Fifth Generation Communication Automotive Research and innovation

Deliverable D1.3
5GCAR Final Project Report

Version: v1.0

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Abstract

This final deliverable contains an overview of the 5GCAR results, their related assessments and evaluations conducted by demonstrations and disseminations.

The 5GCAR project investigated and proved the added value of C-V2X for connected cars, studying the domain from multiple perspectives, including business models, spectrum matters, and contributing to the conception of innovative solution for the radio access network, the system architecture, and the security and privacy framework. Multiple cooperative Intelligent Transport Systems (C-ITS) use cases, which benefit from 5G features, were demonstrated. Moreover, the scientific work within the project impacted standardization by means of project partner contributions. Furthermore, the project has influenced the ecosystem thanks to publications and presentations in major events over the past two years. For instance, the recently rejected Delegated Act on the 8th of July 2019 can be also interpreted as 5GCAR success, because nine partners in 5GCAR are also 5GAA members and a close interworking ensured that 5GCAR visions contributed to C-V2X long term strategy for Europe.

This deliverable highlights the main results and provides references to the relevant deliverables. The results address a wide range of C-V2X challenges, ranging from use case and requirement definitions, investigation of business and spectrum related aspects, development of cellular sidelink and position technical enablers as well as architectural components. The technical work is the foundation of the final four demonstrations (27th of June 2019) of 5GCAR use cases.

The demonstration findings have shown that connected driving has a huge potential for more safety and comfort (assisted and automated) driving use cases. Together with the main dissemination and exploitation activities, the results are also outlined.

Generated technical findings have contributed to pre-standardization and normative standardization bodies like 5GAA and 3GPP to shape eventually 5G Rel-16 Study Items, ongoing Work Item and Rel-17 for some of the technical enablers. In total, 5GCAR partners have successfully placed 40 technical C-V2X contributions to 3GPP and ETSI which are now considered for normative Rel-16 specifications to be finalized by end of 2019. Besides automotive service level agreements we helped to define network and radio level requirements for assisted and autonomous driving use cases supported by C-V2X.

Besides standardization, 5GCAR partners are responsible for 175 dissemination activities like conference papers, journals, talks, panels, workshops and summer schools. In addition, 5GCAR was also able to contribute to the 5G PPP activities by being the major driver for the Automotive working group which is worldwide referenced (e.g. by 5G Forum in Korea) and has published two white papers. More than 215 standardization contributions and disseminations have also underlined our ambition to be a power house for C-V2X targeting to external organizations and the public.

Contents

List of abbreviations and acronyms

3D	Three Dimensional
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G PPP	5G Private Public Partnership
5GAA	5G Automotive Association
5GCAR	5G Communication Automotive Research and innovation
ACC	Adaptive Cruise Control
BF	Beam Forming
BLER	Block Error Rate
BS	Base Station
C-ITS	Cellular ITS
C-V2X	Cellular V2X
CACC	Cooperative ACC
CAM	Connected and Automated Mobility
CEF	Connecting Europe Facility
DA	Delegated Act
E2E	End to End
eMBB	enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
gNB	next Generation Node B
GPS	Global Positioning System
HARQ	Hybrid Automatic Repeat reQuest
HD	High Definition
HMI	Human-Machine Interface
IaaS	Infrastructure as a Service
IEEE	Institute of Electrical and Electronics Engineers
IMT	International Mobile Telecommunications
ITS	Intelligent Transport System
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
KPI	Key Performance Indicator
L	Level
LiDAR	Light Detection And Ranging
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
MNO	Mobile Network Operator
MWC	Mobile World Congress
N2I	Network-to-Infrastructure
NGMN	Next Generation Mobile Networks
NR	New Radio
OEM	Original Equipment Manufacturer
OTA	Over The Air
OTDOA	Observed Time Difference of Arrival
P2N	Pedestrian to Network
PC5	Proximity Services (ProSe) direct Communication interface 5
QoS	Quality of Service
RAT	Radio Access Technology
Rel	Release
RRM	Radio Resource Management
RSU	Road Side Unit
SDN	Software Defined Network
SL	Sidelink
SM-Zone	Smart Zone
SW	Software

UE	User Equipment
URLLC	Ultra-Reliable and Low-Latency Communications
UTAC TEQMO	United Test and Assembly Center Ltd TEQnology for MObility
Uu	Air interface between BS and UE
V2I	Vehicle-to-Infrastructure
V2I2V	Vehicle-to-Infrastructure-to-Vehicle
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Anything
VRU	Vulnerable Road User
VRUP	VRU Protection
WP	Work Package

1 Introduction

5GCAR is a European Union co-funded project that started 1st of June 2017 and ended 31st of July 2019. The total project budget is close to 8 M€ and 28 full time equivalents working during the project duration.

This document is the 5GCAR final report which gives an overview of the 5GCAR achievements during its complete lifetime. One of the highlights are the successfully demonstrated 5G-V2X use cases in June 2019 where it is proven the added value of 5G for assisted and automated driving. Also, the other technical achievements which supported the 3GPP and 5GAA technical advances have contributed to its proliferation goals of C-V2X in Europe and worldwide, e.g. USA. All highlights are on main project results in focus together with references to the deliverables for interested readers who wish to learn more. These project deliverables can be found on the project website, https://5gcar.eu/ [5GC19-D11].

Note: 5GCAR has worked out C-V2X solutions based on cellular networks and radio. Sometimes, the term V2X is used which known since more than two decades and might consider also DSRC (802.11p) use cases and considerations. C-V2X addresses LTE-V2X and 5G-V2X (NR-V2X) depending on the relevant use case. In general, LTE-V2X was mainly developed for Day1 (safety) use cases, whereas 5G-V2X has its major focus on Day2 (sensor sharing) and Day3 (maneuver alignments) use cases [C2C18-CC] which is the main focus of 5GCAR.

1.1 Objective of the document

This final-project deliverable contains an overview of the 5GCAR results attained up until the end of the complete project together with future outlooks for the C-V2X community. References to the 5GCAR project deliverables behind these main results are also provided. The objective of this document thereby goes very much hand in hand with what the 5GCAR project has achieved:

- Clarify use cases and requirements for future connected vehicles as well as identifying innovative business models and important spectrum aspects for V2X links;
- Develop a 5G radio and architecture design that provides
    - very low latencies below 5 ms,
    - with very high reliability (99.999%),
    - at very high vehicle velocities,
    - which enables, even in a very high vehicle density, the support of a broad range of V2X services,
    - and achieves advanced 5G positioning with accuracies below 1 m;
- develop a 5G system architecture that is flexible in its functional and topological configuration, with advanced quality-of-service management to efficiently support a wide range of V2X services and business models;
- demonstrate – with real 5G test equipment and vehicles – four important V2X use cases for assisted/automated merging of multiple lanes, cooperative perception for maneuvers of connected vehicles, and vulnerable road user protection;

- disseminate results into the standardization (3GPP), industry harmonization (5GAA), and regulation via both the telecommunication and automotive industries as well as into international conferences, panels, workshops, peer reviewed journals, magazines and books.

This range of V2X challenges together with the achieved 5GCAR results and status at the writing of this report is what this document is all about, whereas [5GC19-D12] concerns project results and details for the first half of the project.

1.2 Structure of the document

Section 1 gives a general introduction. Section 2 provides an overview of the project use cases, requirements, business models and spectrum aspects. Section 3 contains the 5G V2X radio interface highlights and in Section 4 the 5G V2X system and architecture work is summarized. In Section 5 the demonstration work is presented whereas Section 6 provides information on the dissemination activities. Section 7 concludes the deliverable with a future outlook, while the references are provided in Section 8. The 5GCAR project structure and 5GCAR consortium is provided in Annex A.

2 Scenarios, requirements, business models, and spectrum aspects

To provide a common starting point for the project, the potential use cases were detailed and thoroughly analyzed and defined through their requirements and relevant key performance indicator (KPI) requirements of the future 5G ecosystem in the context of the automotive sector. The underlying business models were studied, and emerging new businesses and players were investigated. Further, certain spectrum issues from the perspective of requirements and limitations were also considered. The key objectives were to:

- Identify and refine key V2X scenarios and use cases in the 2020 to 2030 time horizon, while taking the work in other 5G projects and forums (such as 3GPP, 5GAA, NGMN, ETSI ITS and ITU-R) into account.
- Consolidate the identified V2X use cases into a manageable set to consider within the 5GCAR project, defining performance and functional requirements.
- Analyse the V2X scenarios and use cases from techno-economic perspective, to identify suitable V2X business models for the automotive sector and in its integration with 5G communication systems.
- Analyse the V2X scenarios and use cases from a spectrum perspective, in order to identify suitable ways to make use spectrum in such environments by describing spectrum impacts and usage aspects.

2.1 Scenario definitions and requirement specifications

In [5GC19-D23] 5GCAR provides a vision of the automated driving use cases roadmap in Europe for the next decade and its relationship with the 3GPP releases and the spectrum availability. The C-V2X ITS services possible with 4G are presented as well as the performance limits of this cellular technology compared to the 5G key advantages. The main show stoppers of 5G are explained and highlighted. Finally, a review of the KPI of the project was made under the vision of the 5G PPP framework which has been defined under an infrastructure perspective and does not match precisely with an automotive vertical approach.

Already in [5GC19-D21] the 5GCAR use cases together with their requirements and KPIs were defined: Lane merge, See-through, Network assisted vulnerable pedestrian protection, High definition local map acquisition, and Remote driving for automated parking. These use cases were selected from the following identified use case classes: Cooperative maneuver, Cooperative perception, Cooperative safety, Autonomous navigation, Remote driving. A representative use case was selected from each class. This is illustrated in Figure 2.1.

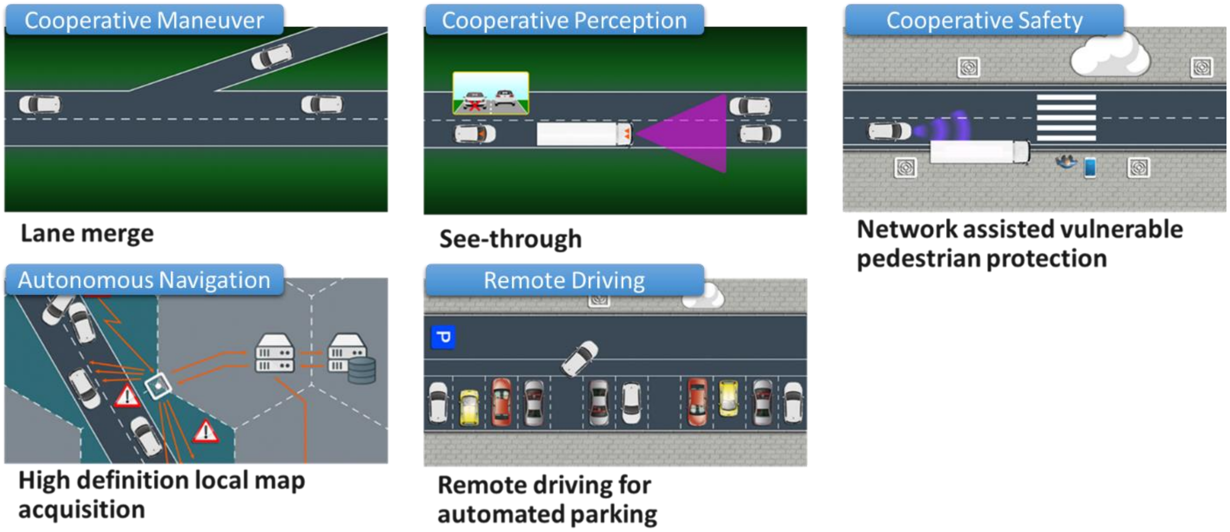

Figure 2.1: 5GCAR use cases and use case classes

In [5GC19-D23] a vision of the automated driving use cases is presented remarking some important elements:

- The automotive lifecycle is slower in the availability and adoption of the chipset compatible with new 3GPP releases than the consumer electronics.
- 4G has enough capabilities for some C-V2X services but has limitations in terms of performances which are overcome by the arrival of 5G.
- The lack of a road infrastructure connectivity deployment agenda is a threat for 5G adoption in the automotive industry.
- The current European regulation has an important effect in the roadmap of the autonomous driving use cases where China and USA will have a faster deployment. On the connectivity side the current status of the Delegated Act was a risk for 5G adoption and must be now modified for full inclusion of C-V2X. In the automotive industry, the arrival of the Clean Air For Europe regulation focuses the main efforts of the OEM in the short term.

2.2 Business models

The 5GCAR business work focused on two main axes. On one side, all the innovations defined in the project and described as technological components, have been grouped and analyzed under a business perspective. On the other side, cost components and market opportunities are studied, mainly from the following three settings: the network deployment costs for 5G in roads and highways, the current security policy for sidelink communications and the possibilities of the vehicle updates over the air using cellular connectivity. For instance, 5GCAR contributed significantly to the highway 5G V2X business feasibility studies [5GA18-WP] and [5GA19-WP] conducted by the 5G PPP Automotive working group, where the network operator business relations are illustrated in Figure 2.2.

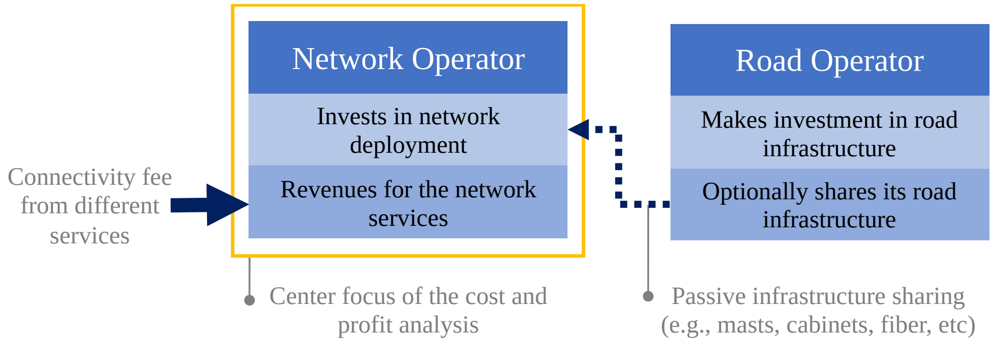

Figure 2.2: Main business setup for the network deployment analysis, containing the roles of the Network Operator

Some of the main [5GC19-D22] and [5GC19-D23] results are highlighted here:

- As it has been pointed out in [5GC19-D23], the connectivity infrastructure in roads and highways is a must for the V2X service deployment. The costs expected are important and several network sharing options are proposed.
- V2X is a social benefit, so all actors in the ecosystem shall contribute to its deployment through a convenient regulation framework enabling different network sharing options.
- The current security policy, proposed in the rejected Delegated Act (DA) for sidelink communications (Note: current DA was rejected on 8th of July 2019 by European Council), based on pseudonyms supposes a cost barrier for its adoption in extremely cost sensitive automotive industry. An estimation of more than 30€ per car in its lifetime and overall market beyond 1 billion € once the solution has arrived at a full adoption.
- Over The Air (OTA) updates was one of the services used in the [5GC19-D22] to explain the evolution of the business models due to the arrival of 5G. Now in [5GC19-D23] a vision of the potential market available for the connectivity in the OTA service is studied. Three factors are considered: the size of the updates with two approaches, one conservative and one non-conservative; the public prices of the GByte in different European markets and finally a foreseen mean price reduction per year. This provides a potential market from 300 million € to more than one billion that could provide a quick win both for the telecom and automotive industries.
- The different technological components provided by 5GCAR have been analyzed under a business perspective and grouped under five categories, namely: positioning, V2X radio design, network procedures, end to end security and edge computing enhancements.

Positioning and edge computing enhancements are those with higher value creation expectations. All those technological components related to mmWave will need more time for the vehicular communication adoption.

2.3 Spectrum aspects

A survey of 5G spectrum auction and regulation has been conducted with a deep dive in the big European markets. A comparison in terms of bandwidth, cost and regulation is provided. Further, there is a qualitative spectrum impact analysis of 5GCAR novelties. One illustration is provided in Figure 2.3.

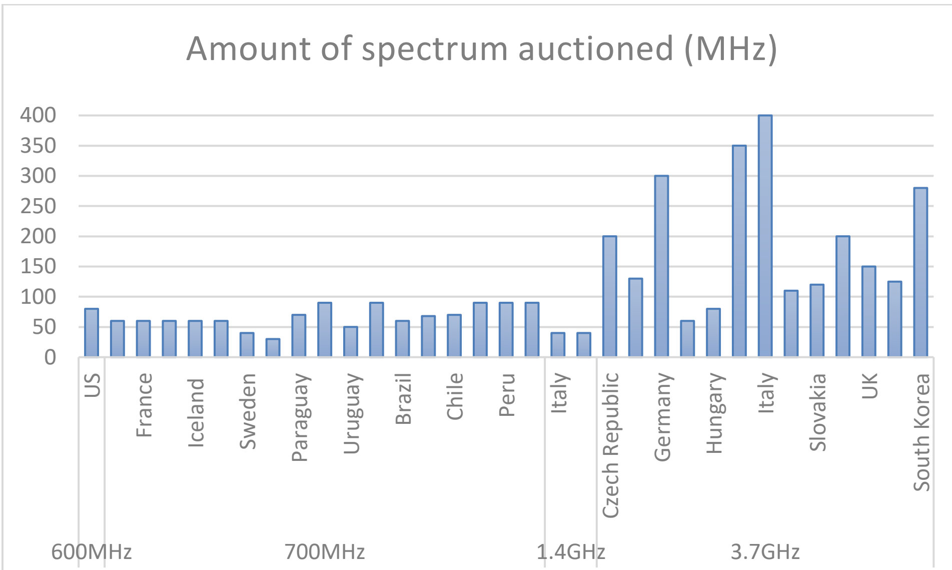

Figure 2.3: Amount of spectrum auctioned worldwide

The key spectrum elements from [5GC19-D22] and [5GC19-D23] are:

- Lower bands (600 and 700 MHz) have an important interest from MNO, reaching important values in the frequency auctions. 5GCAR already highlighted in [5GC19-D22] the important possibilities of this band for C-V2X communications
- Refarming will enable frequencies initially planned for 4G, to be used for 5G deployment
- In spite of the Digital Single Market strategy, each country in Europe has done a different spectrum auction, with different requirements and different timeline for the frequency bands auctions.
- Italy has made already all the 5G frequency bands auctions with high prices especially in low bands. Germany has defined important requirements for road coverage in the 5G auction.

- Several countries in Asia have taken a completely different approach from Europe. In these countries, the deployment has been prioritized over the price of the frequency bands.
- Among the technological components defined in 5GCAR, three provide an important spectrum impact. First, the radio link reliability by combining sidelink and Uu interfaces, this solution potentially doubles the spectrum usage. Second, the location aware scheduling shall reduce the interference between neighbors resulting into a spectrum usage optimization. Finally, the multi-operator solutions for V2X communications shall have an important spectrum impact depending on the type of licensing scenario.

3 5G V2X radio interface

The 5GCAR project aims at contributing to an overall 5G network design on top of the latest development of 5G especially from 3GPP, and specifically to designing V2X technology components to realize the V2X use cases identified in the project. It is quite clear that the key requirements derived from the identified use cases including reliability, (end-to-end) latency, data rates, spectral and energy efficiency are very demanding and cannot be fully supported by today's wireless networks. Therefore, novel V2X solutions in terms of radio design are necessary, which can result in a new radio interface. The 5G radio interface for V2X communication plays an essential role in supporting not only the aforementioned emerging V2X use cases but also ultimately targeting to support fully autonomous driving in all kinds of environments.

As discussed in Section 2.1, the use case classes identified in the 5GCAR project (cooperative maneuver, cooperative perception, cooperative safety, intelligent autonomous navigation and remote driving) impose a broad range of challenging requirements on the radio interface. Especially, it is expected that the radio interface supports high data rates with low latency and ultra-high reliability simultaneously. To meet these 5G V2X requirements, the 5GCAR project have proposed a number of new technology components that can be combined and deployed together. The technology components are summarized in [5GC18-D31] and [5GC19-D33] and have a broad coverage ranging from the Uu interface (i.e., 3GPP terminology used for the wireless interface between device and network) related concepts and sidelink interface (i.e., 3GPP terminology used for the wireless interface between devices), in addition to efficient ways of using positioning information for V2X communications. They include direct communication between vehicles, communication between vehicle and road infrastructure, between vehicle and pedestrian or vulnerable road users and vehicle to radio network. The needed functionality can be provided by different actors as illustrated in Figure 3.1.

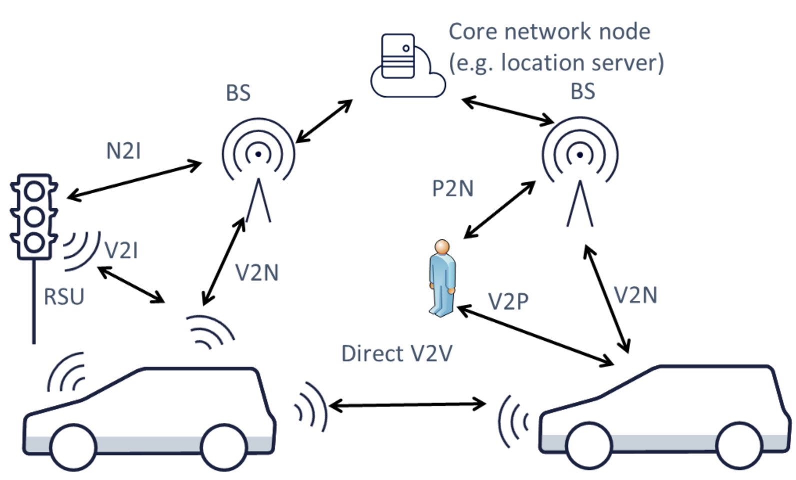

Figure 3.1: Various V2X communication scenarios

(BS: Base Station; N2I: Network to Infrastructure; P2N: Pedestrian to Network; RSU: Road Side Unit; V2I: Vehicle to Infrastructure; V2N: Vehicle to Network; V2P: Vehicle to Pedestrian; V2V: Vehicle to Vehicle)

In total we have proposed 32 technology components for enhanced V2X radio interface which can be applied to improve the identified KPIs in terms of capacity, latency, reliability and positioning accuracy for future autonomous driving. The proposed technology components can be classified into six categories or technology component clusters as summarized in Table 3.1. More details can be found in [5GC18-D31], [5GC18-D32] and [5GC19-D33].

Table 3.1: 5G V2X radio interface technology component clusters and brief description

Technology component clusters	Brief description
Multi-antenna techniques	8 technology components related to predictor antenna, beam management for unicast/multicast/broadcast communications, and optimal antenna design for V2V communications.
Radio resource allocation and management	8 technology components on efficient radio resource management for both Uu and sidelink in either centralized and/or distributed way.
Sidelink design	3 technology components covering basic design for sidelink (discovery, synchronization signal and reference signal design).
Full duplex	3 technology components, on top of general study, cognitive resource usage for V2V communication and collision detection/avoidance are the focus.
Reliability enhancements	4 technology components starting from fundamental trade-off between reliability, latency and capacity to reliability enhancement to both data and control channels.
Positioning	6 technology components covering both the enhancement to real-time positioning, trajectory estimation and tracking.

The outcome from 5GCAR radio interface study has been contributed to 5G standardization development when the relevant topics started in 3GPP, including V2V channel modeling, technology components related to radio air interface design (covering both the Uu interface and the sidelink interface) and positioning as illustrated in Figure 3.2 [5GC19-D33].

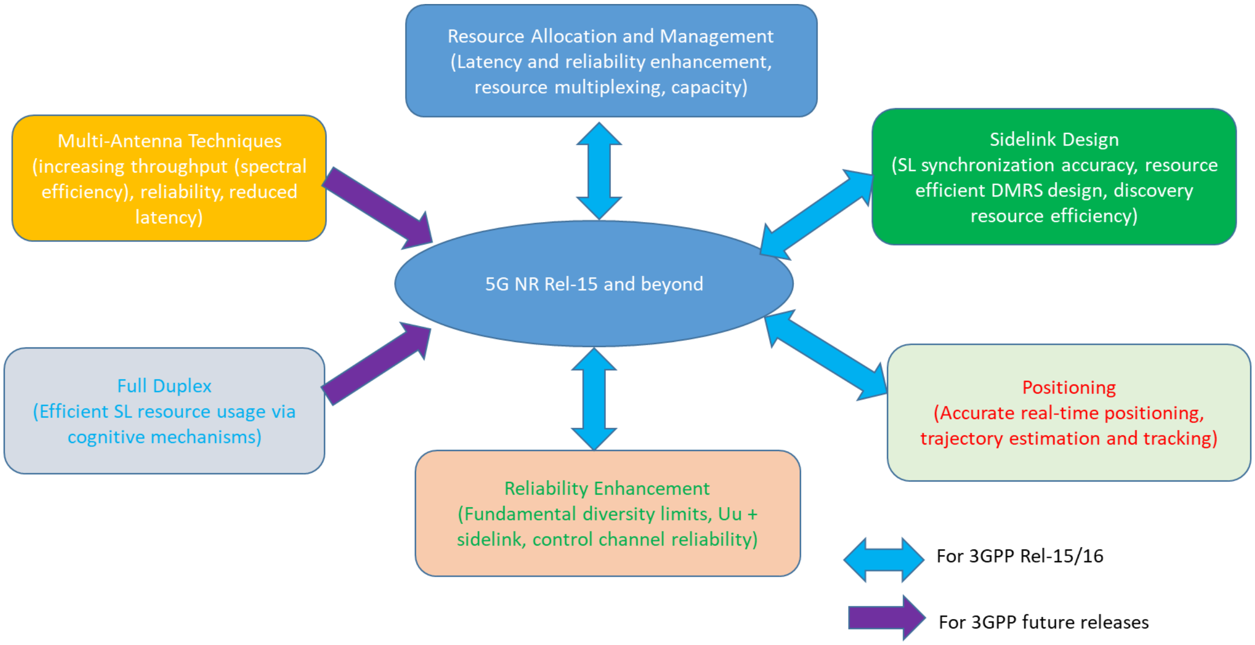

Figure 3.2 Integration of 5GCAR concepts with 5G NR in 3GPP

(3GPP: Third Generation Partnership Project; DMRS: DeModulation Reference Signal; NR: New Radio; Rel: Release; SL: Sidelink; Uu: Air interface between BS and UE)

3.1 Infrastructure-based 5G V2X radio interface

With respect to infrastructure-based technologies, practical multi-antenna channel estimation and prediction schemes, as well as their validation in outdoor field trials were performed. Especially for mmWave transmission, taking into account different transceiver architectures, broadcast and beamforming schemes have been studied to meet different sets of requirements. Multi-beam/multi-node multi-vehicle communication techniques for enhanced reliability with various source of diversity were studied. Reference symbol design for high speed scenarios and optimal power setting between data and pilot signaling were investigated as well. Moreover, it was proposed how to perform dynamic multiplexing between mission-critical messages and other traffic types, and trade-offs between signalling overhead and achievable spectral efficiency were elaborated. Another aspect which has been studied within the project is the radio frame design aspects. Moreover, we have investigated the optimal retransmission schemes to achieve very low block error rate (BLER). The investigated and proposed technology components are following (organized according to the belonged Technology component clusters as shown in Table 3.1):

- Multi-antenna techniques
    - Sensitivity analysis of the predictor antenna system
    - Predictor antenna for massive MIMO adaptive BF

  - Genetic-algorithm based beam refinement for initial access in mmWave mobile networks
  - Beam-domain broadcasting for V2N/V2I links
  - Beam-based broadcast schemes for V2X applications
  - Rate adaptation in predictor antenna systems
  - Beamformed multi-cast with HARQ feedback and retransmission
- Radio resource allocation and management
  - Efficient preemption-based multiplexing of services
  - Decentralized pilot-to-data power ratio configuration in multi-cell multi-user MIMO Systems
  - Joint optimization of link adaptation and HARQ retransmissions for URLLC services in a high-mobility scenario
- Reliability enhancements
  - Enhancing reliability in V2X Communication by exploiting diversity from cooperative links
  - Fundamental trade-offs between reliability and latency

3.2 Sidelink for 5G V2X radio interface

The sidelink-based V2X technology components enable the delivery of V2X services in the absence of infrastructure nodes and take advantage of network assistance under infrastructure coverage. The 5GCAR sidelink technology components include a network-assisted reliable discovery mechanism, synchronization and reference signals design, adjacent channel interference mitigation and several mechanisms for radio resource management, power control and scheduling (with and without network assistance). We have also studied a means to use sidelink for enhancing the reliability for cellular communication. Other outcomes include characterizing the benefits of full-duplex capability for V2X communication and obtaining insights into antenna design for line-of-sight V2X communication with multiple antennas. The list of the sidelink-based technology components is as follows (organized according to the belonged Technology component clusters as shown in Table 3.1):

- Radio resource allocation and management
  - Power control and scheduling to mitigate adjacent channel interference in vehicle-to-vehicle communication
  - Sidelink resource allocation with network assistance using multiple antennas
  - Distributed RRM for direct V2X communication

    - Radio resource management in 5G enabled vehicular networks
    - V2V resource allocation and MAC capacity
- Sidelink design
    - Synchronization for the V2V sidelink: sequences and algorithms
    - Reference signals design for direct V2X communication
    - Code-expanded random access for reliable V2X discovery
- Reliability enhancements
    - Sidelink assisted reliable communication
    - Enhancing control channel reliability by using repetitions
- Full duplex
    - Cognitive full duplex communications in V2X networks
    - Full duplex impact on V2X performance
    - Full duplex collision detection in V2X networks
- Multi-antenna techniques
    - LOS MIMO design for V2V

3.3 Positioning and channel modelling

Concerning positioning, we have studied existing solutions and their limitations including both non-mobile radio (GPS) and mobile radio-based techniques (LTE). 5GCAR has developed the following technology components that are essential for a positioning solution needed to enable 5G V2X use cases:

- Positioning
    - Trajectory prediction with channel bias compensation and tracking
    - Beam-based V2X positioning
    - Multi-array V2V relative positioning
    - Tracking of a vehicle's position and orientation with a single base station in the downlink
    - Harnessing data communication for low latency positioning
    - Enhanced assistance messaging scheme for GPS and OTDOA positioning.

While positioning in LTE is based on time measurements only (OTDOA), most 5GCAR approaches integrate enhanced time measurements with angle measurements. This becomes possible through smaller antenna array sizes in the frequency range above 6 GHz. We have shown that the desired accuracy below one meter is in principle achievable. By rule of thumb this corresponds to an improvement of one order of magnitude with respect to the reference cases LTE and GPS.

5G radio-based positioning has been implemented in one of the demonstrators. Tracking of road users with sensor fusion and trajectory prediction for a collision warning system have been implemented in two demonstrators.

5GCAR has intensively studied V2X channel modeling which has been submitted to 3GPP. At first, state-of-the-art channel models for V2X communications have been analyzed, including their most relevant components LOS blockage, path loss, shadow fading, and fast fading. Based on this existing work the gap in terms of missing components required to complete V2X channel modelling has been identified and the following key extensions have been developed for V2X channel modelling:

- New V2V measurements and characterization of channels above 6 GHz
- Multi-link shadowing model based on measurements below 6 GHz
- Channel measurements for massive MIMO adaptive beamforming.

We claim a very good alignment between 5GCAR activities and ongoing 3GPP NR standardization for both channel modelling and positioning. In particular, our channel modelling activities led to agreements in 3GPP meetings and results achieved in 5GCAR are reflected in 3GPP V2X channel models.

4 5G V2X system and architecture

The system and architectural aspects of the cellular network are of paramount importance for the support of advanced V2X applications and were hence studied in detail in 5GCAR. The technical output consists of 14 technical components, each representing a module addressing a specific need introduced by automotive applications, as well as network slicing for V2X, which is a technical enabler overarching the whole system, whose preliminary description was provided in [5GC18-D41]. The results of the work made within the project concerning the system, architecture, and privacy and security framework were published in [5GC19-D42].

In Figure 4.1, an overall picture is provided of the how the work made on the system and architecture positions itself within 5GCAR, with the E2E specifications and design overarch the whole system, the Quality of Service (QoS) and traffic flow optimization are integrated within vehicular UEs, bases stations and road side units, with the and the security and privacy matters transversally involving all of them.

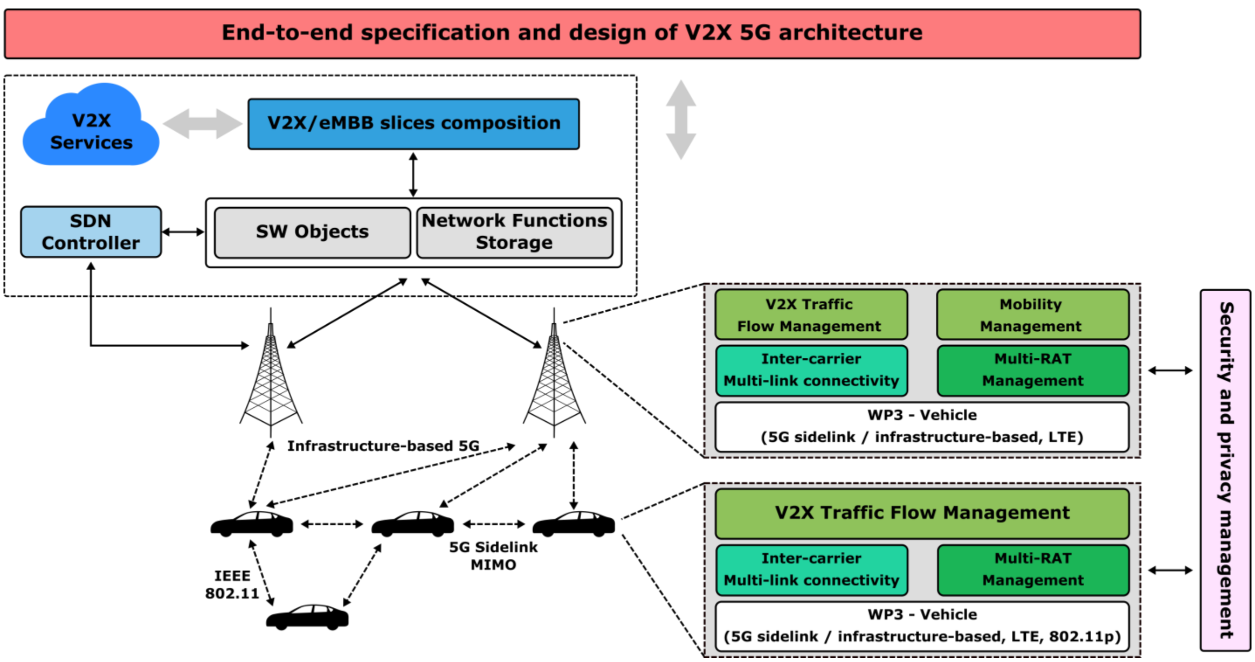

Figure 4.1: 5GCAR Overall system and architecture

(eMBB: enhanced Mobile Broadband; IEEE: Institute of Electrical and Electronics Engineers; LTE: Long Term Evolution; MIMO: Multiple Input Multiple Output; RAT: Radio Access Technology; SDN: Software Defined Network; SW: Software; V2X: Vehicle-to-Anything; WP: Work Package)

In Figure 4.2, an overall picture is illustrating the architecture technical components developed in 5GCAR, their domain of interest, and consequentially their location within the network.

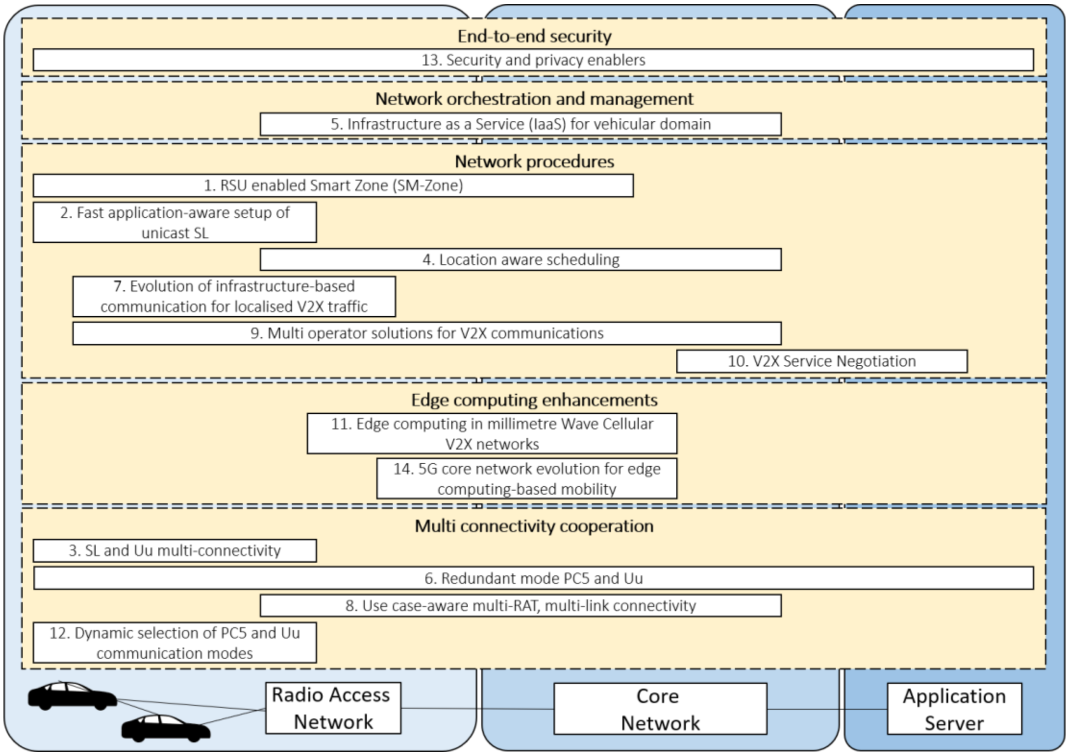

Figure 4.2: 5GCAR 5G V2X system and architecture technical components mapped, organized per area of relevance, highlighting their domain of influence in the end-to-end architecture

(IaaS: Infrastructure as a Service; SL: Sidelink; SM-Zone: Smart Zone; Uu: Air interface between BS and UE; V2X: Vehicle-to-Anything)

4.1 5G E2E architecture for V2X communications

This domain area includes the solutions that directly involve the 5G architecture from an end-to-end perspective. Specifically, the work performed within the task in charge of E2E architecture for V2X communications resulted in four technical components (RSU-enabled smart zone, Infrastructure as a Service for vehicular domain, Multi operator solutions for V2X communications, and 5G core network evolution for edge computing-based mobility), briefly described in the following:

- "RSU-enabled smart zone (SM-Zone)" addresses the fact that V2X communications related to road safety and efficiency have local scope, by partitioning the road network into an ensemble of smart zones. Each of these SM-Zones is served by a 5G-RSU, which is a network entity controlled by the 5G cellular network, capable of supporting local communications using direct transmissions over the sidelink.
- "Infrastructure as a Service for vehicular domain" is a paradigm conceived to ease the deployment, management, configuration, and upgradability of the ITS services and

components deployed on the 5G network, which will include applications developed by both first and third parties.

- "Multi operator solutions for V2X communications" deals with the fact that vehicular UEs will need to be capable of connecting to multiple network operators, to be able to achieve high reliability. To address this issue while respecting the stringent V2X requirements, this technical component proposes a location-based management of the connectivity with multiple operators.
- "5G core network evolution for edge computing-based mobility" is related to the deployment of applications related to the vehicular UEs on computing resources located on the edge of the network. This technical component addresses the timely migration of UE jobs running on the edge when the related UE perform a handover, in order to minimize the service interruption time.

4.2 Traffic flow optimization and coordination of multi-link and multi-RAT connectivity framework

User plane traffic optimization, which includes the management of multiple links and multiple radio access technologies, represents a topical area of research for V2X communications, and thus resulted in nine technical components, described in the next paragraphs:

- "Fast application-aware setup of unicast SL" deals with automotive application requiring direct V2V/V2I unicast links, providing them with tools to enable their quick setup over the Sidelink.
- "SL and UU multi-connectivity", which targets enhancements in the area of multi-connectivity cooperation and aims for enhancing reliability for use cases of 5GCAR such as the see-through use case or the lane-merge use case [5GC19-D21], Section 2.1,, which can be delivered by using SL as the primary means of communications.
- "Location aware scheduling" aims at extending the concept of QoS defined in 3GPP, by also considering the location-specific requirements of V2X data flows. This technical component proposes a mechanism to improve the efficiency of scheduling, allowing the network to optimize the usage of resources when distributing location-sensitive data (such as high-definition maps, which are considered as a case-study).
- "Redundant mode PC5 + Uu" is a technical component the focuses on the contemporary utilization of both the direct PC5 link and of the infrastructure routed traffic, this time in order to improve reception reliability. The problem is treated in terms of redundant scheduler, of which multiple possible implementations are analyzed, each locating the redundant scheduler at a different layer in the protocol stack. Four different configurations of redundant scheduler, based on the layer of the protocol stack wherein the duplication/deduplication layer is located, are proposed and compared based.

- “Evolution of infrastructure-based communication for localized V2X traffic” is a technical component focused on the minimization of the latency introduced by the data path routed via the base station. To do so, an end-to-end local radio path is defined for user plane traffic, along with a low-level radio bearer management, which enables optimized, low latency local breakout communications touted via the infrastructure.
- “Use case-aware multi-RAT, multi-link connectivity” is a technical component focused on the determination of the better combination of links and radio access technologies to efficiently satisfy the requirements of diverse V2X services, while taking into the consideration the high mobility of vehicles.
- “V2X service negotiation” introduces the capability of exchanging information between V2X services and the network, in order to improve the mutual level of awareness, with the goal of optimizing the service delivery.
- “Edge computing in millimeter wave cellular V2X networks” is a technical component that aims at optimizing the data rate and minimizing the energy consumption, in a scenario wherein multiple vehicular UEs cause interference to each other when communicating with mmWave-equipped road side units.
- Finally, “Dynamic selection of PC5 and Uu communication modes” is related to the support of multiple links, specifically PC5 and Uu (i.e. between the UE and the base station). This technical component deals with the dynamic selection of the appropriate link for a specific V2X service, considered the benefit that each interface can provide at a specific point in time and space.

4.3 5G Security and privacy for V2X communications

Privacy and security implications of 5G-based V2X communications constitute a domain that overarches all of the architectural aspects. One major technical component is hence defined, named “Security and privacy enablers”. As a baseline, a state of the art of the security architecture for V2X communication is provided, covering both the European and the American standards. These include the architecture of the public key infrastructure to deliver the digital certificates to on board units and road side units, and the format of the digital certificates.

In the technical component, the legitimacy of the sender, and privacy are identified as key requirements of safety V2X messages. Two different approaches are investigated to offer the highest possible degree of security and ensure the privacy of V2X safety and non-safety transmissions. These solutions respectively foresee end-to-end security, wherein all verifications are performed by the receiving UE, and network-based security, wherein the capabilities of 5G network are exploited to perform consistency and relevance checks against V2X messages.

The first approach was further elaborated during the second half of the project: while end-to-end security is the one approach currently standardized for V2X, it fully and only relies on pseudonym certificates generated by the public key infrastructure; and moreover, for privacy purpose, many such pseudonym certificates need be generated for every car: privacy requires short-lived certificates – typically one week, while multiple ones must be valid at a time – at least twenty. It raises concerns for the public key infrastructure scalability, and overall cost for OEMs and the Infrastructure. The latency induced by signing all messages with a Hardware Security Module, and verifying such messages on receipt, based on public key cryptography may also be an issue for some V2X applications requiring very low latency.

Therefore, a session-based approach was proposed for end-to-end security, while maintaining privacy. Public key certificates are still needed, but only for the authentication and authorization performed when communicating with a new entity called “key manager” in charge of providing shared session keys, all with a short validity duration. Such keys are then used to derive symmetric keys, that are used once to encrypt (and decrypt) messages.

5 Demonstration

The role of the demonstrations in the 5GCAR project is to showcase and assess the potentials of 5G and understand the impact and challenges when combining 5G communication with foreseen use cases in autonomous driving. Also, selected technological advances of the 5GCAR concept work were adopted and successfully implemented in the demonstrations.

The 5GCAR demonstrations were showcased in June 2019 in different parts of the UTAC TEQMO test track (as illustrated in Figure 5.1), offering a complete implementation of the following use cases, based on the use case classes identified in Section 2.1.

1. Lane Merge Coordination, from the Cooperative Maneuver use case class
2. See-Through Sensor Sharing, from the Cooperative Perception use case class
3. Long Range Sensor Sharing, also from the Cooperative Perception use case class
4. Vulnerable Road User Protection, from the Cooperative Safety use case class

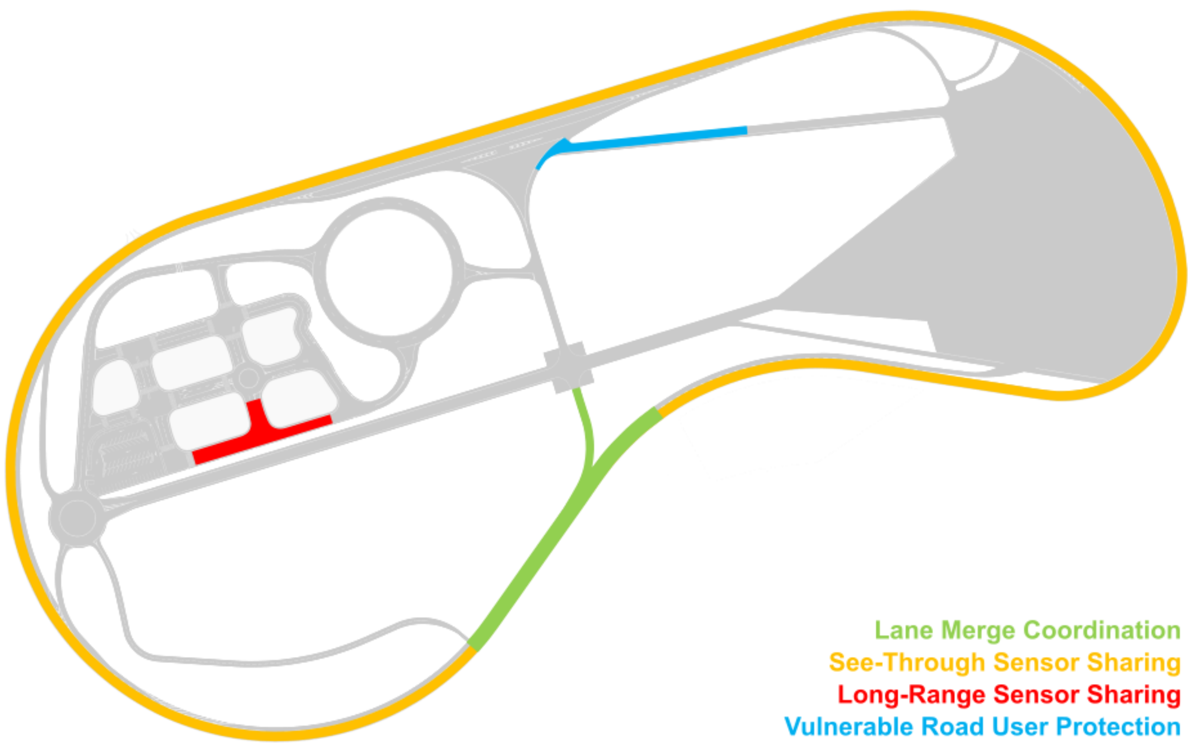

Figure 5.1: Different areas of the test track were used for the four 5GCAR demonstrations, each representing the target environment of the respective use case

Each demonstration was realized as a joint effort among partners of the automotive and telecommunication industry, academia, and smaller or medium sized enterprises focused on specific expert topics. Aside from implementation of individual software components and optimization of existing products, a key focus and challenge has been the integration of such components from different partners for a complete ecosystem, combining the components of all demonstrations. As a result, a representative end-to-end concept is presented, with a focus on individual aspects for the different use cases, which is designed for autonomously driving cars, but also capable of supporting human drivers, as it was done on the 5GCAR final event. In [5GC19-D52] the executed demonstration details are presented and evaluated, whereas the original demonstration guidelines were provided in [5GC18-D51].

5.1 Lane merge coordination

The Lane Merge Coordination use case deals with the orchestrated creation of gaps for cars entering a motorway, using cellular communication and a centralized lane merge coordination function. In the implemented scenario, a fixed camera installation near the merging point is used to detect vehicles that are not connected, and thus cannot receive instructions or communicate information about themselves as illustrated in Figure 5.2. In the demonstration work of the project, a complete system capable of combining input from connected vehicles and roadside cameras and devising individual maneuvers was implemented and evaluated. Communication-wise, all road users were connected using an experimental cellular network, implementing 5G deployment models, namely edge computing, network slicing, and QoS. Several KPIs were evaluated, from both the automotive and the communication domain, where the focus was set on the latency performance and dependencies in the system. It was shown that the latency contribution by the radio access network is significant, but other contributors are at least as significant, mainly the deployment of components (should be coordinated, preferably in an edge cloud), the aggregation of data from multiple inputs for the data fusion, and the proper configuration of higher layer protocols for low latency operation.

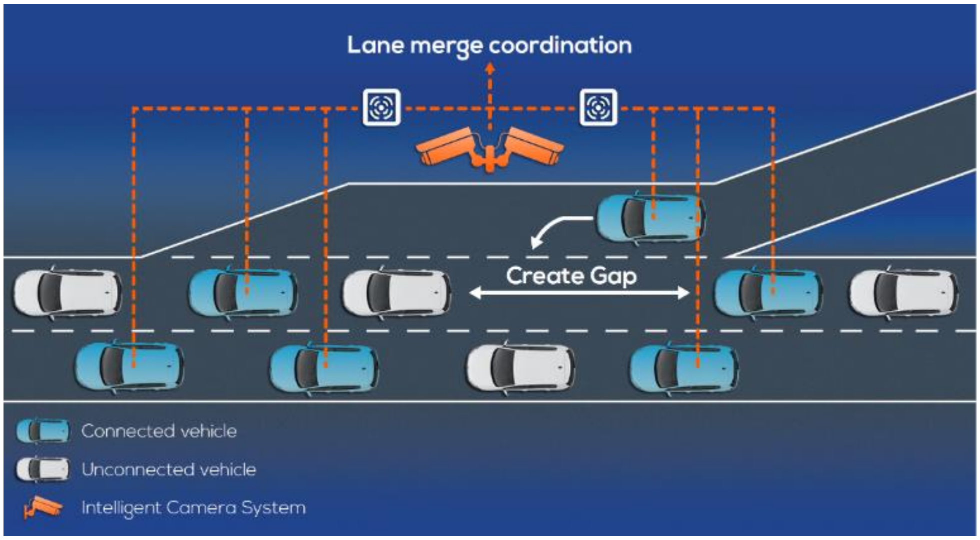

Figure 5.2: In the lane merge coordination use case, a central coordination entity plans the creation of a gap for vehicles entering a motorway

5.2 Cooperative perception for maneuvers of connected vehicles

Two demonstrations have been implemented that tackle different ways of supporting cooperative perception and are described separately in the following.

The see-through demonstration is a cooperative perception application that showcases the extension of the vehicle's awareness using real-time video shared by a nearby vehicle to provide support during overtaking maneuvers. The main idea is to use a stereo vision system mounted on a front vehicle to generate a local 3D map of the environment, in which a rear vehicle could localize itself using a feature tracking algorithm. This means the rear vehicle compares its own camera features with the ones received from the front vehicle. Based on the information about the relative pose (position and orientation) of the rear vehicle, the front vehicle generates a new synthetic image with the perspective of the rear vehicle, from which only the region of interest is transferred to the rear vehicle to be displayed as illustrated in Figure 5.3. In the demonstration work of the project, a 5G-NR prototype was used for a see-through application, which supports a rear vehicle to enhance its range of vision by streaming a video from a front vehicle corresponding to the region occluded by the front car. Application KPIs were evaluated together with the relevant communication KPIs, namely image quality, fit of the see-through overlay and latency of the video stream. These result in the following communication KPIs: high throughput, low packet error rate and low latency. For the demonstration, the performance of the 5G-NR prototype was able to meet the requirements of the see-through application.

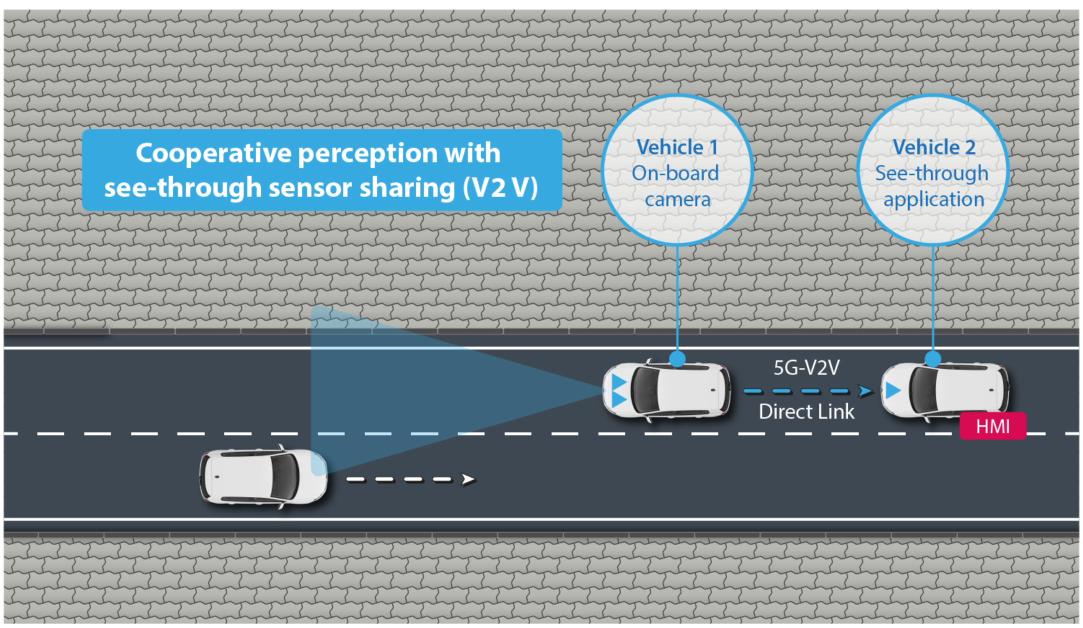

Figure 5.3: In the see-through use case, a front view captured by the vehicle camera is shared with a rear vehicle using a direct V2V link to assist during an overtaking maneuver

(HMI: Human-Machine Interface; V2V: Vehicle-to-Vehicle)

The cooperative perception use case class targets the extension of each vehicle's perception range based on sensor data collected from different sources. Such information can be used to detect critical situations further in advance, either by estimating such situations inside the vehicles (which was done in the See-Through use case), or in an infrastructure component. The infrastructure-based approach offers more computational power in the edge cloud and more dynamic learning skills thanks to the multi-vehicle and multi-scenario input and is pursued in this use case, illustrated in Figure 5.4. In the demonstration work of the 5GCAR project, an on-board LiDAR sensor was used to detect and localize unconnected vehicles. By combining this information with the shared status of connected vehicles, collisions were predicted, and corresponding warnings were distributed to affected vehicles. The evaluation focused on the enhanced driving comfort with respect to reduced deceleration in a collision case due to earlier warnings, and on the collision prediction timing. It was shown that the LiDAR produced useful detections up to distances over 100 meters, and therefore, collisions could be predicted approximately 3 seconds ahead of collision, with a confidence of over 60%. The dynamics between collision forecast time and prediction confidence was presented in more detail.

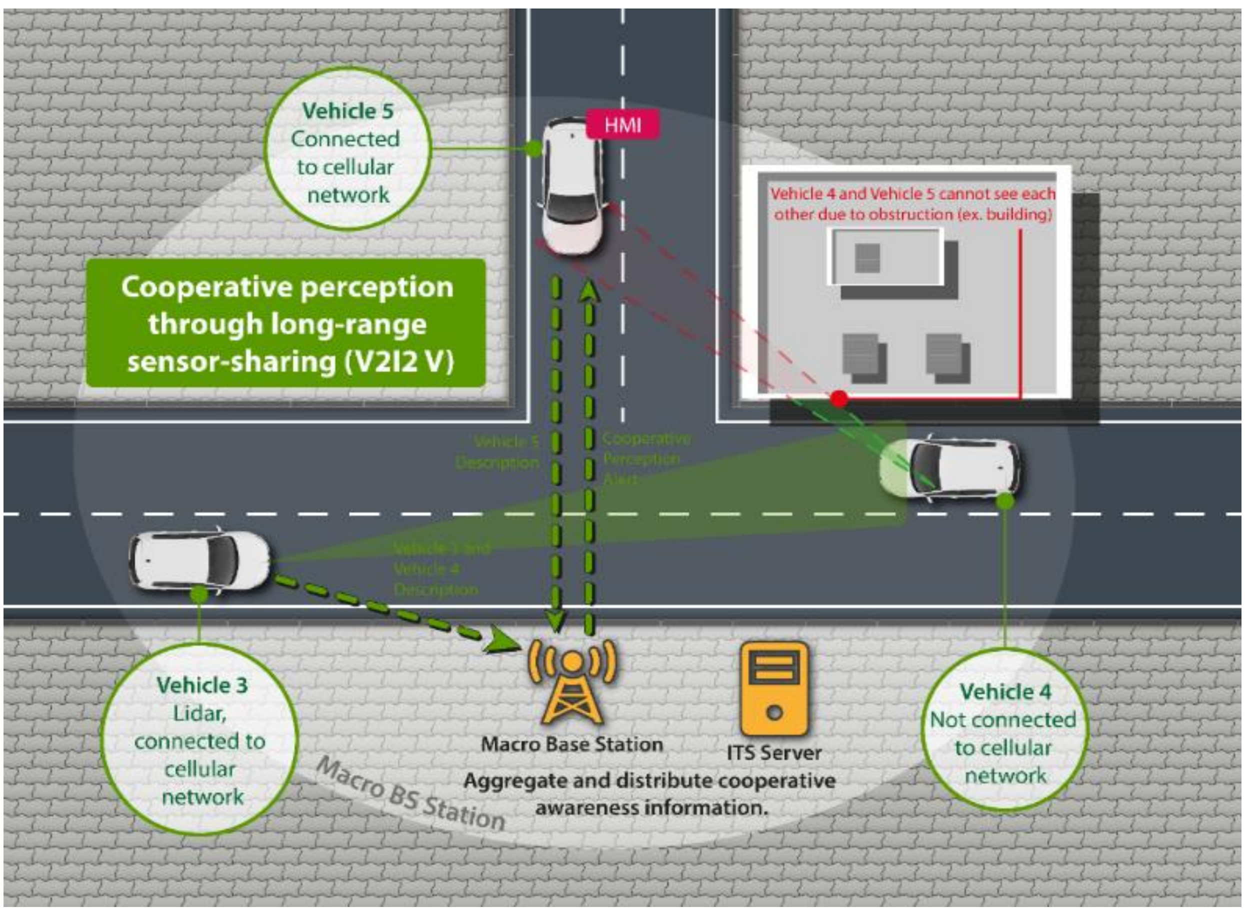

Figure 5.4: Illustration of the Long-Range Sensor Sharing demonstration scenario

(BS: Base Station; HMI: Human-Machine Interface; ITS: Intelligent Transport System; Lidar: Light Detection And Ranging; V2I2V: Vehicle-to-Infrastructure-to-Vehicle)

5.3 Vulnerable road user protection

In the era of autonomous driving and smart mobility, the protection of vulnerable road users (VRU) like pedestrians, cyclists, scooters, etc. becomes increasingly important. With the aid of communication, vehicles and VRUs can be informed by upcoming dangerous situation and reduce risk of accidents. To that end, the 5G radio network serves as additional sensor for the vehicle, complementing vehicle internal sensors e.g., video and radar, offering enhanced position estimation for connected road users. In the demonstration work of the 5GCAR project, a communication network was used to exchange status, sensor data and alarm messages between involved traffic users, illustrated in Figure 5.5. By tracking such road users and extrapolating their trajectories, collisions have been predicted and affected road users have been warned using alert messages. The evaluation focused on the positioning accuracy of the 5G-NR prototype, and the collision prediction performance including the reliability of alarm messages. The positioning accuracy was found to be superior to GPS at higher quantiles in the concrete given scenario, but it should be noted that this is not necessarily universally valid. For the reliability of alarm messages, the dynamics between collision forecast time and collision warning reliability was presented, and it was shown that a time window between 1 or 2 seconds was identified as a good compromise, allowing a collision warning reliability of approximately 90%.

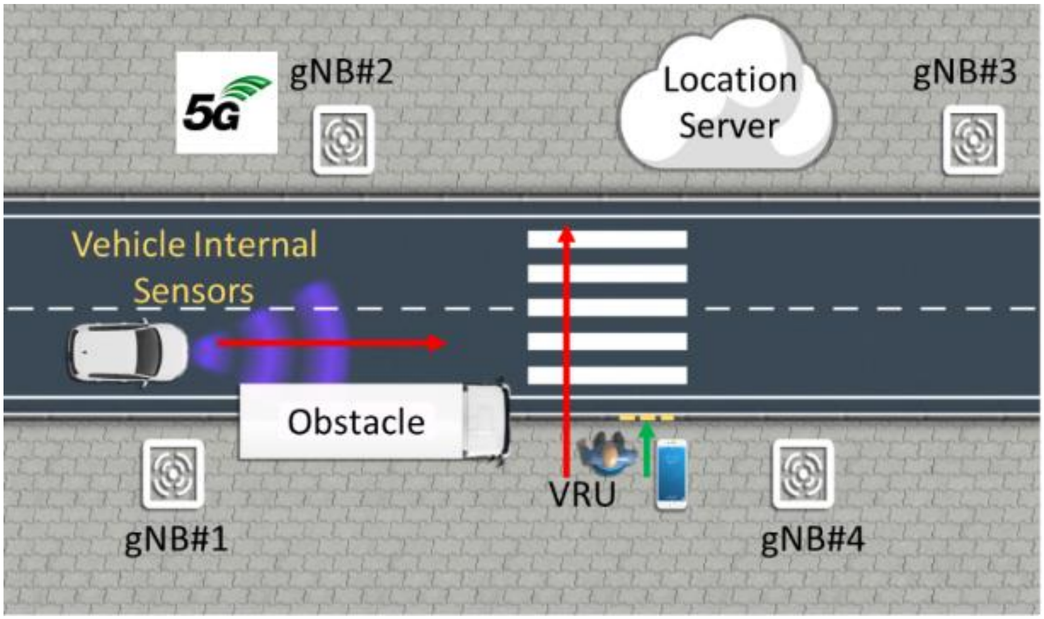

Figure 5.5: The 5G radio network serves as additional sensor. In case of a critical situation (red arrows) warning messages are sent to protect the vulnerable road user

(gNB: next Generation Node B; VRU: Vulnerable Road User)

6 Dissemination and impact

Throughout the entirety of its duration, the 5GCAR project implemented coordinated dissemination activities including the presentation and publication of project results at scientific conferences, journals, workshops, consumer expos, industry groups and forums, magazines and cross-project consortiums. Furthermore, 5GCAR project organized its final demonstration event in June 2019. Moreover, the 5GCAR partners participated and contributed in standardization and regulation bodies such as 3GPP and ETSI, industrial alliances such as 5GAA and the 5G PPP EU project partnership.

Table 6.1 contains the number of dissemination and communication activities for the whole project duration, from June 2017 to July 2019. More details are presented in [5GC19-D62] for the entirety of the project, whereas [5GC18-D61] concerns project details for the first half of the project.

Table 6.1: Number of 5GCAR dissemination and communication activities

Dissemination & Communication Activities	Number of activities
Organization of workshops and special sessions	8
Booth exhibitions in industry forums and events	5
Conference papers published	25
Journal paper published or accepted	19
Talks and presentations by 5GCAR partners	72
Organization of plenary panels	2
Participation in panel as panelist Participation in panel as moderator	24 7
Lectures and training activities	8
Press releases	2
Video/Film	3
3GPP standardization contributions	38
ETSI standardization contributions	2

6.1 Dissemination and public communication

The 5GCAR consortium members organized and participated in a number of major activities for disseminating 5GCAR results. All these dissemination and exploitation activities were selected with focus on technical objectives and performance research as well as on better understanding the societal impacts of various complexity levels of autonomous driving systems. In doing so, 5GCAR project, during the entirety of the project, organized a number of workshops, panels and special sessions as well as demonstrations at various conferences and industrial events. It also published articles in peer-reviewed conferences, magazines and journals. The members of 5GCAR project were regularly invited as keynote speakers to give talks and give short courses on selected topics related to 5G for automotive. Besides that, the 5GCAR project was able to bring relevant knowledge into the collaboration with other 5G PPP projects, for instance in the 5G PPP Automotive working group.

Finally, the presence on social media has also been very important to reach out to a broader audience and share the latest results and activities within the project. To achieve that the 5GCAR project created a website (www.5gcar.eu), and also used Twitter, and YouTube as social media tools for dissemination.

6.2 Standardization and exploitation activities

Even before the project officially started, the consortium identified a list of possible relevant bodies to be monitored (to ensure good alignment with project activities and the major trends of the ecosystems) and for contribution (to promote project outcome at a standardization level), dealing either directly or indirectly with V2X. The 5GCAR project partners participated in the standardization and regulation bodies meetings such as 3GPP and ETSI, industrial alliances such as 5GAA and European Union project partnerships such as 5G PPP with several standardization contributions. The 5GCAR project addressed multiple topics from telco industry to car industry. Standardization and regulation bodies are also.

The exploitation activities in 5GCAR have brought seemingly diverse areas together given the diversity of partners' area in the project. There is a various type of challenges that each of these industries are facing and that these challenges are interconnected to some extent, therefore partners coming together to address these challenges having difference perspective and expertise gave a greater strength [5GC19-D62].

7 Conclusions and future outlook

The 5GCAR main achievements is highlighted in this final project document.

The perhaps most important success is that 5GCAR has helped to convince European Institutions about the hugh advantages of C-V2X against IEEE 802.11p on 8th of July 2019. Now, the originally proposed Delegated Act needs to be revised including also C-V2X in future technical specifications for a clear neutrality.

In general, the research and innovation activities of 5GCAR have contributed to the following topics for C-V2X: Business models, spectrum analysis, link and system level solutions for infrastructure-based communication and sidelink-based communications, network based positioning, C-V2X architecture and their validation by demonstrations at the end of the project. Besides strong contributions to the 3GPP Rel-16 study and ongoing work item for C-V2X, 5GCAR has validated the usefulness of C-V2X assisted driving for lane merging, sensor sharing, see through and VRU positioning to improve safety and comfort for drivers, passengers and other road users. In addition to standardization contributions the project has published many conference papers, organized panels or workshops and summer schools for skill transfers to students and researchers.

5GCAR is also the founder of 5G PPP Automotive working group which two white papers have been published for MWC 2018 and 2019. The published business analysis has shown that 5G connected, cooperative and automated mobility has a large economical potential in coming years. In addition, it has shown the requirements for needed collaboration between road operators, MNOs, OEMs and telecom industry. Furthermore, the project was first in presenting novel business models for C-V2X which is worldwide referenced and has helped to define the planned CEF 5GCAM programme for international EU highways.

The project has proposed a timeline which illustrates the necessity to further invest in C-V2X solution in coming years. In Figure 7.1 the proposed timeline shows how the surrounding network will support future use cases.

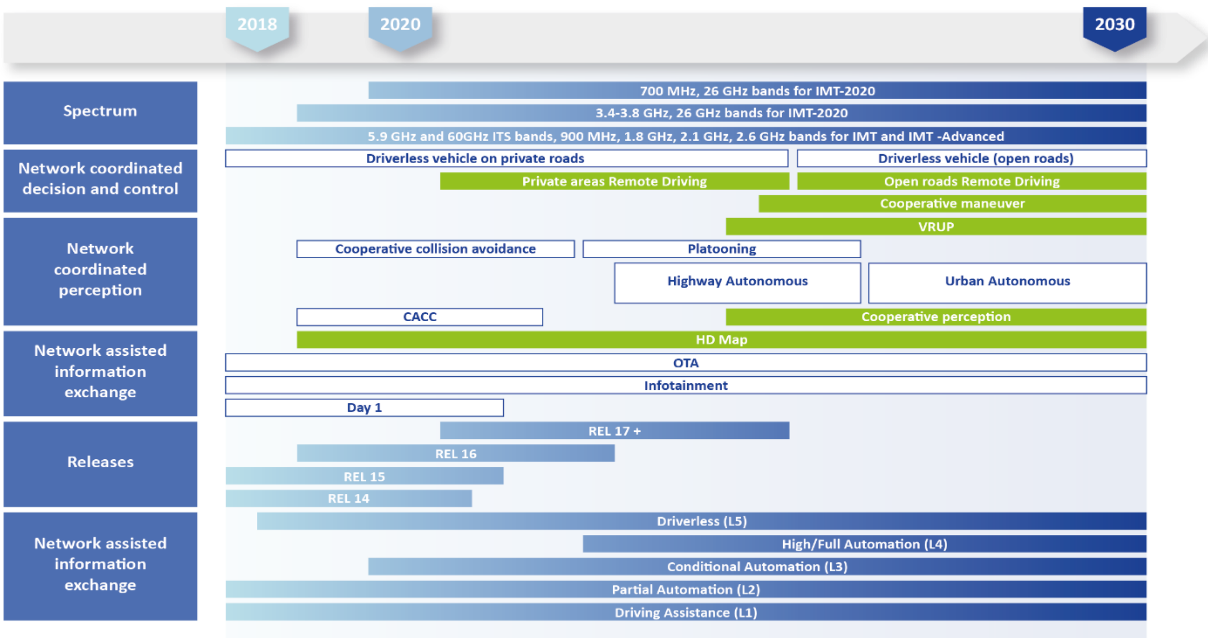

Figure 7.1: C-V2X and use case roadmap for next decade

(CACC: Cooperative Adaptive Cruise Control; HD: High Definition; IMT: International Mobile Telecommunications; ITS: Intelligent Transport System; L: Level; OTA: Over The Air; REL: Release; VRUP: Vulnerable Road User Protection)

From a general view point on C-V2X, we still have to foster collaborations between car and telco industry, because not all requirements, required technical enablers and business cases are still under definition and changing over time. We strongly recommend, that the successors of 5GCAR must still contribute to ongoing eco-system building between the two industry sectors, road operators and regulators.

8 References

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[5GC19-D12] 5GCAR Deliverable 1.2, “5GCAR Mid-Project Report”, January 2019.

[5GC19-D21] 5GCAR Deliverable 2.1, “5GCAR Scenarios, Use Cases, Requirements and KPIs”, February 2019.

[5GC19-D22] 5GCAR Deliverable 2.2, “Intermediate Report on V2X Business Models and Spectrum”, February 2019.

[5GC19-D23] 5GCAR Deliverable 2.3, “Automotive Use Cases and Connectivity Challenges, Business Models and Spectrum Related Aspects”, July 2019.

[5GC18-D31] 5GCAR Deliverable 3.1, “Intermediate 5G V2X Radio”, May 2018.

[5GC18-D32] 5GCAR Deliverable 3.2, “Report on Channel Modelling and Positioning for 5G V2X”, November 2018.

[5GC19-D33] 5GCAR Deliverable 3.3, “Final 5G V2X Radio Design”, May 2019.

[5GC18-D41] 5GCAR Deliverable 4.1, “Initial Design of the 5G V2X System Level Architecture and Security Framework”, April 2018.

[5GC19-D42] 5GCAR Deliverable 4.2, “Final Design and Evaluation of the 5G V2X System Level Architecture and Security Framework”, March 2019.

[5GC18-D51] 5GCAR Deliverable 5.1, “Demonstration Guidelines”, May 2018.

[5GC19-D52] 5GCAR Deliverable 5.2, “The 5GCAR Demonstrations”, July 2019.

[5GC18-D61] 5GCAR Deliverable 6.1, “Intermediate Report on Standardization, Dissemination and Exploitation Activities”, May 2018.

[5GC19-D62] 5GCAR Deliverable 6.2, “Final Report on Standardization, Dissemination and Exploitation Activities”, July 2019.

[C2C18-CC] Car 2 Car Communication Consortium, “C-ITS deployment plans and roadmap”, March 2018. https://www.codecs-project.eu/fileadmin/user_upload/pdfs/City_Pool_Workshop_4/C2C-CC_Deployment_Plan_and_Roadmaps_Rondinone.pdf

A 5GCAR project structure and 5GCAR consortium

A.1 5GCAR project structure

To address the objectives related to a successful deployment and completion of 5GCAR, the project is structured in four technical Work Packages (WPs), one work package for the management and one for the dissemination and exploitation of results. Each WP is coordinated by a WP leader. Each technical WP is further split into three detailed tasks, where each task has a partner appointed as task leader responsible for that task. The overall 5GCAR structure is illustrated in Figure A.1.

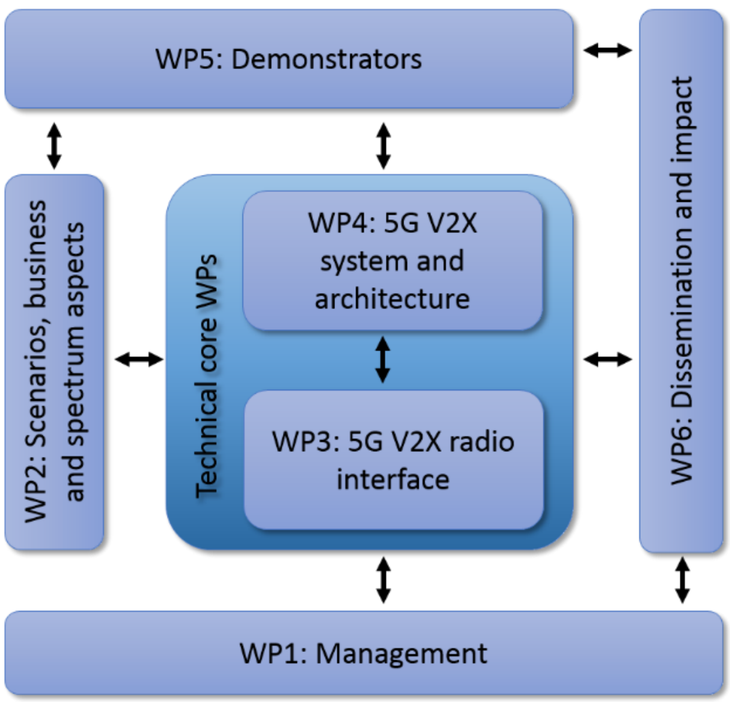

Figure A.1: 5GCAR structure

In this final project report the work packages two to six are presented on section-one-level from Section 2 to Section 6, with the WP2 highlights provided in Section 2, the WP3 highlights in Section 3, WP4 in Section 4, WP5 in Section 5, until the WP6 highlights that are provided in Section 6. Within these sections, the tasks of the respective work packages are being highlighted on section-two-level.

A.2 5GCAR consortium

The 5GCAR consortium consists of:

- **Telecom infrastructure providers**: Ericsson, Huawei, and Nokia
- **Telecom operator**: Orange
- **Car manufacturers**: PSA Group, and Volvo Car Corporation
- **Industrial equipment vendor**: Bosch
- **Academic partners**: Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Centro Tecnológico de Automoción de Galicia (CTAG), Chalmers University of Technology (CHALMERS), and King’s College London (KCL)
- **Small to medium sized enterprises**: MARBEN, SEQUANS, and VISCODA