities easier and more cost-effective, despite the growing complexity.

With the vast amount of data and higher processing requirements in V2X networks, it is wise to view the wireless network as a larger system capable of supporting smart distributed computation, storage and communication functions. Computation-intensive V2X AI-based applications, such as those running on resource-constrained nodes (e.g. vehicles) or requiring collaboration, could be partially or fully offloaded to the network entities which have higher storage and computation capacity. Conversely, the 'compute' consumption of devices at any given time may not be fully utilised, e.g. when a vehicle is parked or is driving in rural conditions with a reduced computational load. In such scenarios, the compute capability in a vehicle may be used to offload computing tasks of a mobile user within the vehicle or of a cloud computing platform or the network itself.

There is a heterogeneity in the 'compute and communication' capabilities of devices in vehicles, handhelds, and cloud computing platforms that are interconnected as shown in the figure below. The interconnection of these devices allows for splitting and executing a computation task originating from one of the devices (e.g. handheld user equipment running gaming application) across all the devices (e.g. across handheld, vehicle, and cloud compute). However, the heterogeneity in the 'compute and communication' capabilities of these devices determine the different trade-off in latency and energy efficiency for different splits of the computation task across these devices. Furthermore, it imposes certain requirements on the vehicular communication systems to be able to support low-latency communications.

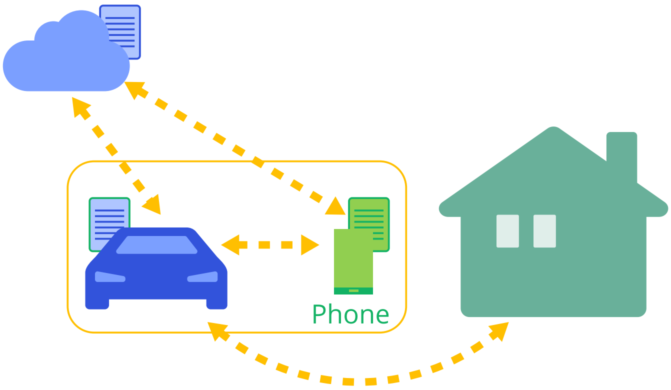

Figure illustrating distributed 'compute' tasks across different computing platforms

There are several challenges in distributing tasks among vehicles, handhelds, and cloud computing platforms that need to be addressed. First, the decision on whether to offload or how to split a task across these 'compute platforms' depends not only on their computing capability, but also the capability and performance of the communication link between these devices. Communication performance of some links may be relatively time invariant (e.g. between handheld user equipment in the vehicle and the vehicle itself), while other links may display significant time variability (e.g. from vehicle to cloud). This requires mechanisms for splitting and executing a computation task to meet the desired latency and energy efficiency, adapt to changing conditions, and migrate across different computing devices. Second, the vehicular communication system may need to support low-latency communication making the sharing of resources for latency-critical 'compute tasks' feasible (e.g. gaming).

To leverage wireless networks from this perspective, mechanisms to efficiently coordinate use of available 'compute and storage' resources will be necessary. This could require the distribution of intelligence and a corresponding architecture plus protocols across multiple nodes to carry out AI/ML operations, such as model training and inference. Furthermore, identifying new interfaces for data exchanges and data flows within the network would be necessary.

The idea of a distributed system is illustrated in the following figure for environmental perception use case. As a vehicle traverses from an urban to a suburban area, it could seamlessly utilise the available network resources to improve its environment perception.

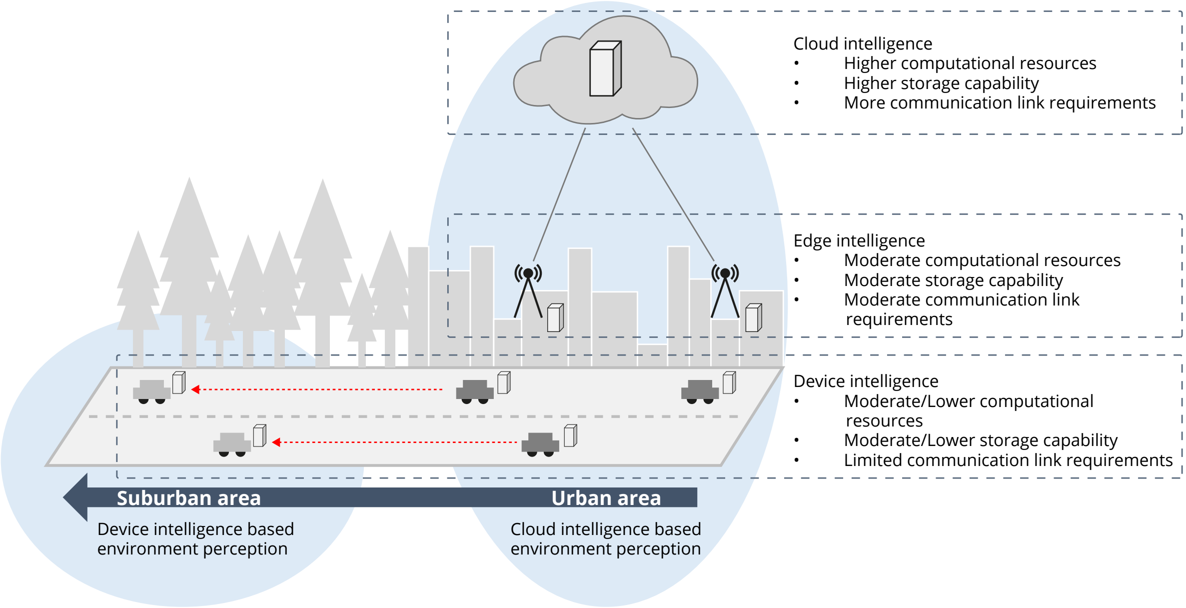

Figure illustrating distributed intelligence and computation in V2X networks

Besides this, efficient and cost-effective designs addressing multiple perspectives, such as infrastructure and hardware, software, and wireless mechanisms, are also necessary. Such an overall V2X architecture could lead to sustainable V2X networks.

Considering the large number of V2X stakeholders and services offered, developing security measures for sharing sensitive data among other entities, such as the capability to identify unknown, unauthorised, or untrusted entities, are also critical.

6.6 New spectrum

The successful proliferation of fully autonomous, smart and connected transportation systems will dramatically increase data traffic requirements (i.e. in terms of throughput, latency, and reliability) on wireless communication systems. A crucial aspect in meeting more demanding requirements is the availability of frequency bands used by V2X communications. Largely discussed candidate frequency bands for vehicular communications have been the low-bands (<1 GHz) and the mid-bands (1-7 GHz), owing to their large geographical coverage with uniformly reliable performance. Although the currently available bands are suitable to support a number of current and envisioned vehicular use cases, it has been identified in [15] that additional spectrum in these bands is required to fulfil the advanced V2X service demands. Being able to acquire more spectrum in these bands would be beneficial.

In addition to existing spectrum bands, frequency ranges 7-24 GHz and 92-275 GHz (sub-THz) are being discussed as promising candidates for future wireless communication systems. The specific bands within these ranges are yet to be identified. First, thanks to very wide continuous spectrum chunks (i.e. a few GHz in mmWave bands 24-92 GHz and up to 100 GHz in sub-THz bands), both bands have the potential to satisfy the high data requirements by providing high transmission rates (i.e. in the order of tens of Gbps or even Tbps, respectively). Second, the abundance of frequency resources allows them to be traded against the time resources, hence the transmission latency can be significantly reduced. Finally, the usage of those two bands enables accurate ranging/positioning and high-resolution imaging (e.g. accurate recognition of other cars and surrounding objects), which might be critical for supporting future connected and automated driving use cases.

Higher frequency bands for vehicular sidelink communications can offer vehicles within relatively close proximity stable line-of-sight (LoS) links to share vast amounts of raw perceptual data with high data rate and low latency. Additionally, following the ISAC concept and high-resolution ranging and positioning capabilities at the newly considered higher frequency bands, vehicles may not only build 3D models of the physical environment, but they may also exchange a comprehensive view of the surrounding environment, and hence anticipate potential hazards.

Given the capability to transfer large amounts of data at high data rates in specific directions, the so-called “information showers” can be enabled in V2X networks. If vehicles are in a specific position or place with respect to the infrastructure, potentially huge amounts of data – in the order of tens of gigabytes per second – could be transferred to the vehicle via beamforming (e.g. software updates, media downloads, HD maps). Such data transfer capabilities could help to offload some data demands from conventional frequency bands used for V2X communications by MNOs.

Moving to the communication systems implementation within vehicles, it is typically based on wired connections between the DUs) and the CU, as previously outlined in this paper. The cabling not only increases the installation cost but also contributes to the weight of the car and limits the placement options of the communication components. The availability of the new high-frequency bands might be an option worth investigating to complement the wired links among the system components with wireless ones without sacrificing on performance such as data rate, latency, or reliability. The wireless links can offer more deployment flexibility and provide greater freedom on where to place or mount DUs, particularly when vehicles are foreseen to house communication-related components.

Despite several potential benefits, communication in mmWave and sub-THz bands introduces serious challenges when applied in vehicular scenarios. Specifically, while bandwidth and data rate are no longer constraints, challenges are expected in terms of medium-access control, interference and coverage, channel estimation, synchronisation, mobility management, and resource allocation. The expected issues are related to highly directional transmissions caused by aggressive beamforming (i.e. so-called “pencil beams” have a width of at most a few degrees), which is nevertheless required to overcome the severe propagation loss experienced in higher frequency bands [17]. As a result, the fast (re)alignment of Tx and Rx pencil beams in highly mobile scenarios may not be achieved with the existing beam-steering implementations [18].

Although, the sub-THz band can potentially provide much higher bandwidth (and hence higher data rates and sensing accuracy) than the mmWave band, its propagation conditions make efficient communication much more challenging [19]. In particular, the higher pathloss in sub-THz frequencies results in short-range communication (tens vs. hundreds of metres in the mmWave band) and requires much narrower beams, leading to very high overhead in the beam-search procedure. Furthermore, sub-THz communication is still in an immature state – demonstrated in practice only in the last decade – and the technology still requires research in various domains, including hardware design, channel measurements and modelling, and waveform and protocol design [19]. On the other hand, mmWave-based communication is already in an advanced state and, in fact, already part of 5G NR. Hence, this band has higher potential to be considered first in V2X communications.

Apart from above discussed frequency bands, the need to ensure 100% coverage of wireless networks for the next generation of connected vehicles, for example, due to potential regulatory reasons, maybe enabled by using as yet unsupported bands for wireless network coverage.

The use of VHF (ranging from 30-450 MHz bands) for automotive purposes can provide many benefits beyond the current reach of available frequencies. Due to the weaker attenuation of the large wavelengths, longer distances can be reached. Many possible use cases with low requirements on bandwidth, but directed at reaching further distances, can be effectively supported. These can lead to improvements in eCall ranges for voice calls and in transmitting the minimum set of data, enabling coverage of larger areas without MNOs having to add infrastructure, but also reaching and 'pinging' vehicles positioned in garages. The last point offers OEMs access to the vehicle without it having to be on the road per se. It is understood that using lower frequencies means the available bandwidth is more limited. Many use cases requiring low data rates, such as eCall, online traffic and also all NB-IoT use cases, will ultimately profit from wider coverage.

A drawback may be the bigger antenna size needed for lower frequencies, but in automotive areas VHF-antennas are very common due to the formerly popular TV installation in vehicles. Furthermore, these antennas have largely been deployed to receive TV broadcast services. Utilising VHF bands for communication purposes in vehicles would, however, need further developments in the area of unicast uplink and downlink transmissions and their mechanisms.

Incorporating VHF bands for automotive purposes may need to deal with regulatory issues, since frequency assignments in this band are not uniform globally. As the availability of dedicated frequency bands for vehicular communication purposes is unknown, solutions enabling the co-existence of multiple applications within the same band may be needed if allocation for V2X services is considered.

6.7 Privacy and security mechanisms

Pseudonym-based schemes for V2X using short-range broadcast technology

Although the current PKI systems provide a foundational set of cyber-security capabilities for C-V2X direct communication, future research should also be planned to identify novel methods for enhancing privacy and data protection in vehicle communication. Seeking to design secure privacy-preserving architectures for C-V2X systems comprising millions of autonomous vehicles, we have to deal with unresolved challenges raised in [14]. Security, interoperability and connectivity in a dynamic network of vehicles, gateways, services and applications across operations, technology and IT stakeholders are demanding a strategic rethinking of policies and processes in the context of cyber-security, privacy and trust. Along these lines, it is worth investigating how new technologies can be used to stimulate new PKI architectures and evolutions in the future.

One alternative is to apply solutions based on decentralised identity management architectures. The idea is to leverage advanced cryptographic protocols designed to guarantee privacy as a way to enable vehicle OBUs to generate and certify their own pseudonyms. In this case, vehicles would not have to interact with the Certificate Authority or Pseudonym Provider. Instead, they could generate pseudonym certificates locally, on demand, resulting in a more scalable system that also offers better privacy protection.

One way to realise decentralised identity management for C-V2X is to rely on platform trust through a Trusted Computing (TC) component, such as a Trusted Platform Module (TPM), inside the vehicle itself. This offers the following advantages:

- Creates an immutable root of trust in the vehicle; a TC represents a commonly trusted and undeniable initial processing step, to which trust in other processing steps can be bootstrapped.
- Policies to access the 'secure memory' – used to store certificates that are then used to attest the security of system components – which is immutable except via the TC component itself.

An in-vehicle TC component enables to use advanced cryptographic protocols for creating an unlimited amount of trusted pseudonym certificates in the vehicle itself. For example, Direct Anonymous Attestation, or DAA, is an anonymous digital signature mechanism, where for each signature no entity can discover the signer's identity. However, DAA still has the property that only a legitimate signer (e.g. vehicle) can create a valid signature through the use of a TC component. Under DAA, vehicles will be responsible for generating their own pseudonyms resulting in simplified infrastructure models, where there is no need for a Pseudonym Certificate Authority, as it is the case in current PKIs. This makes pseudonym provision, management, and revocation much more scalable and removes the need for federated trust of the infrastructure entities in existing C-V2X architectures.

DAA, originally introduced by Brickell, Camenisch and Chen [20], is a cryptographic protocol designed primarily to enhance user privacy within the remote attestation process of computing platforms, which has been adopted by the Trusted Computing Group [21], in its latest specification. DAA allows a user to convince a verifier that it uses a platform that has embedded a certified hardware module, and hence, assures the verifier that a message *m* has been sent by a valid module without any doubt, but revealing nothing about the user's identity. Furthermore, if it talks to the same verifier twice; the verifier is not able to tell whether or not it is communicating with the same user as before or with a different one. There have been several academic papers in the past few years suggesting solutions based on DAA for V2X communication (see for example [22][23][24]). More recently, it has been shown that the DAA-based model supports very efficient revocation of misbehaving vehicles and does not require the use of CRLs, hence removing all the computational and communication overhead that comes with it [25]. Instead, when the Revocation Authority issues a revocation request, this triggers the TC of the misbehaving vehicle to delete all of its pseudonym certificates and cryptographic key pairs, thus rendering the TC unable to generate new pseudonyms in the future. However, experimental evaluation and demonstration of such solutions are yet to come in the near future.

Trust assessment mechanisms

As the services and applications go beyond Day-1 applications and towards overall smart transportation (including autonomous driving), the siloed V2X data model becomes insufficient. Most of the decisions or information required for cooperative vehicular services depend on information from a vehicle's surroundings. This means that a large amount of data processing and sensor information data will need to be exchanged between vehicles and infrastructure. In its guidance for Day-2 and beyond roadmap [26], the Car2Car Communication Consortium points out the importance of trustworthiness in shared information. As the driver will be less and less involved in the driving tasks, the functions relying on V2X information have to guarantee the required quality for functional safety and possibly support higher ASILs. So, vehicles need to transmit accurate information, and this information must be certified up to a determined extent. Hence, establishing a high level of trust in received data and the functions that rely on this data requires new node-centric or data-centric trust assessment methods, enabling the C-ITS stations to assess the trust level of its neighbouring stations and the received data, and further enabling them to make critical driving decisions, i.e. to make an OEM to trust the algorithms used by an external entity.

Towards flexible and innovative end-to-end services with various data from other sources, it is preferable to ensure enhancements to the ITS infrastructure that enable information integration across different platforms. 5GAA has been investigating several technology components to enable V2X services. One key component is Mobile Edge Computing, or MEC. In particular, and as discussed in [7], MEC is a key enabler of several C-V2X applications that require low latency and high reliability. There are many C-V2X use cases with high data-processing demands that could benefit from the use of MEC instead of uploading the data to the cloud, which could cause additional round-trip delays. However, MEC deployments are typically characterised by a complex multi-vendor, multi-supplier, multi-stakeholder ecosystem of hardware and software devices. In these distributed systems, it is difficult to envisage a central entity that implements system-wide security assurances or accepts liability if things go wrong. The multi-party nature of edge environments requires mechanisms to assess the level of trust each party can rely on, in a way that considers the dynamic nature of the environment and life-cycle management issues, such as deployment or migration. Overall, enabling the backend to bear parts of the processing burden of vehicles in the mid- to long term will have a significant impact on the security, safety and trustworthiness of vehicles' operations and decisions.

In both of the above cases – outsourcing remote computations and relying on input from other entities to calculate a function locally – the dynamic nature of the connected and autonomous vehicle applications and computing environment dictates that no initial trust between entities can be assumed.

We would then need to build mechanisms for dynamic and continuous trust assessment and establishment in order to establish a 'reasoned' trust relationships, and hence assess the risk of an operation and the level of trust an entity can put on another entity. Given the nature of these mechanisms, such a reasoning mechanism must have the ability to deal not only with uncertainty, but also previously unknown relationships. For example, subjective logic is a powerful framework to 'reason' over trust relationships in uncertain circumstances and to help build 'trust graphs' that fuse input from multiple sources to come up with an overall opinion on the trustworthiness of a service or data.

A solution based on Trusted Execution Environments, or TEE, could be utilised here to establish a verifiable chain of trust by providing verifiable evidence on the correctness of operations, from their trusted launch and configuration to the runtime attestation of both behavioural and concrete low-level execution properties. This can enable overall 'chip-to- cloud' protection, which is important in the event that an attacker is able to compromise a component in the car. Consider, for example, that the attacker is able to replace a service or a component with another one that has been infected with malware. Without protection, the malicious module can 'misbehave' and jeopardise vehicle safety and security. With TEE and virtualisation as a first line of defence, the system can locally detect the corruption and then limit the attack to the infected module. With chip-to-cloud assurances, other entities can be informed of the corruption and reduce their level of trust in the given vehicle accordingly, however a sensor input can still be faulty or manipulated, meaning that multiple providers are needed to increase the level of confidence following an event.

Post-quantum cryptography

The security of V2X communication relies on a PKI architecture that is a based on Elliptic Curve Cryptography, or ECC; V2X messages include security certificate(s) that provide assurance and integrity protection for the messages. These certificates are signed by an ECC algorithm. Breaking the ECC algorithm will have major impacts on the integrity of the messages and the trust relationship between the communicating parties within the V2X ecosystem.

One of the major threats to V2X in general, and the underlining ECC algorithm in particular, is the potential completion of a practical large-scale quantum computer. Unlike traditional computers, quantum computers exploit quantum mechanical phenomena to solve a set of mathematical problems, such as integer factorisation, discrete logarithms, and elliptic-curve discrete logarithms, in significantly less time than traditional computing. These problems are perceived to be too difficult or mathematically impossible using traditional computers using a finite amount of time and resources. The difficulty in solving them is the fundamental strength of modern public key crypto-systems. If quantum computers become a practical reality, then hackers may be able to undermine the underlining mathematical foundation that public key crypto-systems, such as RSA and ECC, rely on.

Of particular importance to this work is the security of the ECC algorithm in a post-quantum world. The security of ECC fundamentally relies on the difficulty of computing the elliptic-curve discrete logarithm problem. Several research papers have shown that a quantum computer using Shore's algorithm [27] can be used to effectively compute the discrete logarithm and therefore break the ECC algorithm. Roetteler et al. [28] provided a quantum resource estimate to compute discrete logarithm using Shore's algorithm. Their research concluded that the elliptic-curve discrete logarithm can be computed for an *n-bit* elliptic curve defined over prime field using quantum computer with at most $9n+2[\log_2(n)]+10$ qubits using a quantum circuit of at most $448n^3\log_2(n)+4090n^3$ Toffoli gates. To put things in perspective, that will require 2330 qubits and about 128 billion Toffoli gates to tackle a 256 bit (128 bits security level) ECC curve. It is also worth pointing out that their work supported a previous estimate by Proos and Zalka [29] in comparing the quantum resources required to break both ECC and RSA under the same security level. They showed that the number of resources required to attack ECC is less than that for attacking RSA, suggesting that ECC is even an easier target than RSA.

It is not clear when quantum computers are expected to be available at such a large and reliable scale. Many researchers and scientists believe that a computer like this is today an engineering challenge, which means it is not a matter of “if” but “when” it will be built. According to the National Institute of Standards and Technology, (NIST), “Some engineers even predict that within the next twenty or so years sufficiently large quantum computers will be built to break essentially all public key schemes currently in use.” [30]

While it is important to estimate the timeframe – when to expect a large-scale quantum computer – it is equally important to realise the amount of time it takes to define, build and deploy a suitable PKI and technology adapted to the new computing capabilities. In the past, it took about 20 years to establish and deploy public key cryptography infrastructure suitable for contemporary use. For this reason, different standardisation bodies, such as NIST and other organisations around the world, are working on a post-quantum crypto-algorithm and evaluation criteria to be prepared in good time. Therefore, the 5GAA community must be prepared sooner rather than later to assess, evaluate, and get involved with these organisations, helping them assess the impact of these algorithms and potential standards on the latest V2X communication and strategy.

7 Conclusions and next steps

This White Paper presented a comprehensive overview of ‘5G evolution and beyond’ V2X systems. It first tackled the task of identifying the requirements of the system. Two paths were proposed to explore the requirements, one based on consensus from multiple stakeholders for V2X deployment, and the other based on currently observed trends.

Following the discussion related to requirements, essential features for future V2X systems were studied. Since V2X systems are large and complex multi-stakeholder systems, features from multiple aspects were included, such as network capability, device capability, privacy and security, spectrum needs, regulations, policies, and standards.

From a network point of view, it was established that ubiquitous service availability is considered to be a key feature that needs to be supported by future V2X systems. This then calls for synchronised mechanisms across multiple layers of the communication stack that allows efficient and flexible utilisation of all available resources, both within a CSP domain and across multiple CSPs. While combining multiple CSP resources, a harmonised QoS framework was considered beneficial. If communication networks are enablers of critical applications, it was outlined how important it is that sufficient network information is exposed to third-party applications (to enable efficient adaptations).

On the topic of devices, V2X systems were shown to embrace several devices associated with different kinds of vehicles and road users. Their limited size and form can significantly influence implementation of wireless technologies in the devices. In order to fulfil the wireless link requirements given the device constraints, it was identified that novel mechanisms might be necessary, in particular with respect to enhancements of technologies to limit the number of components, and better power management within devices.

V2X systems are fundamentally built around the idea of exchanging sensitive information between different devices and network entities. It was elaborated that existing privacy and security mechanisms applicable to PC5-based broadcast messages could be further enhanced in order to be better protected from both *external* attackers and *internal* attacks (potentially arising from entities managing the privacy and security infrastructure). Additionally, it was illustrated that with the evolution of V2X use cases and the number of ways to be realised, privacy and security mechanisms need to take into account the use cases but also how they can be implemented to fulfil all privacy and security requirements efficiently. For example, if use cases are implemented by using trusted backend systems, such a system can fulfil privacy (anonymisation) and data quality requirements, e.g. multiple inputs to raise trustworthiness.

The spectrum requirements for future V2X networks was discussed in light of several advanced use cases studies in [2]. The studies indicated that the delivery of advanced use cases via LTE-V2X and NR-V2X will require an additional 40 MHz or more of spectrum at 5.9 GHz for V2V/I/P communications. Similar to V2N services, an *additional* spectrum of the order of several tens of MHz (at least 50 MHz) and several hundreds of

MHz (at least 500 MHz) are needed in the low- and mid-bands, respectively, to support the anticipated advanced V2N services. However, the spectrum needs highly depend on the service penetration.

In order to speed up the deployment and efficiently utilise the available resources from different CSPs, it was identified that policies from regional and/or government regulators might be necessary to ensure service continuity at national borders and enable the sharing of public-private, and private-private communication infrastructure. Additionally, it has been recognised that in order to gain people's trust in the system, it is imperative that it meets the necessary regulatory standards and policies with respect to safety, and data protection and privacy (e.g. GDPR).

Following the detailed analysis of some features, a few widely discussed technology enablers for 'beyond 5G' were analysed in the context of V2X. The goal was to understand how these enablers could benefit or enhance the future services, and to identify the potential challenges that need to be addressed to make them a reality. In this regard, six technology enablers were discussed.

1. Integrated sensing and communication: The evolution of communication system towards higher frequency bands offering opportunities to combine sensing and communication systems. This is particularly appealing for vehicular devices as it helps to combine the functionalities and hence deals with limited space and device mounting challenges in and on the vehicles, while offering high-speed communication links. Furthermore, environmental awareness can be utilised to improve the communication performance of the vehicle communication systems with greater reliability and predictability.

2. Integrated terrestrial and non-terrestrial networks: To ensure the availability of communications links everywhere for a vehicle, the combination of NTN for vehicles was discussed as a path to provide ubiquitous coverage. With the ongoing discussion in 3GPP standardisation related to NTN, this technology is gaining significant attention in the industry. 5GAA is investigating this technical enabler with special focus on automotive services.

3. Distributed on-board communication system: Although this approach in vehicles is widely known in the automotive community, its extended use through a wireless interface was brought to light. The identified benefits were mainly with respect to more flexibility in terms of placing the communication devices in the vehicles, and increasing the functionalities with the distrusted units to improve the communication system's performance around the vehicle.

4. Refractive meta-surfaces: This approach to moving antennas inside the vehicle is promising as a key enabler supporting multiple spectrums and terrestrial and non-terrestrial networks.

5. Data-driven networks: The potential of leveraging vast amounts of data was recognised in the paper. The ideas revolved around how the available data could be used to support application and network management for V2X services. In addition, the 'compute capabilities' available on or in the vehicles can be leveraged to offload tasks from other interconnected devices. Distributing computing ('distributed compute') tasks across

vehicles, handhelds, and cloud computing platforms based on the compute-communication capabilities of the devices means lower latency and more energy efficient execution of a computation task.

6. New spectrum band: The potential of high frequency bands (such as mmWave and sub-THz bands), VHF bands (30-450 MHz) for automotive use cases was discussed.
7. Privacy and security mechanisms: Three security and privacy mechanisms were discussed related to pseudonym-based schemes for V2X, trust assessment mechanisms, and post-quantum cryptography for V2X use cases were discussed.

Based on the high-level overall analysis carried out in this White Paper, several areas could be explored for the future study of next-generation V2X systems. Some of them include:

- Identification and detailed descriptions of new and future V2X services and use cases, beyond the ones considered in the 5GAA Roadmap. This could help recognise potential KPIs, service requirements, stakeholders, and business models for V2X evolution.
- Deeper investigation of selected technology enablers by clearly identifying aspects generating greater interest. The analysis could also consider the impact of regulations and feasibility studies.
- Development of business models and go-to-market strategies to drive market penetration of V2X services.

8 Annex A change history

5GAA is a multi-industry association to develop, test and promote communications solutions, initiate their standardisation and accelerate their commercial availability and global market penetration to address societal need. For more information such as a complete mission statement and a list of members please see https:/5gaa.org

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