5G for Connected and Automated Road Mobility in the European Union

Deliverable D3.3
Intermediate report on 5G Technological Enablers for CCAM
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<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>5G</td>
<td>Fifth Generation</td>
</tr>
<tr>
<td>AAA</td>
<td>Authentication Authorisation Accounting</td>
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<tr>
<td>APN</td>
<td>Access Point Name</td>
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<tr>
<td>ARQ</td>
<td>Automatic Repeat reQuest</td>
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<tr>
<td>AWS</td>
<td>Amazon Web Services</td>
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<tr>
<td>BSAF</td>
<td>Back Situation Awareness functionality</td>
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<tr>
<td>CAM</td>
<td>Cooperative Awareness Message</td>
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<tr>
<td>CBAM</td>
<td>CloudBand Application Manager</td>
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<td>CBG</td>
<td>Code Block Group</td>
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<tr>
<td>CCAM</td>
<td>Cooperative, Connected and Automated Mobility</td>
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<tr>
<td>CN</td>
<td>Core Network</td>
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<tr>
<td>DC</td>
<td>Data Center</td>
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<tr>
<td>DENM</td>
<td>Decentralized Environmental Notification Message</td>
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<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<tr>
<td>GS</td>
<td>GeoService</td>
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<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transport System</td>
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<tr>
<td>LCM</td>
<td>Life Cycle Manager</td>
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<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
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<td>MANO</td>
<td>Management and Orchestration</td>
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<tr>
<td>MEC</td>
<td>Multi-access Edge Computing</td>
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<td>MNO</td>
<td>Mobile Network Operator</td>
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<td>NCIR</td>
<td>Nokia AirFrame Cloud Infrastructure for Real-time applications</td>
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<tr>
<td>NF</td>
<td>Network Function</td>
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<tr>
<td>NFV</td>
<td>Network Function Virtualization</td>
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<td>NFVI</td>
<td>NFV Infrastructure</td>
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<tr>
<td>NFVO</td>
<td>NFV Orchestrator</td>
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<tr>
<td>NSA</td>
<td>Non Stand Alone</td>
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<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<tr>
<td>OSA</td>
<td>Own service area</td>
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<tr>
<td>OSS</td>
<td>Operations Support Systems</td>
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<tr>
<td>PaaS</td>
<td>Platform as a Service</td>
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<tr>
<td>PoC</td>
<td>Proof of Concept</td>
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<tr>
<td>PGW</td>
<td>Packet Gateway</td>
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<tr>
<td>RAN</td>
<td>Radio Access Network</td>
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<tr>
<td>RFB</td>
<td>Resource Functional Block</td>
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<td>RNIS</td>
<td>Radio Network Information Service</td>
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<td>RSU</td>
<td>Road Side Unit</td>
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<tr>
<td>SDN</td>
<td>Software Defined Network</td>
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<td>SLA</td>
<td>Service Level Agreement</td>
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<td>S-LDM</td>
<td>Server Local Dynamic Map</td>
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<td>TN</td>
<td>Transport Network</td>
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<tr>
<td>UE</td>
<td>User Equipment</td>
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<td>V2I</td>
<td>Vehicle to Infrastructure</td>
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<td>V2N</td>
<td>Vehicle to Network</td>
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<tr>
<td>V2V</td>
<td>Vehicle to Vehicle</td>
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<tr>
<td>V2X</td>
<td>Vehicle to anything</td>
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<tr>
<td>VIM</td>
<td>Virtual Infrastructure Manager</td>
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<td>VNF</td>
<td>Virtual Network Function</td>
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Executive Summary

The deliverable reports implementation and validation procedure at M31 for the 5G enabling technologies used in the project. Should adjustment or addition be needed once the COVID-delayed testing gets under way, they will be reported in a later amendment of this document.

Section 2 of the document reports the 5G infrastructure deployment plans by the operators involved in 5G-CARMEN (TIM, DTAG, MTA).

Section 3 reports in detail the 5G-CARMEN Distributed Edge Cloud, with special focus on technologies, services and application deployed therein, and laboratory activities that were conducted to test the technical enablers.

Section 4 addresses the technologies for the interworking between C-V2X and ITS-G5 in relation to information dissemination, as well as in-lab testbed implementations aimed at testing and providing pre-deployment, pre-integration results of some of the solutions selected for network-based range extension and interworking.

Finally, Section 5 discusses positioning solutions based either on cellular-network radio link information or network real-time kinematic in support of GNSS positioning.
1 Introduction

This deliverable reports the implementation and validation procedures as well as the status at M31 for the 5G enabling technologies used in the project. The components listed in the deliverable either appear in their version ready for integration in the respective pilots that will be demonstrated in the final stretch of the project, or are presented as planned but not yet ready for integration (as is the case for the Local Break Out option). It should be remarked that, although the large part of the implementation reported here will be in its final form, there could be minor adjustments that will, of necessity, be considered once the on-the-road testing gets under way and reaches a mature stage. The lack of on-the-road testing, forced by the long periods of lockdown or restricted mobility caused by the COVID-19 pandemic, has resulted in the inability by partners to implement and test in real conditions crucial pieces of equipment and configuration of the 5G network deployed on the border areas of the 5G-CARMEN corridor. Any adjustment or addition, if needed, will however be reported in a later amendment of this document.

Section 2 of the document reports the 5G infrastructure deployment plans by the operators involved in 5G-CARMEN (TIM, DTAG, MTA).

Section 3 describes in detail the 5G-CARMEN Distributed Edge Cloud, with special focus on technologies, services and application deployed therein. The section also presents the integration of the 5G-CARMEN field test infrastructure into the live 5G networks of the three operators, highlighting the different approaches and strategies for the implementation of the edge cloud in each country. Specifically, these strategies are oriented at the management of the different service continuity in roaming scenarios and at the way the different applications can interwork, in view of the physical interconnection between the MEC platforms. The section also reports the laboratory activities that were conducted to test the technical enablers, i.e., the current technological solutions that can be put in place to support the project use cases. As it is, not only technical enablers deployed in the pilot (i.e., pre-integration activity) are covered, but also technical enablers that can be leveraged in the future but not deployed in the pilot due to limitations in the adopted commercial networks.

Section 4 covers the technologies for the interworking between C-V2X and ITS-G5 in relation to information dissemination. It examines the interworking features of prioritized use cases to be validated by 5G-CARMEN (automated and cooperative lane changes, fast delivery of messages based on the geographical position of recipients, interoperability among vehicles). This section presents two solutions aiming at the swift pushing of information from service providers to end users involved in the use cases, namely AMQP and GeoService. Both implement a transparent message-based communication between service providers and end users that is independent of the underlying communication technology. Following the same structure of Section 3, this section then presents in-lab testbed implementations aimed at testing and providing pre-deployment, pre-integration results of some of the solutions selected for network-based range extension and interworking. First, an evaluation of a MEC-based deployment of an AMQP message broker is presented, showing the measured end-to-end delay (from a producer, hence to the broker, hence to a consumer), experienced under different configurations with and without a MEC deployment. Next, a solution involving a Multi-RAT dual connectivity solution addressing enhanced communication reliability is discussed and investigated using simulation, which highlights different packet reception rates when a Multi-RAT management solution is used versus a case where it is not used.

Finally, Section 5 discusses positioning solutions based either on cellular-network radio link information or network real-time kinematic in support of GNSS positioning.
2 5G deployment plans

Italy
TIM has started the development of the 5G network with a 5G NSA (Non-StandAlone) option 3 architecture. This type of architecture has been adopted by all the main European operators pending a greater implementation maturity of the 5G SA (StandAlone) architecture both in terms of innovative features available on the network side and in terms of 5G terminals availability with these functionalities.

To date, TIM has reached over 90% coverage in Milan with 5G. The 5G TIM is already available in numerous other cities, with services for citizens and businesses at a speed of up to 2 Gigabits per second: Rome, Turin, Florence, Naples, Ferrara, Bologna, Genoa, Sanremo, Brescia and Monza with the first racetrack Europe connected in 5G, as well as some tourist resorts such as Cortina d'Ampezzo, Livigno and Selva di Val Gardena.

By 2021 TIM will cover the main cities, tourist destinations and industrial districts in 5G and the entire national 5G coverage is expected in 2025.

Austria
MTA is already deploying 5G NR countrywide on various frequency bands, including 5G “pioneer” band 3.7 GHz.

MTA activated LTE / 5G NR DSS (Dynamic Spectrum Sharing) on specific frequency bands to enlarge 5G coverage. MTA is currently serving more than 40% of households and businesses with 5G using more than 1300 base station sites across Austria.

Since 2019, a 5G NSA network configuration is being deployed and used, with LTE providing the control plane part for 5G NR, while the 4G core (EPC) continues performing all core network functionalities.

The full potential and capability of 5G NR and network slicing to enable URLLC (Ultra Reliable Low Latency Communication), mMTC (massive Machine Type Communication) in addition to current eMBB (enhanced Mobile Broadband) will be enabled within the introduction of 5G SA (Stand-Alone) core.

The preparatory work on a 5G SA network has been started; however, it will not become available yet for public usage including 5G-CARMEN pilot operations on the corridor.

Germany
DTAG, through its German subsidiary Telekom Deutschland, has been deploying 5G NR since 2019. While initial RAN deployments had been made using 3.6 GHz spectrum in hot zones and special areas of interest (including 5G-CARMEN) primarily in more than 30 cities, a push for substantial wide-area 5G coverage has been made since 2020 with the deployment of 5G NR and LTE in refarmed spectrum previously used for 3G (2.1 GHz), based on Dynamic Spectrum sharing.

Based on 5G NR Deployments in these two bands, more than 80% of the population can potentially use 5G; this number is planned to grow to 90% by the end of 2021; as the 3G footprint has also been covering all motorways in Germany, similar continuous coverage by 5G is expected to become available soon.

The current commercial 5G service is based on 5G NR NSA mode 3.x in combination with the 4G EPC core network. In parallel, the introduction of 5G SA is under way, currently with a limited deployment for intensive internal trials.

International outlook (Focus: EU/EEA and geographic Europe)
While 5G NSA has been and continues to be the approach of choice across Europe for early initial 5G deployments leverage widespread 4G infrastructures and coverage, 5G SA still requires significant integration efforts and testing, before a widespread deployment across Europe can start. More importantly, cross-border capabilities based on extended international interconnect and roaming, plus advanced features such a local breakout in the visited network and accelerated network reselection or even seamless handover need to be implemented and made available in public mobile networks in Europe and beyond. First interconnected and interoperable 5G SA networks beyond national “island” level in Europe can be expected to become available during the late 2022 / early 2023 timeframe.
3 Implementation of the Distributed Edge Cloud

3.1 Overview

The distributed Edge Cloud has been implemented across the networks of TIM, MTA and DTAG in Italy, Austria and Germany respectively. It is based on edge cloud / MEC platforms embedded in the three networks and enabling low-latency communication and computing capabilities for the CAM use cases chosen by 5G-CARMEN. The following sections provide insight into the respective technologies, services and applications and how they have been implemented and how they will serve the respective use cases on the 5G-CARMEN corridor and its special focus on cross-border operation.

The following illustration from Deliverable D2.2 - 5G-CARMEN Preliminary System Architecture and Interfaces Specifications gives an overview of what constitutes the 5G-CARMEN distributed edge cloud. (middle layer plus “cloud-based” service orchestration functions NFV-SO in the top layer).

![5G-CARMEN System Architecture incl. key reference points](image)

**Figure 1: 5G-CARMEN System Architecture incl. key reference points**

3.1.1 Use Case Matrix

After reassessing the use cases presented initially in D2.1 and D3.2, and having their 5G network requirements and their relevance to higher levels of automated driving in mind, it has been decided to reshape some of them and prioritize the ones with stronger requirements for further analysis. The outcome of this work is the following set of cooperative maneuvering use cases with their respective scenarios, which is presented in Table 1.

It is important to note that testing of these use cases has a local context, and not all of them are available throughout the whole corridor, from Munich to Bologna. The mapping between the use cases and the local/cross-border pilots is presented in the table below. The table also lists the applications supporting the use cases on the relevant MEC location. These applications are described in Section 2.1.2 “2.1.2 Services & Applications for CCAM”.
3.1.2 Technologies, Services and Applications for the Distributed Edge Cloud

The current section describes the Technologies, Services and applications deployed in 5G-CARMEN components, both on board the vehicles and in the MEC/Cloud, to enable the use cases of Cooperative and Automated in-Lane Maneuvers and Cooperative and Automated Lane Change Maneuvers. While D2.2 describes the high-level functionality, requirements, architecture and interfaces among components, D3.3 reports the inner characteristics of the components\(^1\). The following technological components, services and applications have been developed:

- GeoService
- AMQP Broker
- Maneuvering Service
- S-LDM
- Response Router
- Back Situation Awareness
- AMQP client producer/consumer on board
- V2X Component
- Cooperative and Automated Manoeuvering component for L4 driving
- Quality control on board
- Road operator infrastructure and back-end

These technological components are illustrated in the following subsections.

### 3.1.2.1 GeoService

The GeoService (GS) is an application deployed on the MEC which offers Connected Car basic messaging. In the 5G-CARMEN project the GeoService is utilized for use cases such as Green Driving and Back Situation Awareness.

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\(^1\) Some components have been reported in D2.2 already, in which case we provide only the reference.
The GeoService maintains an overview about all the vehicles in a given area (based on CAM, Cooperative Awareness Message, sent by each car). Its major task is to receive/forward/store messages from vehicles and road users. It also supports the dissemination of messages received from applications via the Message Ingestion Interface. This interface is used for the Green Driving use case where GeoService facilitates the dissemination of Infrastructure to Vehicle Information Messages (IVIM) to vehicles in a specified area, and for the Back Situation Awareness use case where GeoService supports the dissemination of Decentralized Environmental Notification Messages (DENM) to vehicles in the Dissemination Areas (DA).

![Figure 2. Nokia GeoService Architecture](image)

The GeoService deployed on a MEC node for the 5G-Carmen project supports:

- **CAM dissemination to Area of Relevance (AOR)**
  GeoService disseminates received CAMs only to those vehicles that are in an area around the originator of a CAM. This area is also known as Area of Relevance (AOR). The radius of the AoR is a configurable parameter (default value: 200m). This functionality supports both signed and unsigned CAM messages.

- **DENM dissemination to Destination Area (DA)**
  GeoService forwards incoming DENM messages to all vehicles that are inside the Dissemination Area (DA). DA is defined as a geographical area that can be a rectangle, circle or ellipse, as specified in ETSI EN 302 931 V1.1.1. This functionality supports both signed and unsigned DENM messages.

- **Message Ingestion interface**
  GeoService provides a generic REST interface to external applications for the purpose of injecting ETSI ITS messages, e.g. DENM or IVIM, for dissemination to vehicles in a specified area. Third party applications shall be responsible for generating the message from GeoNetworking layer upwards before handing it over to GeoService - including signing and/or encryption. In addition to the ITS message, the third party applications shall also determine the dissemination area for the message as part of the message injection. The ingestion message is typically a JSON encoded AVRO message. There are mainly three different types of message: Trigger, Update and Terminate. Depending on message request type as well as the timing parameters in the AVRO message, the injected message will be retransmitted by GeoService.

- **Own Service Area (OSA) support**
  OSA indicates the geographical area being served by a GeoService. Multiple GeoService instances can have different OSA serving different geographical areas (represented as a polygon...
of GPS coordinates). A GeoService instance queries a central repository to learn about the OSA of adjacent GeoService instances. Knowledge of adjacent GeoService instances and their OSA is considered in the Inter-GS forwarding logic.

- **Inter-GS communication**
  GeoService forwards messages received from vehicles to a neighbor GeoService instance if the Area of Relevance (AoR) or the Dissemination Area (DA) intersects with the neighbor’s Own Service Area (OSA).

### 3.1.2.2 AMQP Broker

The AMQP Broker deployed on the MEC implements the specification currently defined by the European C-Roads Platform program. The Goal of C-Roads platform is to harmonize the deployment of interoperable cross-border C-ITS services for road users. Specifically, the Task Force 4 or Working Group 2 defines the IP based interface profiles that are needed to provide interconnection of backend systems to allow sharing of C-ITS information. The primary scope of the AMQP Broker is to enable messages exchange between information producers (e.g. Road Operator) and service providers; however, it can also be used, as done in 5G Carmen, to send messages directly to vehicles. The specified interface is called Basic Interface (BI), currently used in 5G Carmen.

AMQP protocol (version 1.0) is a standard messaging protocol implemented by an over the top application platform running on VM installed in the MEC instance used in the project.

The broker is use case independent and can be used in every ETSI-ITS use case. The AMQP broker is network independent and can be accessed from every data network (mobile 4G/5G or fixed) with TCP/IP protocol. In case the clients are on the big Internet, the AMQP broker needs to be exposed on the big internet (TCP ports 5671 and 5672).

The Broker API exposed are as from AMQP protocol standard 1.0 and as from the specification (C-Roads European platform): “Specification for interoperability of backend hybrid C-ITS communication” V1.6 and are used by client “producers” and “consumers” to publish and to consume messages. No other/different API can be provided.

The producers (Road Operators) publish C-ITS messages (DENM, IVIM, …) adding ETSI ITS and geographic information in the AMQP “envelope”, the consumers (service providers/vehicles) subscribe to messages from AMQP broker specifying some filter criteria based on envelope properties. Therefore the AMQP broker dispatches messages to service providers/vehicles which are subscribed to events (e.g. accidents, traffic jam, etc.) relevant to their geographic localization and produced by road operators (geocasting), using a PUSH paradigm based on AMQP protocol (see Figure 3. AMQP broker, filtering).

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**Figure 3. AMQP broker, filtering**
Geocasting is done through Quadkey. Quadkey is a string that uniquely identifies a tile square of the terrestrial projection calculated from latitude/longitude and a particular level of detail. It is a hierarchical spatial data structure that subdivides space into buckets of grid shape. Quadkeys offer properties like arbitrary precision and the possibility of gradually removing characters from the end of the code to reduce its size (and linearly lose precision). See Figure 4. Quadkey example.

**Figure 4. Quadkey example**

### 3.1.2.3 Maneuvering Service

The Maneuvering Service’s task is to monitor the current state of the road traffic and the intentions of vehicles; determine the most suitable moment to execute a lane change if requested; manage the gaps between vehicles, such that the maneuver can be done safely and efficiently; and generate recommendations for vehicles to follow if possible. The Maneuvering Service will be implemented in both a decentralized and a centralized manner. The decentralized Maneuvering Service is hosted inside each vehicle and leverages information that is exchanged by means of V2V direct communication using the PC5 interface and via the network (V2N2V) using Uu interface.

The limited range of this approach, however, may render suboptimal in some cases. Hence, a centralized Maneuvering Service is hosted at a MEC to gather a broader overview and consider more traffic participants for an optimal cooperative lane change maneuver.

This requires the usage of a Uu interface. In a cross-border scenario, situations will arise where different vehicles are connected to different mobile operators, and different MEC instances, respectively. At the same time these vehicles may be in proximity of each other and be affected by a cooperative lane change attempt.

Hence, interfaces for the exchange of information between 'neighbouring' MECs need to be established.

In order to allow flexible recommendations and be as close to the State of the Art as possible, a Model-Based Control Approach is chosen [1]. The proposed algorithm consists of a Tactical- and Operational-Controller. The Tactical-Controller computes the most efficient merging sequence and time instant. The Operational-Controller generates the optimal control output for the car. The initial algorithm implementation utilizes the Tactical-Controller only, while the Operational Controller will be left for a later development.
Figure 5 shows a complete system diagram.

3.1.2.4 S-LDM

The S-LDM (Server Local Dynamic Map) component is a 5G-enabled MEC service acting as a local dynamic map for other services that require up-to-date data on the situation of the road.

Its main target is to store and process the data of objects on the road, which may be both connected (i.e. vehicles sending CAM messages) and non-connected. In this second case, the S-LDM can be informed of non-connected objects thanks to connected vehicles sending CAM or CPM messages or by means of IVIM and DENM messages coming, for instance, from a road operator backend.

As the S-LDM runs as a MEC service, it provides a much wider and precise view of the situation on the road than what could be achieved by relying only on a decentralized communication (e.g. PC5 or V2I2V via GeoService).

When a certain triggering condition is detected (e.g. a vehicle showing the intention of initiating a lane merge), the S-LDM is able to compute a context around a reference vehicle or object (which could be, for instance, a vehicle with an active turn indicator for the Cooperative Lane Change case).

This context includes the objects within a certain radius around the reference vehicles and it contains all the relevant data which is needed by other services to manage L4 automated driving in the best possible way, including up-to-date vehicle-related information (vehicle size, position, path history points, and so on) and relative positioning of objects. The context is then transmitted to the services requesting this information.

The most important example of a service that benefits from the presence of the S-LDM is the Centralized Maneuvering Service when performing a Centralized Lane Change. It is important to mention that, as explained in [19], despite being developed mainly as part of the Cooperative Lane Change scenario, the
S-LDM can provide its data to any MEC service and it is developed with a modular and easily extensible paradigm.

The S-LDM is thought to be instantiated multiple times on each MEC installation, with each instance covering a specific area and portion of the road.

The area of “neighboring” S-LDMs is partially overlapped, in such a way that some portions of the road will be covered by more than one single S-LDM, increasing the range and the number of vehicles covered by the single instances. However, when a context should be computed (e.g. a Centralized Cooperative Lane Change is going to happen), only the S-LDM containing the reference object will perform the necessary steps and communicate the context to the other services, as described more in details in [19].

This, together with the instantiation of multiple S-LDMs, each covering a specific area, enables a much better scalability of the component.

A second important point, which should be mentioned, is the choice of AMQP as the main message ingestion interface.

The S-LDM is indeed getting all the data it needs from an AMQP broker, following the specifications described earlier.

As the AMQP brokers should already take into account inter-broker communications for cross-border scenarios, the S-LDM can leverage directly on the underlying architecture, together with the scalability mechanism described before, to tackle the cross-border use cases analyzed in 5G-CARMEN.

### 3.1.2.5 Response Router

In the centralised lane change sub use case, several components need to cooperate and provide feedback to a vehicle. While messages are published via the AMQP Broker with topics defining a specific car to be addresses, other components (e.g., the Maneuvering Service) are supposed to be agnostic to the message delivery approach and running only the application logic. The Response Router is a component supporting other MEC components in dispatching their messages toward specific destination cars via the AMQP Broker. In principle, it could be embedded into each of those modules that are supposed to interact with the AMQP Broker. However, the decision to keep it as a distinct component would simplify the maintenance of the MEC applications in case of changes in the topic name creation rule, and also allow using the module to support services others than the Maneuvering Service. It leverages on the following assumptions:

1) each car relying on a given service (e.g., Maneuvering Service) is subscribed to the AMQP Broker to a dedicated topic with a univocal topic name;

2) given a certain car identifier, the module can retrieve the name of the topic which the car is subscribed to.

From an operative point of view, the Response Router receives a collection of messages (each one with an identifier of the destination car) and, for each of those messages, it uses the identifier for retrieving the subscribed topic name and then publishes the message to the AMQP Broker on that topic.

To speed up the overall process, messages are opaque for the Response Router: it does not parse the message to be delivered, but it assumes to receive an identifier of the destination car that allows it to retrieve somehow the correct topic name and publish that message on that topic.

How this module retrieves the proper topic name is an implementation choice: for the Maneuvering Service, the Response Router knows the topic name creation rule adopted by the cars when registering to their dedicated topic. This rule creates univocal topic name just using the car identifier, the same car identifier that is received by the Response Router together with the message to be sent to the AMQP Broker. By applying the creation rules, the Response Router can generate on the fly the topic name and thus can publish the message to be dispatched on it. The correct and in time message delivery is left to the AMQP Broker.

The Response Router shall be fast and highly scalable in performing its task: if the topic name creation rule follows a stateless approach and the destination AMQP Broker is known, the overall operation can be performed in a minimal amount of time.
3.1.2.6 Back Situation Awareness

Overview

Emergency vehicles (EmVs), when on rescue operation, have the right of way on the road. This means, lane clearance should be guaranteed on the corridor, and possible obstructions due to lane change manoeuvres by ordinary vehicles should be prevented or suspended when the EmV is in the area. These manoeuvres can lead to unexpected emergency situations and are thus borderline for conditional automation (SAE L3); this means, in an L3 system they would most likely lead to disengagement or to lower level of automated manoeuvres. On the contrary, a SAE L4 automated driving designed for a highway needs to cope also with such events.

In practice, this means that the L4 automated vehicle can clear the overtaking lane or decide to remain in the first lane even if its original plan was, for instance, to overtake. In the ideal case (i.e. well within L4 Operational Design Domain (ODD)) this has to happen without any user intervention or monitoring (hands off, heads off). Any deviation from the ideal case (i.e. borderline with respect to L4 ODD) needs to be communicated at least 10s in advance in order for the Autonomous Driving system to draw drivers’ attention, and be still capable of handling the situation in case the driver does not intervene.

To design an EmV service that alert L4 vehicles along a highway corridor, the following aspects are key:

- Warn proceeding vehicles that are beyond the Visual Audible Range of the EmV. Possibly, providing a warning to all proceeding vehicles all along the corridor path, so that each L4 vehicle is made aware of the timing boundaries and take the best decision.
- Provide the vehicles with an Estimated Time of Arrival (ETA) of the EmV. This has to be as accurate as possible, taking the traffic conditions into account, and constantly updated.
- Provide a continuous service, from long-range warning/alert of the EmV’s ETA when the EmV is still not in sight of the L4 vehicle, to short-range awareness of the EmV’s ETA when the EmV is within direct communication range of the L4 vehicle.

These high-level requirements are addressed by the Back Situation Awareness (BSA) solution, which has been developed by NEC, IMEC (in the orchestrated platform for CCAM) and CRF (on board the vehicles) and leverages on the 5G connectivity to MEC.

BSA service design on the MEC infrastructure:

The BSA service is designed to run as a virtualized container function, which is deployed and instantiated on a MEC platform as a virtual application function. Figure 6 illustrates the BSA service design, which is composed of several functional components, which are described below.
1) **BSA Application:** This is the heart of the BSA service and is identified as BSA Algorithm functional entity in Figure 6. This is deployed as a MEC application and implements the main logic. Its task is to assign waypoints along the route of the emergency vehicle (EmV) and compute the Estimated Time of Arrival (ETA) values with reference to these waypoints. The ultimate goal is to provide an in-advance warning/information about the ETA of EmVs at different segments of the route-path. It should be noted that the area between two successive WPs is referred to as a dissemination area (DA).

2) **C-ITS protocol service:** This is a MEC service supporting the BSA application. It decodes/encodes the received/disseminated C-ITS CAMs/DENMs for information relevant to the BSA application instance, and for encoding ETA values in the DENM messages for notifying the vehicles. This corresponds to the ITS protocol stack and the decoding/encoding helper function entities in Figure 6.

3) **Map service:** This as an auxiliary MEC service supporting the BSA application. It gathers the geospatial information, such as route-path information/plan based on which BSA service can specify way points along the route-path. For the implementation we are using open street map for this purpose.

4) **Database (DB) Application service:** This is proposed to be a MEC application which stores the meta-data/state-information of the EmV decoded/parsed by the C-ITS protocol service from the periodically received CAM/DENM messages. This information is consumed by the BSA service for calculating ETA values, and optionally manoeuvre recommendations. This corresponds to the State DB entity in Figure 6.

Figure 6 also depicts the required interfaces enabling the BSA application to connect with the external entities. These interfaces A, B, and C, are designed in a respective order to: i) receive upstream CAM messages originating from the EmV with a frequency of 10 Hz, ii) dispatch a DENM message containing an ETA calculated value for a specific dissemination area, and iii) maintain connectivity with a peering BSA application instance that may be running in another edge domain that may belong to a different operator, or across border in our case.

As depicted in Figure 6, the BSA service is instantiated on the MNOs’ MEC platforms as soon as these platforms receive the trigger from an emergency headquarter, such as Emergency Management Authority (EMA). The EmV is then dispatched by the EMA towards a specific destination where the emergency event occurred. In order to instantiate BSA service on top of the MEC platform, the EMA sends instantiation request to the NFV-SO within the CCAM platform in one MNO domain. The set of federated orchestration operations, which are performed within the two involved CCAM platforms, results in two BSAF instances running on the MEC platforms that belong to different MNO domains, which in our case are across the border. These two BSAF instances, running in two MEC platforms on each side of the border, shall connect in order to transfer the latest state information about the EmV that is being sent.
periodically by the EmV itself towards the BSAF instance via the cellular network infrastructure over the Uu interface. The BSAF instances shall continue to calculate the ETA of the EmV and then disseminate it to the vehicles at the front via the cellular network infrastructure.

As response to the instantiation request from the EMA, the NFV-SO will return the IP address of the MEC host where the BSA service is instantiated. The EMA will send this IP address to the EmV, which will start to transmit the CAM messages periodically towards the BSA service on the MEC host. These messages will be received on interface A, to be processed/decoded by the ITS protocol stack. In our case, this stack is provided by Vanetza\(^2\), an open-source implementation of the ETSI C-ITS protocol suite. The receive function of the Vanetza protocol suite will extract the CAM message from the received IP packet. The decoding function, which is a simple helper function supporting Vanetza, will extract/filter the information relevant for the BSA algorithm from the CAM message, and prepare an input for the BSA algorithm. The input to the BSA algorithm represents a refined information about:

i) the identification of EmV (EmV ID),
ii) the speed of the EmV,
iii) the current location of the EmV,
iv) EmV destination, and
v) EmV direction of travel.

\[\text{Figure 7. Workflow of the BSA service algorithm}\]

Based on the above inputs, the BSA algorithm will compute the ETA for each DA with reference to the respective WIs. The algorithm follows the workflow as shown in Figure 7. At first, the system waits for input information. If there is a service request and the input information is available, for each input data containing the above-required information, the algorithm collects and analyzes the input data. After that, the algorithm checks the location of the EmV and the required destination. If the EmV still has not reached the destination, it uses the MEC Map Service to determine the route/path that EmV should follow headed for the destination. The algorithm uses the Kalman filter to predict and correct the ETA value. The resulted value is generated as output information. Afterwards, the ETA calculation is performed; based on the received information from an EmV the results of such calculation are encoded and packed into the corresponding DENM format by the encoding function (see Figure 6). For each dissemination area, whose

borders are defined during the ETA calculation, a specific ETA value is obtained and disseminated via the GeoService to all vehicles in the area.

Moreover, the BSA use case also utilizes PC5 side link to directly communicate the CAMs with vehicles that are within the direct communication range of the emV. In such a scenario, the OBU of each vehicle receiving the CAM via PC5 will compute the ETA, which will be compared with the ETA values received from the infrastructure and the lesser of the two ETA values will be displayed.

**BSA on the Vehicle**

Onboard the vehicle, the L4 automated driving system has the objective to give way to emergency vehicles. This means clearing the lane and avoid any cut-in maneuver if the emergency vehicle is approaching. The main factor influencing decision making is the ETA, and when the EmV is close, the distance, too. The on-board system will mainly rely on:

- ETA received from BSAF service when the vehicle is farther away than 500m
- ETA and distance from direct communication with EmV when the vehicle is less than 500m

### 3.1.2.7 AMQP client producer/consumer on board

The AMQP client application represents the interface on the vehicle side with the network and the AMQP broker described in chapter 3.1.2.2. The application developed from CRF, respecting the compliancy to the latest C-Roads Platform specification, enables the Vehicle-to-Network communication (V2N) and the exchange of C-ITS messages between the information producers (e.g. Road Operator) and the connected vehicles through the Basic Interface.

The CRF AMQP client application runs on vehicle On-Board Unit (OBU) and it is connected to the C-ITS application (that manages V2X information) through a local UDP connection. The connection to the AMQP broker relies on TCP/IP protocol and it is network independent: the broker can be accessed from every data network.

In 5G CARMEN, the developed application provides two different connections to the AMQP Broker running on MEC. The two connection can also run individually and, from broker perspective, they are perfectly distinguishable.

The first connection defines the producer and it aims to open a connection to the broker through which the C-ITS application running on vehicle can send messages regarding its status or external detected situations.

The second connection settles the consumer and it aims to define connection to the broker through which the C-ITS application running on vehicle can receive messages from third parts as Road Operator.

CRF AMQP producer adds to the C-ITS published messages an AMQP “envelope” that contains the ETSI ITS and geographic information while, in subscription, specified a series of filters based on the same envelope properties as described in chapter 3.1.2.2. The geographic information considers the current position of the ego-vehicle.

The published and consumed AMQP v.1.0 messages are compliant to the C-Roads Platform specification defined in “Specification for interoperability of backend hybrid C-ITS communication” V1.6.

### 3.1.2.8 5G and PC5 message processing on board: the V2X Component

On board the vehicle, there is a V2X component that has the task to send, receive and process all the messages from 5G Uu connectivity and also from PC5. The following scheme shows the main features of V2X component. Namely, from the lower layer to the upper layer, the module has:

- PC5 interface and connection to an external 5G Radio Access

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3 Actually positioning information is used by the AD component too. Implementation details are part of WP5
– Parallel handling of peer-to-peer PC5 cooperation (through the ITS stack) and client-server communication with the network (AMQP, BSAF, Geoservice, predictive QoS)
– Facility layer, providing host vehicle, cooperative, timing and positioning information to the application layer. In particular
  • Vehicle data are retrieved by the Controller Area Network of the car
  • Messages are seamlessly received from PC5 and/or from the V2N services clients, and presents to the application layer
  • Host vehicle precise position is received from the external precise positioning unit.
– At application layer,
  • messages are filtered for relevance and handed up to the AD component. This component includes the V-LDM described in D2.2.
  • a specific quality control application computes the quality of information and also uses the predictive QoS client, to send information quality meta-data to the AD component.

**Figure 8. V2X component, high-level view**

### 3.1.2.9 Cooperative and Automated Manoeuvering component for L4 driving

An on-board application on the L4 AD prototype unit (called AD component) can be divided into sensing and localization, perception, decision and action.

**Sensing and localization**

The AD component sensing and localization subsystem gets the following information:

– Sensed objects, from the ego-vehicle (host vehicle) on-board sensors
– Presence and On-board sensors information of other vehicles (remote vehicles) from the V2X/5G unit
– Road events via the V2X/5G unit
– Positioning data from 5G-CARMEN positioning unit

**Perception**

The AD component perception subsystem

– Reconstructs the scene and context around the vehicle from sensing and positioning data
  • Obstacles (5G-equipped vehicles and non-equipped vehicles)
  • Boundary conditions (allowed lanes, speed limits, geometry, visibility, etc.)
• Other factors (weather, hazards) etc.
  - Gets the quality of V2X/5G information (actual and predicted) and positioning information from the data quality and trust module
  - Evaluates if the driving context and the quality of information (related to the KPI outlined in D5.1) allows a specific AD level of automation (i.e. the Operational Design Domain of SAE L1 – SAE L4 ODD or L0= manual driving).

Decision

The AD component decision subsystem constantly evaluates the current and predicted SAE level ODD along the corridor based on the perception module.

Depending on the current SAE automation level, it (1) can keep it, (2) interact with the driver to suggest another level (disengage the current, or (3) keep it and show the possibility to switch to higher automation. In the following, we assume that the system is in automated mode (L3/L4).

At strategic level, if the system drives autonomously to the intended destination. In our use cases, it will drive through the corridor, until a motorway exit, depending on the trip plan4.

At tactical level it will have short terms trajectory plans, to satisfy the trip plan along the corridor. The system will tackle the different driving scenarios along the route.

In the default scenario of a clear road with a specific geometry (width, curvature) and no intersection (as in the motorway with no traffic) the vehicle will head towards destination controlling at allowed cruise speed (longitudinal control) and keep lane-centering (lateral control). If events happen, it will decide on specific manoeuvres, for instance the ones piloted in 5G-CARMEN Cooperative and automated lane-change and cooperative and automated in-lane manoeuvres:

1. Cooperative and automated lane change manoeuvres
   • **Lane change as planned**, if it needs to overtake, go back to the first lane, or exit the motorway
   • **Lane clearance for emergency vehicle** based on estimated time of arrival

2. Cooperative and automated in-lane manoeuvres
   • **In-lane manoeuvres** based on forward detection (cruise control)
   • **In-lane manoeuvres** based on lateral detection (prevented lane change)
   • **In-lane manoeuvres** based on backward detection
   • **In-lane manoeuvres** based on emergency vehicle approach (prevented lane change)

In the first part of the project we focused on how the vehicle, L3-based, reacted in-lane to weather warnings, speed suggestions and vehicle in-front by setting a new speed target and perform longitudinal control according to these basic scenarios.

Lately, in order to show the 5G enabling role for higher level of automation, we have upgraded our prototype on-board system to SAE L4 driving capability (up to decision level). We are also tackling more complex tactical decisions, enabled by the fact that environment can be thoroughly monitored and predicted thanks to 5G connectivity.

It should be noted, that at tactical level both L3 and L4 automated driving can decide and pursue optimal manoeuvres autonomously. But while in L3 the system assumes that the driver is hands/off and eyes on, in L4 the system assumes that the driver is hands/off and eyes off and has to handle exceptional situations if they meet the ODD conditions. Even for situations that fall outside the ODD, the “exit” is more critical for L4 than for L3, as the driver could take back control as late as 10 s after. Therefore, the ODD specification (which is to be given the AD vehicle customer *a priori* in the product card, e.g. “L4 driving

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4 Here a complete L3/L4 system is described. The 5G-CARMEN prototype by CRF focusses on the perception and the tactical decision module, and on measuring if the system can keep automated (L4) in exceptional situations. In other words we don’t implement the connection with the navigation system, but only assume that the system pursues a specific high-level navigation plan. This does not prevent us from measuring the needed KPI’s.
enabled in motorway”) has far more technical implications in L4 than L3. While emergency situations in an L3 “highway pilot” simply ask the driver to take back control, the same situations for L4 need to be handled automatically or else, to be declared a priori as falling “outside” the ODD. 5G here has a threefold role:

1. to extend the ODD conditions (e.g. emergency vehicle approach);
2. to help the L4 decision making to replan and keep within the ODD;
3. to anticipate any exit from the ODD more than 10 seconds ahead.

All above scenarios are pertinent to both L3 and L4, but two of them are particularly representative of the difference between automation and high automation in case of lane change and in-lane manoeuvre.

The lane clearance for emergency vehicle with a higher speed than the limit (an exceptional situation): here the L3 system would simply inform the driver and ask for an early disengagement due to the unsafe situations (optionally warnings and suggestions can still be given to the driver to change lane). The L4 needs to cope with the automated lane change even with two complications:

1. possibly a congested situation, where vehicles can do sudden manoeuvres due to the incoming emV;
2. time constraints given by the estimated time of arrival of the emV. Since having an emV right at the back of would require asking for driver intervention, the system would possibly ask for disengagement and retake control in the last 20 to 10 seconds.

The prevented lane-change due to lateral detection of a queue (or an accident). For instance, the vehicle needs to change to the right lane in order to exit or keep left at a junction. If an issue is detected in the right lane at the last seconds, an L3 automated system, depending on the time/space advance, would disengage in advance and let the driver decide (exiting the ODD), or it would perform the lane change and then eventually exit the ODD. The L4 system, instead, can evaluate whether to perform change tactics to an in-lane manoeuvre and keep the system in the ODD.

The kind of decision (and the goodness) of decision is out of scope of this investigation, whereas the focus is on time advance, data quantity and quality that enable such decisions and changes by a robot-driven car.

The following flowcharts represent a high-level scheme of the lane-change and in-lane manoeuvres. They are simplified to show how cooperative information is taken into account in the main manoeuvring steps. Actually, the control algorithm is more complex, and constantly monitors the received data and combines them with onboard detections.

**Lane change/clearance**

Hereafter we report the scheme and flow chart of a lane change/clearance operation, in a scenario that will be addressed in the pilot.

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3 Even if the driver does not retake control, an L4 system is designed for a safety manoeuver, such as safe stop in the emergenct lane. In 5G-CARMEN we are measuring 5G contribution to the time advance, while we are not addressing safe stops manoeuvres (these are studied by AD-focused projects).
In the example:

- A is automated and connected with Level 4 automation. It is equipped with surround sensors.
- B has the same equipment of A. In this demonstration, B is used as perception probe and has no application purpose.
- C can be automated and connected or only connected (receiving warning to slow down)
- D is any non-connected vehicle or in-movement obstacle
- Potentially all vehicles could be automated and connected communicating with each others.

Hereafter the flowchart within Vehicle A and Vehicle C (the latter needs to be cooperative and give space). The emV is not represented, but it adds timing constraints. If the conditions for cut-in manoeuvres are not met and the vehicle A is in lane with an ETA < 30s, the system needs to ask for driver intervention.

![Figure 10. Lane change flowchart onboard vehicle A](image-url)
**Prevented lane change**

Hereafter we report the scheme and flow chart of a prevented lane-change that will be addressed in the pilot.

![Diagram](image)

**Figure 11. Lane change flowchart onboard vehicle C**

The particular scenario of congested exit lane corresponds to the “*keep in lane*” end of the flow chart.

![Diagram](image)

**Figure 12. Prevented lane-change scenario**
Actuation and control

The vehicle can perform longitudinal and lateral control. In 5G-CARMEN open road corridor this will not be demonstrated and the control strategies are also out of scope of the project.

3.1.2.10 Quality control on board

Autonomous vehicle manoeuvres, such as in-lane manoeuvres and lane changes described above for the scenarios envisioned in the case of the “Cooperative and Automated Manoeuvring for L4 driving”, are enabled by the V2X/5G communication. The use of the V2X/5G-based communication mean for supporting such autonomous vehicle manoeuvres explicitly relies on the capability of the communication mean to guarantee the expected Quality of Service (QoS), e.g., the performance of the communication links required to use effectively data and information for supporting the manoeuvres. However, for instance, in case of insufficient mobile network coverage and/or in case of degradation of the network performance (e.g., due to network overloading), the expected level of QoS could be not guaranteed in a continuous manner by the communication mean. This performance degradation could lead to unexpected effects in the execution of the autonomous vehicle manoeuvres, which rely on the vehicle communication capability and use data and information received from external sources (other vehicles, infrastructure, online services), thus compromising the capability of the vehicle to adequately reacting and effectively taking decisions. With the aim of avoiding this kind of situations, the 5G-Carmen vehicle architecture is equipped with a software module that continuously monitors and checks that the QoS requirements are constantly met during the execution of the scenarios. We call this module “in-vehicle QoS module” or in-short invQoS. The monitoring activity conducted by the invQoS module allows the vehicle to be ready for proactively adapting its behaviours and decisions on the autonomous manoeuvres, thus avoiding interruptions or unexpected, and potentially dangerous, situations. Within the vehicle architecture, hence,
invQoS has a connection (invQoS input) with the in-vehicle network, aiming at acquiring data to be used for the QoS monitoring activity, and it has also a connection (invQoS output) with the AD component subsystem named Perception. This subsystem of the AD components (see above), in fact, is devoted to collect also the V2X/5G quality information so that the Decision subsystem of the AD components can consider it, together with the other information, to make decisions about the current and predicted SAE level ODD. The invQoS module continuously executes the following six logical activities according to the flow below:

1. Collect data measures from different sources
2. Pre-process data and measures and predict trends
3. Verify and check the QoS requirements on data and measures
4. Evaluate and suggest whether to enable autonomous vehicle manoeuvres
5. Enable autonomous vehicle manoeuvres
6. Prevent autonomous vehicle manoeuvres

![Figure 14. Quality control on board](image)

In the activity nr.1, invQoS collects data coming from different sources. In particular, invQoS collects both instantaneous data and average values of (sliding windows) data related to the quality of V2X/5G communications. For instance, it collects data related to the performance and accuracy of the communication with remote vehicles, such as the measure of end2end communication latency, communication jitter, packet delivery ratio of the V2X/5G messages, and the position accuracy of remote vehicles communicating via V2X/5G. invQoS also collects data related to the position accuracy of the ego-vehicle and data about the measured (actual and/or predicted) QoS at the network level (through APIs provided by the network operator), which indicates the expected network performance. The output of this step is a set of measures of data quality related to (i) V2X/5G and (ii) positioning data at application level, as well as related to the (iii) performance of the mobile network.

In the activity nr.2, invQoS conducts some pre-processing and data elaboration (cleaning and fixing data and measure format) on the collected data. Moreover, it measures and elaborates some prediction, if needed, for anticipating possible trends of the data. The output of this step is (i) a set of pre-processed data and measures and (ii) a set of prediction data elaborated on top of them.

In the activity nr.3, invQoS verifies the values of the observed and computed data and measures and it compares them with expected QoS requirements ranges, depending on the vehicle autonomous manoeuvres supported by the V2X/5G communication. In this activity, the value of observed and measured data is compared with a range of its expected validity values, so as to check if the expected QoS requirements of the vehicle autonomous manoeuvre under analysis are met. The output of this step is,
hence, the evaluation of the QoS requirements required to realize the autonomous manoeuvres based on V2X/5G information, with respect the observed, measured and predicted quality data.

In the activity nr.4, the computed data and measures about the QoS are evaluated by an algorithm, implemented inside the invQoS module, that suggests if autonomous manoeuvres can be enabled (activity nr.5) or not (activity nr.6), depending on the level of achievement of the QoS requirements. This information is then used outside the invQoS module, by the Perception subsystem of the AD component. The Perception subsystem collects all the information produced by the invQoS module (QoS data and measures, as well as the suggestions about enabling or preventing autonomous manoeuvres) for passing them to the Decision subsystem of the AD components, which makes decisions on the current and predicted SAE level ODD.

Summing up, the in-vehicle QoS module (invQoS) takes as input data about: (i) V2X/5G message quality, (ii) (ego and remote) vehicles position accuracy, and (iii) mobile network quality and performance. As output, instead, invQoS produces (i) a set of (actual and predicted) data and measures about the QoS, (ii) evaluations on whether the QoS requirements have been met, and (iii) suggestions on whether enabling or not enabling autonomous vehicle manoeuvres.

### 3.1.2.11 Road operator infrastructure and back-end

The A22 C-ITS system is an existing infrastructure that has been adapted and configured for use within the 5G-CARMEN project.

The basic functioning of the infrastructure requires the information concerning potentially dangerous situations on the motorway axis to be detected by sensors, cameras and reports from professional operators responsible for traffic control. They are then validated by the Traffic Control Centre (TCC) of Autostrada del Brennero, called CAU, and included in its management system.

Events are notified to the C-ITS Server (C-ITS-S) with push methodology, using a DATEX II-based protocol without extensions. This structure allows the easy realization of a possible interconnection with a generic TCC.

The C-ITS-S integrates information of current events coming from the TCC with detailed geographical data in the area concerned by the events and precodes information in a suitable format (pre-coding of DENM, IVIM, CAM structures) to air transmission for the Road Side Units (RSUs).

The C-ITS server also manages the dissemination policies of C-ITS messages along the motorway axis, activating the transmission of I2V communications in an area of interest according to the event, its location and the RSUs next to it. The DENM and IVIM messages are thus distributed geographically on the RSUs based on the position of the event, involving only the RSUs that are in proximity to the event itself. The computer protocol used for the communication between the server C-ITS and the RSUs is the HTTP protocol and Websocket protocol (allowing then both the server and the client to push messages at any time).

The C-ITS server integrates a management web interface dedicated to the management and visualization of the events in progress on an interactive map and to the management of the C-ITS infrastructure.

The RSUs distributed along the motorway axis manage the transmission and reception of the I2V and V2I messages on the DSRC ETSI ITS-G5/802.11p wireless network and will include also the transmission via PC5.

In the hybrid approach, these technologies are combined and integrated with solutions based on mobile networks using a cloud-based solution to make the service available even in areas not directly covered by the RSUs. A serializer has been implemented which writes messages to AMQP brokers. This approach has the advantage of maximizing coverage, but also the disadvantage of a higher communication latency compared to direct short-range communication between vehicles and infrastructure.

The hybrid communication architecture foresees three players:

- the producer (typically a virtual RSU), delivering messages
- the consumer (typically the OBU), subscribing and receiving messages
the broker: acting as a mediator and redistributing to consumers the messages obtained by the producers.

The connection between producers / consumers and the broker is persistent and the forwarding of messages is asynchronous, thus allowing having a real-time notification not requiring continuous interrogations by users as the paradigm foresees an initial subscription mechanism.

Figure 15. Motorway service back-end

3.1.3 Cloud infrastructure

This paragraph will illustrate the various components that can affect network performance and the actions that can be taken to improve them. The focus is specifically on the implementation of low latency networks, which is also the main requirement for the Use Cases developed in the project.

3GPP 5G Network Slicing Architecture

With the implementation of 5G networks, the concept of Network Slicing is expanded, i.e. the possibility of Running multiple logical networks on a common physical infrastructure allows a UE to access to a portfolio of possible Network Instances offering different Control Plane and User Plane behaviors, and different customized Service Levels (i.e. meeting certain SLAs which are associated to the concept of Tenancy of a Network Slice) with efficient utilization of the network resources.

Figure 16 shows the characteristics of the main slices identified i.e.:

- eMBB
- URLLC
- MIoT
Figure 16. Characteristics of the main types of slices

The main characteristic of the URLLC-type slice is that of placing the User Plane as close as possible to the point of use of the service where the service infrastructure must also be located. Therefore, the Core Network functionalities involved are the CUPS that is already present in 4G networks and becomes native in 5G networks and the selection mode of the MEC platform where the service logic is located. Apart from these features, there are no other advantages introduced by the 5G core network in terms of latency reducing.

Clearly in the 5G Carmen project, having to use the real network where a 5G NSA is available, the more flexible methods introduced by 5G SA for the slice will not be available, but the methodology of creating a dedicated APN to services is used. V2X services will use this APN that guarantees network component selection for low latency.

Surely, a big contribution to the latency reduction is with NR access. This aspect will be dealt with in the next paragraph.

MEC architecture and LBO

The MEC platform or more properly the platform of EDGE computing is the platform where the applications are located; it must be as close as possible to the PGW component (UPF in 5G SA networks). Clearly, the concept of proximity depends on the overall network architecture and on a trade-off between cost of infrastructure and benefits. It is also necessary to consider that in the case of V2X services an excessive number of Edge Computing infrastructures can lead to an excessive use of ”service continuity” procedures (passage from an Edge Computing infrastructure to another located in a different geographical point) which currently are being defined in the various standardization bodies.

Considering the various sites where telco components and Edge Computing could be co-located, the following sites are identified:

- Local Edge (Thousands of sites distributed nationwide)
- Regional Edge (Hundreds of sites distributed nationwide)
- National DC (dozens of sites distributed nationally)

Considering the Local Edge site as the most remote site, it has been verified that by implementing the Edge Computing platform on a Local Edge we have to add 0.5 ms to latency of Mobile network while implementing the Edge Computing platform on Regional Edge we have to 1.5 ms to latency of Mobile network.

Therefore, surely the implementation of an Edge Computing solution at the Regional level rather than at the Local level does not involve an excessive increase in the value of latency compared to the variance of the latency.
introduced by the radio access. On the other side, this reduce the problem of service continuity moving from one Edge computing to another Edge computing site.

The solution implemented in the 5G Carmen project is based on Local Break Out (LBO), i.e. placing the Edge Computing platform in the nearest PGW site and implementing the network functions that allow to direct specific traffic for the services of the 5G Carmen project from PGW to the Edge Computing platform through the use of a dedicated APN that allows for optimized routing that is not available in generic APN.

**Service and network continuity**

Another aspect to consider is the continuity of the service on the Cross Border. The theme of network and service continuity was analyzed in 3GPP in TS 23.501. Clearly, these aspects are defined only for 5G network and nothing has been defined for 4G network.

Session and service continuity (SSC) modes in 5G System architecture were designed as depicted in Figure 17:

![Figure 17. Session and service continuity modes in 5G](image)

With SSC mode 1, the UPF acting as PDU Session Anchor (PSA) at the establishment of the PDU Session is maintained regardless of the access technology (e.g. Access Type and cells) a UE is successively using to access the network.

With SSC mode 2, the network may trigger the release of the PDU Session and instruct the UE to establish a new PDU Session to the same data network immediately.

With SSC mode 3, changes to the user plane can be visible to the UE, while the network ensures that the UE suffers no loss of connectivity. A connection through new PDU Session Anchor point is established before the previous connection is terminated in order to allow for better service continuity.

These solutions have been defined in case of the same MNO domain and it is not applicable in case of cross-border where 3GPP further studies are needed.

Considering the actual 5G NSA, we have to consider the functionalities available on 4G networks. In this scenario, different options when crossing the border between two PLMNs are available as follows:

- No specific procedure. In this scenario, moving from HPLMN to VPLMN there is a session drop with a session establish moving from HPLM to VPLM. The duration of lack of connection depends on all the procedures to re-establish a new session. A possible scenario of dual SIM has been evaluated but it is to complex, considering ME availability of dual USIM and all different USIMs for all VPLMNs.
- Equivalent PLMN and Release with Redirect. This is the solution that has been evaluated for 5G Carmen project as the best compromise considering the live network.
- Inter PLMN handover. This solution reduces the user plane interruption to few hundreds of milliseconds but require implementation of network interfaces not available in actual Roaming Agreement in real network.

These are the aspects taken into consideration to limit the user plane interruption in the transition from HPLMN to VPLMN. Another aspect to consider is the issue of guaranteeing low latency values in Roaming. This is ensured with the implementation of the LBO in roaming.
This feature, which eliminates the Home Routing problem by delegating routing directly to the Visited PGW, although defined at the 3GPP level, is currently not present in commercial roaming agreements as many of the following aspects are not defined, that is:

- Need of unique APN between different MNO (3GPP defined only unique APN for VoLTE service)
- Charging. Charging in roaming is mainly managed by HPLMN. With LBO in roaming this functionality is completely delegated to VPLMN
- Lawful Intercept. Lawful Intercept in roaming is mainly managed by HPLMN. With LBO in roaming, this functionality is completely delegated to VPLMN.

In the scope of 5G Carmen project the LBO in roaming has been implemented but with limitation in terms of APN, charging and scalability (limited to few subscribers). We expect that other organization like GSMA will include definition of LBO in roaming in technical specifications of roaming.

Another aspect to take into account is the continuity at the application level in the transition from a Home Edge Computing to a Visited Edge Computing. In this case, the continuity aspects are delegated to the application level with the appropriate exchanges of information between the application redeeming on Home Edge Computing and the one residing on Visited Edge Computing. The element of orchestration was taken into consideration to ensure continuity in some specific use cases.

As described in this paragraph, there are many elements which have to be worked on in order to build a low latency slice, while the simple introduction of a 5G Stand Alone solution will not be sufficient.

### 3.1.3.1 Edge Cloud

The previous paragraph describes the various components and the relative solutions to direct traffic to the application residing on Edge Computing by reducing latency. Regarding the Edge Computing platform, it is important to design it in order to avoid bottlenecks due to factors such as NAT, local or remote DNS resolutions, protective Firewalls and of course inefficiencies within the applications themselves.

The following aspects should be considered from application side:

- Transport protocol (TCP vs UDP)
- Implementation of TLS
- Packet length
- Transactional vs. repetitive “fire & forget” mechanisms
- The utilisation of horizontal services / enablers and their respective interfaces
- Protocols and interfaces to applications outside of the MEC / edge cloud domain, such as on backend clouds

### 3.1.3.2 Backend Cloud

As far as the back-end is concerned, this component must normally be developed in such a way as not to be influential for the aspects of latency as currently, except for dedicated point-to-point connections, it does not provide specific connection mechanisms for reducing latency. The approach that has been followed is to distinguish between non-latency-sensitive back end components and latency-sensitive components.

In the latter case -see the orchestration component-, this has been divided into the latency-sensitive component that has been installed on the MEC platform and the non-sensitive component that has been installed in the centralized cloud.

Examples of applications and services used in 5G-CARMEN that are operated on backend cloud systems are the Precise Positioning correction service, the Predictive Quality of Service API and prediction service, and the A22 Backend System.
3.1.3.3 Network Integration Options

There are various options for providing a service infrastructure, services enablers and applications in a network, specifically within mobile networks and in cross-border cross-MNO setups. The main options are:

MEC / edge clouds can be integrated in the network in two different ways: between the RAN and Core Network ("bump in the wire", intercepting traffic) or behind the packet gateway functions, which depend on the core network structure (centralised vs decentralised). 5G-CARMEN implements the MEC / edge cloud deployment collocated with core network packet gateway locations, which provides more efficiency, flexibility and scalability and also overcomes security and data privacy/integrity issues intrinsic to bump-in-the-wire approaches.

The next integration option depends on the approach taken for data flow in case of roaming: home routing vs. local breakout. While home routing of traffic is the current common practice across virtually all public mobile networks, it does not enable low-latency communication and computing for services used by a roaming appliance like a CCAM vehicle in the visited network. With home routing, all traffic goes back to the home network, before "tromboning" back to a service running on a MEC / edge cloud located in the visited country and network. In such a setting, experienced latency while roaming is potentially worse than latency experienced with services running on generic backend cloud infrastructures, especially if the latter make use of intelligent routing mechanisms to ensure optimised routes to the closest cloud service infrastructure in the Internet. Only local breakout in the visited network can leverage the advantage of low-latency communication and computing offered by the MEC / edge cloud approach. Due to the significant effort for enabling local breakout in production networks for visiting subscriptions, 5G-CARMEN adopts an approach, where the primary roaming subscriptions hosted by TIM and DTAG can make use of local breakout to the MEC in the network of MTA, while secondary subscriptions from MTA will continue to use home routing back to the MTA network in case of crossing the border to Italy or Germany and roaming on the networks of TIM and DTAG/Telekom Deutschland respectively.

3.1.4 5G NR Enablers for Ultra-Reliable and Low-Latency Communication

5G NR provides enablers for URLLC (Ultra-Reliable and Low-Latency Communication) type-of-services where very high reliability and availability are required, combined with low latency and, specifically for V2X scenario, with mobility. The 5G-CARMEN use cases Cooperative Maneuvering and Situation Awareness (scenario Event Horizon) will benefit from 5G NR enablers to meet strict timing requirements.

5G NR provides the following new enablers for low-latency communication:

**Short slot duration**

LTE resource scheduling is done at per subframe (1ms). In 5G NR, the scheduling is done per slot whose duration depends on the subcarrier spacing. A higher subcarrier results into a shorter slot duration. Shorter slot duration can reduce latency, but as it also reduces cyclic prefix of OFDM symbol. Thus, this enabler can be used only in the deployments when the cyclic prefix length is still enough to avoid inter-symbol interference. The possible slot durations in the deployment are dictated by the carrier frequency and cell range to be supported.

**Mini-slot transmission**

Scheduling decisions in LTE are taken each subframe (1ms) and data transmission is aligned to subframe boundaries. For low latency communication, 5G NR enables the data transmissions over a fraction of a slot (so-called "mini-slot") and neither the scheduling decisions, nor the data transmission must be aligned with the slot boundaries. It allows starting data transmission requiring very low latency almost immediately. This helps to enable low latency communication for all subcarrier spacings.

**Self-contained slots**

A further enabler related to mini slots are the self-contained slots that include the DL control part, data transmission and UL control part (acknowledgement) to occur in the same slot. The short PUCCH feature
(in the last one or two symbols of a slot) allows providing very fast HARQ feedback in the same slot within tens of microseconds. The self-contained slots speed up the usage of the HARQ processes for following data and the overall latency can be reduced.

**Pre-emption**

For the case when urgent data arrive and have to be transmitted immediately, but all radio resources in the current slot are allocated to other devices due to high load, 5G NR supports the pre-emption mechanism, in which some already ongoing transmissions can be pre-empted. It means that a part of the radio resources scheduled for UE (with ongoing transmissions) is used for the device requiring urgent transmission.

**Configured grant**

To reduce latency for uplink, the configured grant can be used. It configures the device in advance with fixed resources for uplink data transmission. When data are generated in the fixed interval, the alignment of the interval with the period of configured grant allows the device to send immediately without time-consuming procedure of grant request.

**Processing times**

The requirements on processing times for devices and base stations are set significantly higher in 5G NR than in LTE (3 ms). HARQ feedback on the downlink data transmission and the time from grant reception to uplink data transfer is one slot or even less depending on device capabilities, the subcarrier spacing and the reference signal configuration.

**Low latency support at Radio Link Control (RLC) layer**

To reduce latency, in-sequence delivery feature from receiving RLC layer was removed from 5G NR to avoid delay incurred by the reordering mechanism. The waiting time for retransmissions of missing packets will not delay delivery subsequent correctly received packet to the PDCP layer. At the transmitting RLC layer, the concatenation feature was removed to be able to prepare RLC packets before knowing scheduling decision.

**Low latency support at Medium Access Control (MAC) layer**

To reduce latency, 5G NR changed header structure in MAC PDU to reduce processing time at MAC layer. In LTE, the header fields that correspond to RLC PDU are placed in a consecutive order at the beginning of the MAC PDU. In 5G NR, the headers are distributed and located just before corresponding RLC PDU. With this new header structure in 5G NR, MAC PDU can be prepared in advanced (before knowing scheduling decision) as there is no need any more firstly to assemble the full MAC PDU before the header fields can be added.

**Configuration of front-loaded demodulation reference signals**

In 5G NR as in LTE, demodulation reference signals are used for the channel estimation, but the locations of these signals in 5G NR are flexible. In LTE, they are interleaved in the OFDM time-frequency grid (e.g., for downlink they are inserted within the first and third last OFDM symbol of each slot). It requires data buffering due to waiting for channel estimation prior to data decoding. In 5G NR, demodulation reference signals can be configured to be at the beginning of transmission to start decoding the received data immediately at the beginning of reception. Due to this, the decoding latency is reduced comparing to LTE and it contributes to the overall latency reduction in 5G NR.

**Flexible positioning and monitoring of the physical downlink control channels (PDCCHs)**

In LTE, control channels have fixed positions at the beginning of each LTE subframe. In 5G NR, for urgent transmission it is possible to configure PDCCHs flexible within the slot. Thus, it will not be needed to wait for the beginning of the slot to schedule low-latency data transmission. This feature is useful for mini-slot transmissions occupying only a fraction of the slot.
**RRC Inactive state**

5G NR introduced a new RRC state: RRC_INACTIVE with a purpose to reduce latency related to frequent idle-to-active transitions. This new state allows keeping core network connection for the device in the idle state so that returning to RRC_CONNECTED state from RRC_INACTIVE state is much faster as from RRC_IDLE than in LTE.

**Prioritization of time-critical information for multiplexing in uplink grant**

In 5G NR, each UE can be configured with a rule that determines which logical channels can be multiplexed in the uplink grant with specified property. It means that for each logical channel it possible to configure a set of allowed subcarrier spacings, the maximum PUSCH duration, and used cells. This makes possible to avoid situation when low-latency traffic is multiplexed in the transmission with long PUSCH duration or with long slot duration.

**Mapping logical channel to scheduling request configurations**

In 5G NR, a logical channel can be mapped to scheduling request configurations. When base station receives a scheduling request (SR), the gNB can derive what type of data are waiting for transmission. This feature can be used to separate the scheduling requests for resources for latency-critical information from the scheduling requests for non-latency-critical information.

**Network slicing**

Network slicing is a set of functions from 5G service-based architecture configured together to serve specific application or service domain. A specific slice for latency-critical traffic safety application can be created that includes radio network, core network and edge computing functions.

**Edge Computing in 5G architecture**

Architecture of 5G core network enables distribution of core network functions over edge cloud servers. User Plane Functions (UPF) for low latency service can be placed at edge cloud servers and route low latency traffic to the local network.

**3.1.4.1 3GPP analysis on radio latency**

3GPP submitted to ITU-R the “3GPP 5G” for inclusion in IMT-2020. Part of the submission process was the self-evaluation of NR and LTE radio interfaces to demonstrate the fulfilment of IMT-2020 requirements. The results are collected in TR 37.910 “Study on self-evaluation towards IMT-2020 submission” [43].

The following sections provide a summary of the relevant aspects and indications on what can be achieved in commercially deployed 5G networks due to deployment constraints.

**NR User Plane latency**

The methodology is explained in TR 37.910, based on the following figure

![Diagram of User Plane Procedure for Evaluation](image-url)
The results are summarized in the following tables and consider the NR TDD case only due to the fact that the NR frequency band being used for 5G-CARMEN trial activities, i.e. band n78 (3.4-3.8 GHz), uses such kind of duplexing. In particular, UE capability 1 is referring to an eMBB device, while UE capability 2 is referring to an URLLC device.

### Table 2. DL user plane latency for NR TDD (ms) (Frame structure: DDDSU) [43]

<table>
<thead>
<tr>
<th>DL user plane latency - NR TDD (DDDSU)</th>
<th>UE capability 1</th>
<th>UE capability 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SCS</td>
<td>SCS</td>
</tr>
<tr>
<td></td>
<td>15 kHz</td>
<td>30 kHz</td>
</tr>
<tr>
<td>Resource mapping Type A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M=4 (4OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>1.57</td>
<td>0.86</td>
</tr>
<tr>
<td>p=0.1</td>
<td>1.95</td>
<td>1.05</td>
</tr>
<tr>
<td>M=7 (7OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>1.69</td>
<td>0.92</td>
</tr>
<tr>
<td>p=0.1</td>
<td>2.07</td>
<td>1.11</td>
</tr>
<tr>
<td>M=14 (14OS slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>2.38</td>
<td>1.26</td>
</tr>
<tr>
<td>p=0.1</td>
<td>2.78</td>
<td>1.46</td>
</tr>
<tr>
<td>Resource mapping Type B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M=2 (2OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>1.16</td>
<td>0.65</td>
</tr>
<tr>
<td>p=0.1</td>
<td>1.52</td>
<td>0.83</td>
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<tr>
<td>M=4 (4OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>1.28</td>
<td>0.71</td>
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<tr>
<td>p=0.1</td>
<td>1.64</td>
<td>0.90</td>
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<tr>
<td>M=7 (7OS non-slot)</td>
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<td></td>
</tr>
<tr>
<td>p=0</td>
<td>1.49</td>
<td>0.82</td>
</tr>
<tr>
<td>p=0.1</td>
<td>1.86</td>
<td>1.01</td>
</tr>
</tbody>
</table>

### Table 3. UL user plane latency for NR TDD (ms) (Frame structure: DDDSU) [43]

<table>
<thead>
<tr>
<th>UL user plane latency - NR TDD (DDDSU)</th>
<th>UE capability 1</th>
<th>UE capability 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SCS</td>
<td>SCS</td>
</tr>
<tr>
<td></td>
<td>15 kHz</td>
<td>30 kHz</td>
</tr>
<tr>
<td>Resource mapping Type A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M=4 (4OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>3.57</td>
<td>1.86</td>
</tr>
<tr>
<td>p=0.1</td>
<td>-</td>
<td>2.11</td>
</tr>
<tr>
<td>M=7 (7OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>3.68</td>
<td>1.91</td>
</tr>
<tr>
<td>p=0.1</td>
<td>-</td>
<td>2.16</td>
</tr>
<tr>
<td>M=14 (14OS slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>-</td>
<td>2.16</td>
</tr>
<tr>
<td>p=0.1</td>
<td>-</td>
<td>2.41</td>
</tr>
<tr>
<td>Resource mapping Type B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M=2 (2OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>2.58</td>
<td>1.36</td>
</tr>
<tr>
<td>p=0.1</td>
<td>3.07</td>
<td>1.60</td>
</tr>
<tr>
<td>M=4 (4OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>3.12</td>
<td>1.63</td>
</tr>
<tr>
<td>p=0.1</td>
<td>3.62</td>
<td>1.88</td>
</tr>
<tr>
<td>M=7 (7OS non-slot)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p=0</td>
<td>3.23</td>
<td>1.69</td>
</tr>
<tr>
<td>p=0.1</td>
<td>3.72</td>
<td>1.93</td>
</tr>
</tbody>
</table>

In general, it can be stated that the User Plane radio latency is influenced by the following factors:

- Sub-carrier spacing, which influences the slot and symbol duration
- Number of OFDM symbols per slot $M$
- Duplexing (FDD or TDD)
Frame format (TDD) - note that the national regulators in Italy, Austria and Germany imposed a frame format in band n78 (3.4-3.8 GHz), the one commercially deployed and available for the activity of the project; the difference in the frame format between IT/AT on one side and DE on the other side is given by the protection of LTE/WiMAX-based legacy FWA applications existing in IT and AT. This difference is requiring mitigation measures (downlink symbol blanking) to avoid collision of downlink and uplink transmission in the same slot of two or more neighboring networks applying different frame formats, resulting in capacity degradation in such border zones.

- Initial transmission error probability $p$ and network congestion
- Equipment implementations (e.g., radio resource management algorithms)

The frame structure imposed by the regulator is not the same in the three countries. The following table summarizes the adopted configurations.

### Table 4. Frame structure used in commercial networks of interest to 5G CARMEN

<table>
<thead>
<tr>
<th>Country</th>
<th>Sub-carrier spacing</th>
<th>Duplexing</th>
<th>Frame format</th>
<th>Symbols per slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Italy</td>
<td>30 kHz</td>
<td>TDD</td>
<td>DDDDDDDSUU</td>
<td>D = 14 downlink symbols</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U = 14 uplink symbols</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S = 6 DL, 4 silent, 4 UL symbols</td>
</tr>
<tr>
<td>Austria</td>
<td>30 kHz</td>
<td>TDD</td>
<td>DDDDDDDSUU</td>
<td>D = 14 downlink symbols</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U = 14 uplink symbols</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S = 6 DL, 4 silent, 4 UL symbols</td>
</tr>
<tr>
<td>Germany</td>
<td>30 kHz</td>
<td>TDD</td>
<td>DDDSUDDDSU</td>
<td>D = 14 downlink symbols</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>U = 14 uplink symbols</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S = DL, silent, UL symbols</td>
</tr>
</tbody>
</table>

Note that the frame structure adopted in Germany is the same as the one used by 3GPP in their evaluations. The frame structure adopted in Italy and Austria implies worst RTT latency performance since a longer time lapses between two UL occurrences in the frame.

By taking into account the German frame structure and the corresponding table from the 3GPP table for a number of OFDM symbols per slot $M = 14$, we can conclude that (note that the use of the so-called “mini-slots”, i.e. slots with $M$ lower than 14, is not foreseen for the project activities):

- The minimum guaranteed RTT is equal to 3.42 ms (sum of the values in the cells highlighted in blue in Table 2 and Table 3) for eMBB devices
- The minimum guaranteed RTT is equal to 3.02 ms (sum of the values in the cells highlighted in yellow in Table 2 and Table 3) for URLLC devices

This value is obtained with an initial transmission error probability equal to zero ($p=0$). In commercial networks, real propagation conditions, cellular coverage and traffic congestion will influence such error probability and therefore the RTT may significantly increase the radio latency.

Also note there is no URLLC device commercially available; therefore, all the following considerations are related to eMBB devices.

Moreover, the resource allocation algorithms (which are not standardized) have a significant impact on latency. In general, if the user equipment (UE) needs to have the radio resources allocated by the network when a it has data packets to be transmitted, the UE has to first request the resources, wait for the network to provide feedback and then transmit in the first available transmission occasion (i.e. UL slot within the frame) as indicated by the network.
The above considerations are valid in both NR SA (Option 2) and NR NSA (Option 3) networks. In particular, in NR NSA networks it is possible to configure the transmission of the user plane over the NR leg alone. If the user plane is transmitted over the LTE leg only (or over both LTE and NR legs), the predominant factor becomes the latency introduced by LTE.

In fact, 3GPP TR 36.912 [44] evaluated the LTE performance when it was submitted to ITU-R for inclusion in IMT-Advanced. The assessment stated the LTE user plane latency of 8ms (with initial transmission error probability equal to 0).

- **User plane RTT latency:** 8 ms

3GPP specified some techniques to reduce latency in NR. However, these features are not currently supported in the commercial network and/or may not be compatible with the frame structure imposed by the regulator.

**Usage of “Mini-slot” transmission.** Scheduling decisions in LTE are taken each subframe (1ms) and data transmission is aligned to subframe boundaries. For low latency communication, 5G NR enables the data transmissions over a fraction of a slot (so-called “mini-slot”) with a reduced number of OFDM symbols per slot, and neither the scheduling decisions nor the data transmission have to be aligned with the slot boundaries. It allows starting data transmission requiring very low latency almost immediately.

**Pre-emption.** For the case when urgent data arrive and have to be transmitted immediately (e.g. by using “mini-slot”), but all radio resources in the current slot are allocated to other devices, 5G NR supports the pre-emption mechanism, in which some already ongoing transmissions can be pre-empted. It means that part of the radio resources scheduled for one device (with ongoing transmissions) is assigned to the device requiring urgent transmission. The pre-empted transmission will be likely not received properly and this is resolved by Hybrid-Automatic Repeat Request (HARQ) or Code Block Group (CBG) based retransmissions performed by the pre-empted device. 5G NR additionally offers a feature to inform the pre-empted device (in the following slots) about radio resources where pre-emption took place, so that the pre-empted device can be aware where invalid data in the soft buffer are located and discard them accordingly. **Not supported and not compatible with the adopted NR TDD frame structure.**

**Configured grant.** To reduce latency for uplink, the configured grant can be used. The device is configured in advance with fixed resources for uplink data transmission. When data are generated in the fixed interval, the alignment of the interval with the period of configured grant allows the device to send data immediately without performing the time-consuming procedure of grant request.

**Prioritisation of time-critical information for multiplexing in uplink grant.** In 5G NR, each device can be configured with a rule that determines which logical channels are allowed to be multiplexed in the uplink grant with specified property. It means that for each logical channel it is possible to configure a set of allowed subcarrier spacings, the maximum Physical Uplink Shared CHannel (PUSCH) duration, and used cells. This makes possible to avoid situation when low-latency traffic is multiplexed in the transmission with long PUSCH duration or with small subcarrier spacing (i.e., using slot with long duration).

**NR Control Plane latency**

The NR control plane latency is evaluated from RRC_INACTIVE state to RRC_CONNECTED state. Figure 19 provides an example control plane flow for NR Rel-15 [43].
3GPP evaluated the control plane latency to be in the range 13.4-14.4 ms for the German frame structure (the range is due to different RACH formats specified by 3GPP).

The impact of the control plane latency could be the predominant factor in case of small infrequent packets transmission. In such a case, the network may decide to send the UE in idle mode after the transmission, therefore having the control-plane latency as a predominant factor. To alleviate this issue, 3GPP defined an intermediate state (RRC_INACTIVE) which allows a shorter delay when moving the UE to RRC_CONNECTED state for subsequent data transmission.

However, current commercial networks deployment is based on 3GPP NR NSA architecture, where the control plane is transmitted over the LTE leg. Therefore, the control plane latency is regulated by LTE: 3GPP evaluation for IMT-Advanced (TR 36.912) estimated a control plane latency when moving the UE from RRC_IDLE to RRC_CONNECTED equal to 50 ms.

### 3.2 Field test infrastructure

#### 3.2.1 Introduction

The MECs / edge clouds were implemented by the three MNOs each in their respective network data centers:

- Munich (Deutsche Telekom AG)
- Vienna (Magenta Telekom)
Turin (TIM)

Inter MEC/App communication is done via public IPs and the Internet. No special communication paths (networks), like the IPX for PLMN interconnection were used for Inter/Intra.MEC/App communication, as these do not deliver latency improvements compared to Internet connections but rather focus on managed connectivity and monitored service-level agreements, hence operational and commercially relevant aspects.

Figure 20. Abstract view of the project MNOs’ edge clouds and associated address configurations

For use cases which build upon the project’s orchestrated 5G edge computing and networking solution (Orchestrated 5G Edges), relevant components of the development are being integrated with the three MNOs’ production network’s edge clouds. For the connectivity between the deployed orchestrated edge platform and orchestration layers, as well as between orchestrated edge components, which are deployed in different MNO edge clouds, the network structure and interfaces per Figure 20 apply.

Figure 21. Architecture of the Cloud Native Orchestrated Edges for CCAM in the three MNOs’ network
Figure 21 shows the high-level architecture of the Cloud-Native orchestrated edge cloud for CCAM for the three countries (Italy, Austria and Germany) in the respective MNOs (TIM, Magenta and DTAG) domain indicating the main components that enable federation and cross-domain management and orchestration. The orchestrated edge platform design follows container-based cloud-native principles while being aligned with standardization framework provided by ETSI MEC, NFV and 3GPP. This design enables collaboration among 5G edges, thereby extending the range of the services/applications running on top of these edges, in order to enable service continuity.

As illustrated in Figure 21, there are two tiers for the management and orchestration layer, a) top-level service orchestration and b) edge-level orchestration. This functional split enables delegating/offloading orchestration tasks from top-level to edge level orchestrators to reduce latency and make local orchestration decisions/operations handled by edge-level orchestrator, thereby decrease the processing load from top-level orchestrator. The mapping between top-level orchestrator and edge level orchestrator is 1: N, while top-level service orchestrator is at MNOs level (for example one NFV-SO per country), edge-level orchestrators to achieve low latency orchestration operations are geographically distributed and collaborate via local federation interfaces for services that span across multiple edge domains. Details of federation interfaces and delegation mechanisms is available in [[45]].

The edge-level orchestration platform at the respective MNOs comprises, [[45]] Mv1’ abstraction layer, Mobile Edge Application Orchestrator (MEAO) and NFV local orchestrator (NFV-LO), each module designed following cloud-native design principles running as Kubernetes Pods/Services and communicate using service-based communication via REST to perform edge level orchestration tasks. The edge-level tier also comprises an Edge platform component with an Edge Controller (ECON) based on Kubernetes functions and APIs to enforce application lifecycle-management operations and extends the open-source container network interface (CNI) of Kubernetes to perform MEC platform management as well as connectivity control supporting Fast Data Input/Output operations on additional and customized data plane interfaces for Kubernetes PODs.

Multiple private and public routable IP addresses apply to the different interfaces of the deployed orchestrated edge components, which are labelled with a circle in Figure 9 to which a colour code applies. As follows:

- **Red circle** – interfaces for the communication between applications of distributed orchestrated edges (service mesh)
- **Blue circle** – interfaces for the communication between orchestration components
- **Green circle** – interfaces for the communication between applications and external entities, such as vehicles (via mobile data plane anchors / LBO of the cellular network)
- **Grey circle** – local communication interfaces

### 3.2.2 Network setup Germany

#### 3.2.2.1 Network Integration

DTAG has provided bespoke 5G NR 3.6 GHz coverage at the Kiefersfelden/Kufstein border through its German subsidiary Telekom Deutschland, which already operates a 5G NSA network with significant coverage along the corridor and throughout Germany, primarily in the 2.1 GHz Band, complemented by 3.6 GHz deployment in high data traffic zones and POIs in larger cities like Munich. The network will support fast network reselection at the border to Austria with MTA based on ePLMN configuration enabled for the German SIMs used for 5G-CARMEN, plus local breakout for outbound roaming of these SIMs in the MTA network in Austria.

The following coverage predictions plots show the 5G NR 3.6GHz coverage prediction (values: RSRQ) for two antenna configurations, i.e. 4x4 and Massive MIMO, plus the LTE1800 anchor cell.
NR 3,6 RSRQ

Standordhöhe: 25m
Ausrichtung: 30°
180°
Tilt: 3°
3°
Antennen: ARI3239

FARBLICHE SKALIERUNG:
- RSRQ (Received Signal Reference Quality) A: 0°
  - 0° <= x < 10
  - 10 <= x < 15
  - 15 <= x < 20

Figure 22. 5G NR coverage with massive MIMO

 NR 3,6 RSRQ

Standordhöhe: 25m
Ausrichtung: 30°
180°
Tilt: 0°
0°
Antennen: CMAX-OM60-43-UW03

FARBLICHE SKALIERUNG:
- RSRQ (Received Signal Reference Quality) A: 0°
  - 0° <= x < 10
  - 10 <= x < 15
  - 15 <= x < 20

Figure 23. 5G NR coverage with 4x4 antenna
3.2.2.2 Cloud Infrastructure Implementation

DTAG has set up a MEC system from Nokia, vMEC 17 based on KVM virtualisation and accessible via a dedicated APN on a packet gateway in an innovation lab environment co-located with the production core location in Munich. The dedicated APN internet.mu1.m supports private and public IP addresses for services running on the MEC, same as the UEs in the vehicles have private IP addresses assigned (NAT to public IP addresses is being applied in the standard Internet APN). The services / application also have public IP addresses assigned to communicate northbound via the Internet to corresponding services / applications on the MECs of the respective other MNOs (or any other cloud computing environment). Strict firewall rules control the access to the applications from the Internet.

3.2.3 Network setup Italy

3.2.3.1 Network Integration

The solution implemented in TIM involves the deployment of a MEC platform that provides a virtualization environment based on Open Stack on which the applications deployed in 5G Carmen project run. The platform is then interconnected through a dedicated VPN to a specific PGW of the 4G/5G TIM operation network in order to reduce latency time. In addition, a dedicated APN to the 5GCarmen project has been deployed in order to optimize and control the accesses that will take place via dedicated SIM TIMs.

The system architecture is represented as shown in Figure 25. TIM system architecture.
Access to V2X-type services by vehicles takes place through TIM live’s LTE / 5G network. Each vehicle is equipped with an on board unit and a modem unit equipped with TIM LTE / 5G SIM. The interaction between MEC-vehicle platforms is in Machine-to-Machine mode. Each vehicle has a public IP address assigned by the mobile network and therefore known and defined.

The MEC platform will also have to communicate with other external platforms for the acquisition of additional information for the provision of the service. Specifically, the following platforms are provided:

- A22 Brennero motorway platform that sends information on certain situations envisaged for specific use cases.
- CCAM orchestration platform for the BSAF service and CLM service
- MEC platform in Austria. This platform is similar to those of TIM and provides similar services when the vehicles are roaming in Austria.

Every application has a dedicated IP address used to communicate with: 4G/5G TIM network via a VPN connection, other applications (MAGENTA MEC applications) or servers (A22 Brennero Motorway server, CCAM central orchestration platform) and others Network (DTAG, MAGENTA) if needed.

For ITALY environment a dedicated APN 5gcarmen.tim.it has been developed to optimize the routing towards ITALY MEC platform.

5G radio access will be granted through the deployment of two 5G-enabled sites, with gNBs operating at 3.7GHz in a Non-Standalone architecture; therefore co-located 4G eNBs will also be upgraded to support the E-UTRA - NR Dual Connectivity (EN-DC). The first site will be installed in the proximity of the Italian-Austrian border, to support cross-border testing (see Figure 26). For this site, a detailed propagation study has been carried out using TIM proprietary network planning tool, using also some information shared by Magenta on their expected 5G installations on the Austrian side of the border.
As shown in Figure 26, two sectors will be deployed in the site, one pointing to the north (angle from the north axis, 20°), and one pointing to the south (angle 210°). Figure 27 shows the current 4G coverage (LTE @800MHz) in the Brennero Area considering only TIM deployed cells, and in particular, the areas where the North (dark blue) and South (light blue) sectors of the selected site are received with the highest power between the available cells in the region. Similarly, Figure 28 shows the area that is covered with LTE@800 MHz by the Magenta site. Figure 29 shows the overlapping coverage, obtained with both TIM and Magenta networks in the considered area. The green area highlights regions where both networks could be received. It should be noted that coverage in the Brennero tunnel is not granted, as the used network planning tool does not take into account the extra attenuation that the transmitted signal would experience to reach the highway inside the tunnel.
A similar analysis has been carried out also considering the upcoming installation of the new 5G gNBs. Figure 30 shows the coverage that will be granted by TIM installation (a) and Magenta installation (b) at the cross-border.
The two coverage areas are actually overlapping, as shown also in Figure 31; however a coverage gap is expected inside the Brennero Tunnel. The figure also details the difference between the coverage that should be granted on the road (green areas, outdoor coverage), and coverage that can be reached “in car” (light blue areas), i.e. considering also the extra attenuation due to the car metallic structure that impairs electromagnetic waves propagation. As it can be seen, not considering the gap in the Brennero tunnel, a good 5G NR coverage should be reached also inside cars along the considered A22 stretch, as well as in the national road the runs alongside the highway (light red line in the Figure).

Figure 32 shows more in details the areas that will be covered by TIM installation (in light blue), by Magenta installation (in yellow), and where both signals will be actually available (in green). Note that a good overlapping region seems to be available only on the national road, while the transition from TIM coverage to Magenta coverage would happen in the Brennero Tunnel, where however a gap in coverage...
is expected. This result will be verified once the actual installations, which have been delayed due to the Corona Virus outbreak, will be completed and on field measurements will be possible.

Figure 32. Overlapping coverage regions for 5G NR @3700 MHz with TIM and Magenta sites

A second site will be deployed near Trento, providing coverage in a section of the A22 highway in the area between the toll stations of San Michele all’Adige - Mezzocorona and of Egna-Ora-Termeno, close to the town of Laghetti (see Figure 33). This section has been selected to allow some preliminary evaluations of 5G-CARMEN solutions, as it is also covered by the BrennerLEC (Brenner Low Emission Corridor) service that will be used in the green driving use case. For this site a detailed analysis with TIM network planning tool has not been carried out, being the site isolated from the Magenta network, and used only for preliminary testing, not for the final cross border trials.

Figure 33. Location of TIM site near Laghetti
The A22 back-end system

The C-ITS Server represents the heart of the infrastructure:

- it integrates information of current events coming from the TCC (e.g. integrates detailed geographical data in the area concerned by the events);
- it pre-codes information in a suitable format (pre-coding of DENM, IVIM, CAM structures) to air transmission for the Road Side Units (RSUs) and to transmission to the AMQP broker in the cloud;
- it integrates a management web interface dedicated to the management and visualization of the events in progress on an interactive map and to the management of the C-ITS infrastructure.

The information detected through the sensors on the Brenner motorway axis are sent through FEP to the Traffic Control Centre (TCC) for approval. Through a DATEX based protocol channel, the TCC generate and notify events with push methodology to the C-ITS Server (C-ITS-S) that represent the heart of the infrastructure. Messages are received and processed by the C-ITS server, which integrate and pre-codes information in a suitable format for transmission. Messages are subsequently sent, through an internal protocol, to the Road-Side Units (RSUs) of interest located in the proximity of the localization of the event itself along the highway axis. In the same way messages are sent as a producer to the AMQP broker in the cloud through BI, exploiting a particular gateway point called "virtual RSU" that appears to the C-ITS-S server as a normal RSU.

![Figure 34. Interface with road-side sensors and Cloud Analytics platform](image-url)

3.2.3.2 Cloud Infrastructure Implementation

The MEC in Italy is based on Nokia’s MEC19 release. It is compliant with LTE networks supporting 3GPP Release 15 Dec 2018 and supports LTE Radio Access for Edge and onboarding of Nokia and 3rd party MEC applications based on either virtual machine. For the 5G-CARMEN project the MEC19 release has been deployed on the Nokia AirFrame Rack Mount and OpenEdge platforms. Nokia hybrid NCIR provides the hybrid cloud environment using OpenStack (for VMs) and Kubernetes (for containers).

Some of the entities for MEC19 platform and applications are realized as virtual machines while others are containers. For life cycle management of services and applications there are following mechanisms available:

1. For container-based services and applications orchestration is provided using Helm charts.
2. VM based components HEAT based templates are used for orchestration. MEC platform VM can be orchestrated using Nokia CBAM as well.

Figure 35 provides a view of the Nokia MEC system architecture.

![Figure 35. Nokia MEC system architecture](image)

### 3.2.4 Network setup Austria

#### 3.2.4.1 Network Integration

MTA set up respectively extended its 5G network for Carmen 5G along the corridor and specifically at the borders to IT and DE with five sites.

These RAN sites provide 5G NSA coverage according to the following coverage plots (LTE & 5G as per H12021)

#### 5G NSA LTE anchor

![Coverage prediction of 5G NSA LTE anchor sites](image)

Figure 36. Coverage prediction of 5G NSA LTE anchor sites
3.2.4.2 Cloud Infrastructure Implementation

The initial MEC setup for Carmen 5G was done on a reference environment of a Redhat Openstack cloud. To enhance the onboarding capabilities an additional framework from MobileEdgeX was used for easier onboarding services to the MEC platform.

Through the prolongation of the project, the initial setup has to be redeployed now within MTA due to a change in the underlying edge cloud infrastructure.

The new Openstack-based cloud is a production environment already available on three core DC sites within MTA. A co-location between the P-GW and the MEC deployment is possible on all three sites.

For the Carmen 5G setup, only one DC core site will be used – Vienna, T-Center.

For the MEC service, deployments the following settings apply:

Deployment of each service as at least one VM (could be more than one VM e.g. for the Orchestrated Edge Cloud.)
vCPUs will be shared resources (maximum overbooking 1:3). RAM and storage will not be overbooked. Network storage will be used (3 times storage redundancy on site).

3.2.5 Interconnection Austria-Italy

To manage the different Service continuity in Roaming scenario a specific architecture has been defined. The physical interconnection between the MEC platforms is based on public internet and is defined at application level. This means that the single applications have to interwork to deliver the scenario in roaming conditions.

Concerning roaming scenario two configuration have been implemented:

- Phase 1 – Home routing in a first project phase, as depicted in Figure 38.
- Phase 2 – LBO in roaming as a final configuration, as depicted in Figure 39.

Figure 38. Roaming outbound – Home Routing

Figure 39. Roaming outbound – LBO in roaming

3.2.6 Interconnection Germany-Austria

The inter-PLMN interconnection between Germany and Austria is based on the IPX network. For the interconnection of the respective MEC platforms, public Internet is being used, as the MEC locations are not
ideally placed in proximity to IPX connection points, but rather in reasonable proximity to the 5G RAN areas served by the MEC platforms. However, the MEC platforms are located at Internet PoPs, hence a good performance for the communication between MEC platforms is given despite being only a “best effort” interconnection via Internet.

In contrast to standard roaming procedures, where all traffic in the visited networks is being routed directly back to the home network, local breakout of traffic for German 5G-CARMEN SIM cards from DTAG is being enabled when visiting (i.e. roaming) on the Austrian network of MTA, hence data traffic between UEs in vehicles with these SIM cards and the5G-CARMEN MEC applications will go directly to the MEC platform of MTA and not “tromboning” back via Germany. This local breakout setting is not configured / not configurable for the DTAG SIM cards visiting the Italian network of TIM, same as for MTA SIM cards in vehicles visiting the Italian network of TIM or the German network of DTAG/Telekom Deutschland; in this case, standard home routing to the MTA core network will persist.

### 3.2.7 Applications

In Germany, applications running at the orchestrated edge platform are developed as Docker container-based applications and deployed as Kubernetes Pods/Services. We use Helm to manage Application descriptor. Main applications running at the edge-orchestrated platform are Back Situation Awareness (BSA) and Cooperative Lane Merge (CLM).

The following application have been deployed on the three MEC/edge cloud platforms:

- AMQP Broker: this application, developed by TIM (for Italy) and by Swarco (for Austria and Germany), will be used in the cooperative manoeuvring applications (CLM and S-LDM) GeoService:
  - this application developed by NOKIA will be used for Back Situation Awareness
  - BSAF orchestration component: this component developed in WP4 is the component running local on MEC and interworks with the central CCAM orchestration platform for Back Situation Awareness service delivery.
  - Cooperative Maneuvering components will be integrated inside the WP4 Edge Platform, like BSAF

In Italy, applications running at the orchestrated edge platform are developed as Docker container-based applications and deployed as Kubernetes Pods/Services. We use Helm to manage Application descriptor. Main applications running at the edge-orchestrated platform are Back Situation Awareness (BSA) and Cooperative Lane Merge (CLM).

The following application have been deployed on Italy MEC platform:

- AMQP Broker: this application, developed by TIM, will be used in Sensor and state sharing and Green Driving service
  - GeoService: this application developed by NOKIA will be used for Back Situation Awareness
  - BSAF and local orchestration component: this component developed in WP4 is the component running local on MEC and interworks with the central CCAM orchestration platform for Back Situation Awareness service delivery.
  - Cooperative Maneuvering components will be integrated inside the VM hosting BSAF components.

### 3.3 Laboratory implementation and validation of technical Enablers

#### 3.3.1 Overview

In the WP3 context, laboratory activities have been carried out to experiment on the technical enablers. The objective of these experimentations is to test current technological solutions that can be put in place to support the project use cases. It is worth to mention that this section not only addresses technical enables that will be deployed in the pilot (i.e., pre-integration activity), but also presents technical enablers that can be leveraged in the future but not deployed in the pilot due to limitations in the adopted commercial networks (i.e., evolution of the technical enablers). An overview of the experimentations covering these two aspects is provided below.
Pre-integration activity: this part includes the precise positioning technique, especially useful to build an accurate local dynamic map with a precise knowledge of the cars surrounding, and the accelerated network reselection, especially relevant to reduce the connectivity gap while a car changes the network operator in cross-border scenarios.

Evolution of the technical enablers: this part includes an experimentation on the Radio Network Information Service, which is an important component in the 5G system providing useful network-related information to the MEC application, and enabling RAN status aware logics (e.g., anticipate/postpone cars lane merging in case of issues in the access network). Moreover, an extreme edge deployment with MECs collocated with the RSUs is investigated in a real testbed deployed in the E313 highway in Antwerp, Belgium.

3.3.2 Edge service continuity enablers – Inter-MEC operations and demand prediction

MEC enables decentralized deployment of services and helps to improve a variety of KPIs, incl. potential decrease in latency when serving mobile users due to the topologically closer position of services to their clients, and localization of traffic and data to where it is generated, processed and needed while offloading large parts of the network. One the other hand, CAM represents a quite agile customer of such network infrastructure due to arbitrary mobility patterns of vehicles. In order to keep the benefit of providing services to mobile clients continuously from the closest MEC, fast mobility may require re-configuration of service endpoints when deployed at MEC level, as well as mid-session context transfer between services on different MECs and associated routing policies.

The 5G-CARMEN project is investigating technology for service continuity in a MEC-enabled cellular network infrastructure, which includes the provisioning of local orchestration at network edges, as well as suitable interconnect between MEC sites within as well as between MNOs’ administrative domains on Management, Control- and Data plane level. The orchestrated 5G edge platform per the project’s WP4 enables inter-connect between services on distributed MEC platforms at service mesh- and data plane level. This helps to transfer a client’s session context between MEC services and to steer traffic at the level of the 5G architecture’s N6 reference point between the 5G UPF and the MEC services by means of a programmable infrastructure representing a data plane overlay.

The transfer of mobile users’ session context between MEC services assumes availability of sufficient capacity at the service and MEC platform, which imports the transferred states and the resulting load. This may require scaling out service instances at the target MEC platform or scaling up resources associated with the running service instances. Whereas reactive approaches may result in some service interruption until the target platform has implemented the local resources, the service’s session context and traffic routing policies, smart services with potential support from MEC Value Added Services, such as RNIS or location services (LS), as well as smart orchestration layers can enable proactive preparation of such transfer in support of smoother service continuity performance.

In addition, data analytics and machine learning algorithms help to assess the situation in a network in advance by situation classification and prediction. The remaining section describes some results in using machine learning to anticipate the demand for network re-configuration.

When dealing with a multi-MEC environment, the timing at which a MEC application (or its contexts) is moved from one MEC location to another is fundamental for the performances of the entire system. The impact is even wider when considering cross-border MEC deployments, such as in 5G-CARMEN. The best case occurs when it is possible to determine in advance when a service will be needed in a specific location: e.g., if we are able to know beforehand where vehicles will be located, we will be also able to allocate accordingly Application Services serving these vehicles. This is known as the proactive approach for MEC application relocation.

In 5G-CARMEN, and particularly in NEC Laboratories, investigation is ongoing on how to take such proactive decisions in order to gain the maximum benefits for Application Services migration. The main enabler is given by mobility forecasting, i.e., predicting in advance the positioning or vehicles or their expected distribution within a wide multi-MEC-served area. In our lab activity we deploy at the scope our AutoMEC solution, mainly built of two phases: (1) a forecast phase in which the mobility of vehicles is forecasted using machine learning techniques and (2) a decision phase in which forecast results are leveraged to take actions on a MEC Application Service migrations.
The aim of the forecast phase is to predict the density of vehicles for each MEC location at a given time, i.e., the number of vehicles attached to the network that will be consuming from a MEC Application Service located in a specific MEC location. The prediction is based on the history of previous densities of vehicles and consequently can be considered as a time series forecasting. For each MEC location, we need to predict the density of vehicles at time $t+1$ ($U_{t+1}$), knowing the past density of vehicles from time $t-N$ to time $t$ ($U_{t-N}, \ldots, U_{t-1}, U_t$). The $N$ parameter determines how many past measurements we need in order to make the prediction.

In our lab activity, we use a real map comprising a 20km segment of a German highway and including three small urban areas in the proximity of the highway. Figure 40(a) depicts the aforementioned map, while Figure 40(b) shows only the road edges extracted from the map. We then divide our map in equally sized 500x500-meters squares, each of them representing a MEC location were MEC Application Services can be deployed; this is depicted in Figure 40(c). Finally, we use SUMO simulation tool to generate realistic vehicular traffic in the highway and in the different urban areas. Table 5 depicts the main characteristics of the generated traffic, e.g., vehicles travel according to a normal speed distribution (average speed = 0.8 of the road speed limit; std.dev.=0.1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Vehicle dimension</td>
<td>5 m</td>
</tr>
<tr>
<td>minGap</td>
<td>Minimum distance between vehicles</td>
<td>1 m</td>
</tr>
<tr>
<td>DepartSpeed</td>
<td>Initial speed of vehicles</td>
<td>rand(0, max)</td>
</tr>
<tr>
<td>speedFactor</td>
<td>Vehicle speed distribution</td>
<td>norm(0.8,0.1)</td>
</tr>
<tr>
<td>DepartLane</td>
<td>Initial lane selected by vehicles</td>
<td>best</td>
</tr>
<tr>
<td>DepartPos</td>
<td>Initial position within the lane selected by vehicles</td>
<td>base</td>
</tr>
<tr>
<td>ArrivalLane</td>
<td>Final lane selected by vehicles</td>
<td>current</td>
</tr>
<tr>
<td>ArrivalPos</td>
<td>Final position in the lane</td>
<td>max (far reachable)</td>
</tr>
</tbody>
</table>

Figure 40. Highway and urban area map and cell division of the map

Table 5. Parameters for vehicular traffic generation in SUMO

For the time series forecasting, Recurrent Neural Networks (RNNs) are generally the best solution, since they are able to detect patterns in sequential information, by learning the relationship between present inputs and previous ones. Nevertheless, RNNs have a short memory limitation: they tend to prioritize most recent inputs, while knowing a larger history of the vehicles positioning would help to better capture long-dependencies behaviors (e.g., the daily traffic routine, or the effect of a traffic light routine in a big road intersection). At the scope, Long-Short Term Memory (LSTM) and Gated Recurrent Unit (GRU) are variants of RNN used to overcome the aforementioned short memory limitation.

LSTM uses an additional state called cell state ($C_t$), partially aggregated to the new input at each step through Sigmoid and Tanh functions. The output hidden state ($h_{t+1}$) takes therefore into account the effect of the cell state. GRU uses a similar approach, but avoiding using the additional cell state and taking advantage only the hidden state. Depending on the specific configuration and dataset used as input, GRU could offer similar accuracy as LSTM but with a reduced complexity, because of the lower number of operations used. The set of operations composing an LSTM and a GRU single unit are depicted in Figure 41 (left side).

In the lab activity for 5G-CARMEN, both LSTM and GRU were tested in order to determine the best configuration in terms of prediction accuracy and loss. Preliminary results showed that LSTM allows, with the dataset utilized and described above, a higher accuracy and lower loss compared to GRU and needs lower time for training. In particular, different configuration of LSTM and GRU were tested and the best in terms of
accuracy and loss resulted to be LSTM with four layers, achieving an accuracy above 0.8 after about 10 training epochs. On the opposite side, GRU configurations seem not to be able to achieve an accuracy level above 0.7. Figure 41 (right side) shows the complete accuracy and loss results for the configurations tested.

![Figure 41. LSTM and GRU accuracy and loss results for traffic forecasting](image)

Based on the forecast results, we built an Experimental Decision Algorithm to take allocation decisions for MEC applications, i.e., to decide if to relocate applications in different MEC locations proactively.

The decision algorithm runs for each MEC location and takes into account parameters from the current location and the (eight) neighbor locations \( (n_1, n_2, \ldots, n_8) \), as depicted in Figure 42 (left). The input parameters include the user density predicted \( (U_{\text{pred}}) \), the current number of users \( (U_{\text{curr}}) \), as well as the predicted density for the neighbor cells \( U_{\text{pred}}(n_i), \, i=1..N \). More, resource-related parameters are considered, including the storage utilization for each MEC location and for its neighbors \( (\text{stut}) \), the number of instances of the application already allocated \( (\text{inst.alloc}) \), and the maximum number of vehicles each instance can serve \( (\text{inst.cap}) \). Finally, an application-related requirement level \( (\text{req.lev}) \) indicates how strong the low-latency requirement is for the service: a higher value forces the decision towards the local allocation of instances despite the potential drawback in terms of resource consumption. The decision algorithm can take different decisions based on the input parameters:

1. **Migration**: an instance is migrated from one MEC location to another;
2. **Replication**: an instance is allocated in a new MEC location but the previous instance is not deallocated from the previous location;
3. **Scale**: the number of instances of a MEC application in a MEC location is increased or decreased;
4. **Retain**: no change is performed.

The algorithm is depicted in Figure 42 (right) and mainly includes two main conditions:

1. \( U_{\text{pred}} > \mu \times U_{\text{curr}} \): compares the predicted number of vehicles in the cell with the current number and if an increase is expected, takes actions in terms of new instances to be instantiated. The condition takes also into account resource- and service-related parameters (through the multiplier \( \mu \)).
2. \( U_{\text{pred}} > \rho \times \prod_{i=1..8} U_{\text{pred}}(n_i) \): compares the predicted number of vehicles with the predicted number of vehicles for all the neighbor locations, again considering resource- and service-related parameters (through a multiplier \( \rho \)). When this condition is true, the considered MEC location expects a higher demand than neighbors do; hence, a migration rather than a replication of instances is preferred.
For evaluation purposes, we compare the output of the decision algorithm applied to the LSTM forecasts with the output of the same algorithm without forecasted values (i.e., only based on latest historical variations), and again the algorithm considering as input the real future data extracted from the simulation (i.e., testing the case of 100% accurate predictions as an ideal case). The results are shown in Figure 43, considering 120 time samples (i.e., 20 minutes is the overall simulation time). Results show that the decision algorithm leveraging LSTM-based predictions offers a strong gain compared with the case in which past data variation are used: whereas the case without prediction shows to be a bit less aggressive in utilizing available storage, it results in significantly higher delay values and therefore using predicted data achieves higher efficiency, meaning it is able to find a better trade-off between latency requirements and storage utilization. More, the decision algorithm behaves very similar to the ideal case of 100% accuracy predictions.

3.3.3 Radio Network Information Service

Radio Network Information Service (RNIS) is a service that provides RAN information to MEC applications and allow MEC applications to execute UE-level radio link control. RNIS service is to deployed in MEC and will use common frontend (function calls) to the vendor-specific RNIS connector that allows the RNIS service to connect to the LTE/5G core network and base stations for the purpose of extracting KPI/channel information and performing radio link control. RNIS is one CCAM enablers identified in WP3 and is a part of 5G-CARMEN system architecture specified in WP2. As the base stations in the pilot deployment does not support RNIS, RNIS can be demonstrated only in the lab environment.

The usage of RNIS in 5G-CARMEN addresses the use case of cooperative lane merging in centralized manner where robustness and delay of radio communication with involved vehicles play significant role. RNIS is of special importance in the cross-border scenario to preserve QoS and avoid long-term interruption of a communication during maneuvering execution for each involved vehicle.

The general software architecture is presented in Figure 44.
The interfaces are described in D2.3.

Typical interface actions enabled by RNIS API are listed as follows:

**Subscribing to the RNIS information**

MEC application can request RNIS service to provide RAN information for specific vehicles. To receive notifications on selected RNIS events, the application sends a subscription to certain specific RAN information. The subscription information request includes an IP address of the vehicle, a KPI subscription type (CQI, RRC measurements, and handover status change), a reporting configuration. The reporting configuration supports 3 modes: periodically, one time only as data is available or on a value update.

After receiving the subscription request, the RNIS contacts the core network (via Vendor-specific EPC’s API), identifies base stations serving UEs (the vehicles) and UE identifiers within base stations and configure base stations (via vendor-specific base station’s API) to report subscribed RNIS information about these UEs.

**Unsubscribing to the RNIS information**

MEC application can unsubscribe the RNIS information for specific vehicles (e.g. if no further actions are planned with these vehicles).

**Receiving RNIS information**

Base stations report subscribed RNIS information (CQI, RRC measurements, handover status change) to the RNIS that in its turn passes this information to the MEC application.

**Sending a request for RAN control**

MEC application evaluates received RAN information and the API allows MEC application to send a request to RAN to block handover operation, request for high-priority handling and higher robustness against transmission errors till the end of maneuvering for the involved vehicles. After completion of the maneuver, the handover blocking and high-priority handling and higher robustness for UEs involved in the past maneuvering is not needed anymore, so the MEC application unblocks the handover and reset the scheduling priority of vehicles to the default settings.

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**Figure 44. RNIS interfaces in software architecture**

The interfaces are described in D2.3.
Figure 45 explains usage of RNIS in the CLM use case. The CLM application at the centralized entity (MEC server) can use a knowledge over the radio network conditions of involved vehicles and request RAN to guarantee continuous service with minimized delay for the vehicles involved in lane merging.

Before starting lane merging, MEC application for cooperative lane merging (CLM) will request RAN about radio conditions of involved vehicles. If MEC application detects a risk that for some vehicles the radio conditions could result into handover or unacceptable high delay (e.g. due a larger radio resource demand or retransmissions), it may instruct RAN to block handover operation for specific UEs for a short time to avoid handover during the lane merging and/or request a high-priority handling and/or increased transmission robustness for specific UEs (vehicles) in RAN during the lane merging.

The RNIS vendor-specific library is implemented as a shared library component that is linked into the RNIS service at MEC. The interface contains a number of C/C++ functions that can be imported from the library and called by the RNIS.

The following section explains the interaction between RNIS abstraction layer and the RNIS vendor-specific library.

1) Initialization phase
Before the RNIS connector can be used, it shall be initialized. This is done by calling the rnis_connector_init() function and providing a list of MMEs/AMFs and base stations to connect to. The RNIS connector is designed to provide its KPI data in an asynchronous manner using callback functions provided by the RNIS service. The callback functions shall be registered before any requests for RNIS information by using the rnis_connector_register_callbacks() function. There are three types of callbacks currently specified: UE DL/UL CQI information callback, UE RRC measurements information callback, UE handover status information callback.

2) Request RAN information for vehicles involved in cooperative lane merging
Before starting lane merging, MEC application determines UEs to be involved in maneuvering and requests RNIS service to provide RAN information about these UEs (vehicles). RNIS service invokes rnis_connector_ue_subscribe() function at the RNIS connector for each vehicle with parameters: an IP address of the UE.
address of the vehicle, a KPI subscription type (CQI, RRC measurements, HO status, or all types), a reporting interval (in ticks of 0.25 ms) and a handle (the handle is used in callback functions to identify the vehicle to which the RNIS report belongs to). The RNIS Connector has the ability to report KPIs in 3 modes: periodically with a granularity of 0.25 seconds, one time only as data is available or on KPI value change.

The RNIS connector contacts the core network, identifies base stations serving UEs (the vehicles) and UE identifiers within base stations and configure base stations report RNIS information for these UEs.

3) Obtaining RNIS information
Base station reports subscribed RNIS information to the RNIS connector that in its turn passes this information to RNIS service via callback functions registered at the initialization phase and then RNIS service provides it to the MEC application.

4) Evaluation of RNIS information and decision about RAN control
MEC application evaluates received RAN information and if it detects a risk that for some vehicles involved in the maneuver the radio conditions could result into handover or unacceptable delay (e.g. due a larger resource demand or retransmissions), it may instruct RAN to block handover operation for a short time to avoid handover during lane merging (by blocking handover with rnis_connector_ho_control() function call) and/or request high-priority handling of specific vehicles in RAN during lane merging (by invocation rnis_connector_ue_air_link_control() function).

5) Deinitialization
When the RNIS service is not needed anymore/or for a graceful reboot of it, deinitialization of the RNIS connector library is performed with the function call rnis_connector_deinit().

3.3.3.1 Evaluation
The evaluation of the RNIS usage for cooperative maneuvering service was executed in a lab setup with 2 base stations, 3 commercial UEs, EPC and a host PC where a CCAM test application used RNIS to obtain real-time RNIS information and to allow execution of RAN control command (see Figure 46). An adjustable attenuator between UEs and base stations (not shown in the picture) is programmed to change channel attenuation emulating movement of UEs from one base station to another one and creating a handover scenario.

![Figure 46. Lab setup](image-url)
Experiment 1: Handover impact from CCAM test application

At the start, the CCAM test application gets information about attached UEs and subscribes for RAN information about these UEs. The RAN information is received and printed for each UE in the console (Figure 47). This console also shows handover status of each UEs and whether RAN control for specific UEs is enabled.

![Figure 47. RNIS debug console](image)

The traffic to all UEs is generated with ping tool from the host PC. It emulates CCAM short messages sent over air interface. Then, the test script was changing attenuation between base stations and UEs emulating movement of UEs from one base station to another. Then, the maneuvering starting point for UE1 and 2 is selected in such a way so that handover triggering conditions became fulfilled during the maneuvering period. The CCAM application issued a RAN control command to disable handover at RAN for UEs 1 and 2 until the end of maneuvering (for 10 seconds), while for UE 3 a handover was executed (see Figure 48).

![Figure 48. Experiment 1](image)

The ping delay for UE 3 due to handover was temporally increased by 1.6 times while for UE 1 and 2, the ping delay was stable during maneuvering period. Thus, it is validated that the postponing handover will reduce probability of service interruption and increase of delay during the maneuvering.

Experiment 2: UE priority control rom CCAM test application

At the test start, the CCAM test application gets RNIS information about attached UEs and subscribes for RAN information for these UEs. The RAN information was periodically received for each UE. Then, the UDP traffic was started that resulted into 40% of the cell utilization, low delay and no packet losses (see Figure 49).
After adding traffic to other 2 UEs, the cell utilization gone to 100 % and all UEs started experiencing packet losses and increased delay. To validate RAN control from CCAM test application, the CCAM test application simulated the maneuvering start for UE1 and issued the RAN control command with priority increase for UE1 to the RNIS. RNIS sent the command to RAN and increased priority of UE 1. It could be observed that packet losses for UE1 disappeared and the delay was reduced after this command and so high-quality connection to UE1 could be maintained in this cell overload scenario.

In both experiments, we demonstrated the possibilities of the RNIS for CCAM applications.

### 3.3.4 MEC collocation with RSUs

As one of the main IMEC’s laboratory activities, here we briefly present experimentation on the collocation of MEC platforms within Road Side Units (RSUs) (Figure 50), which enables the distributed edge cloud environment. The RSUs are installed as a part of the Smart Highway testbed, which is the test site built on top of the E313 highway in Antwerp, Belgium. In Figure 51, the map showcases the locations of some of the RSUs that are successfully installed along the highway site. In order to differentiate edge domains in our internal experimentation, we mimic the multi-site deployment by dividing the RSU units into groups (as shown in the left-hand side of Figure 50). The deployment of applications in different RSU domains mimics the scenario with three countries, as in the 5G-CARMEN cross-border scenarios, with multiple edge domain per each. Each RSU consists of a large electrical cabinet, containing all the different modules, such as: i) modules for wireless communication (ITS-G5 and V2X with PC5 interface on 5.9GHz, and the long-range communication based on 4G on 3.5GHz, i.e., with Uu interface), ii) modules for local processing on the RSU, and iii) modules that allow us to remotely manage and orchestrate the RSUs. In particular, the General Purpose Computing Units (GPCUs) are enabling edge computing and extending the capabilities at the edge, allowing us to deploy MEC applications closer to the users (i.e., vehicles), thereby decreasing the latency.

The experimentation of the MEC collocation within RSUs so far included: i) performing preliminary tests of the MEC application orchestrator (MEAO), which is developed as an orchestration component for the Orchestration edges platform, ii) performing preliminary tests of the cloud-native Docker-based application for Back Situation Awareness (BSA), and iii) deploying microservices in the form of Docker containers for virtual Content Delivery Network (vCDN), on top of the GPCUs. For this purpose, we have used the permanent site of the Smart Highway. The instantiation and termination of Docker containers were managed and orchestrated by open source NFV MANO solutions (i.e., OSM and Open Baton), and Kubernetes with MEAO. The feasibility tests that were performed with BSA application included: i) dynamic instantiation of Docker containers for BSA application within one MEC node (i.e., GPCU within RSU on the highway), ii) retrieving real-time monitoring data from deployed containers and NFV infrastructure resources that are used by MEAO to perform orchestration operations, iii) instantiating peering BSA application instances on multiple RSUs along the highway, and iv) enabling state sharing between container applications running on multiple sites.
The orchestration of container applications can be done from the UAntwerp (University of Antwerp) Cloud that is deployed as a backend for the Smart Highway testbed, but also from the edge computing nodes (i.e., GPCUs in RSUs). One of the ongoing activities is connecting the vehicles (equipped with OBUs) to the applications running in MEC platforms collocated within RSUs. Thus, the value-added support in terms of Vanetza containers is deployed on top of RSUs to enable the reception of upcoming CAM messages from testing vehicles, processing of these messages, and using the infrastructure to disseminate the messages towards vehicles.

The Smart Highway testbed is leveraged only as a lab facility, as it provides the means for experimental evaluation of the performance of orchestration functions and BSA application in a more realistic environment. Thus, IMEC is leveraging this testbed facility only for the purpose of performing preliminary and feasibility tests of the software components of the Orchestrated edges platform (i.e., MEAO), and the cloud-native application for BSA, before they are i) integrated with other partners’ components, ii) deployed on the MNOs’ infrastructure, and finally iii) demonstrated in cross-border trials.

3.3.5 RTK-based positioning

Following the automotive sector demands for precise vehicle localization with a positioning accuracy below one meter, IMEC has investigated the Real-Time Kinematic (RTK) based positioning.

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6 Vanetza - An open-source implementation of the ETSI C-ITS protocol suite, supporting CAM and DENM messages
In order to determine the vehicle location coordinates with the required accuracy, GNSS techniques are investigated. In this research, GNSS receivers are deployed on the existing Smart Highway testbed in E313 highway, in Antwerp, Belgium.

The Smart Highway testbed is treated as a lab facility. Due to the opportunity to perform the test and evaluation in a more realistic environment, IMEC has worked on field measurements on RTK-based positioning. This activity is not selected as a candidate solution for the 5G-CARMEN trials, this activity is considered as lab activity based on the realistic data measured on the Smart Highway testbed. The infrastructure used, required deployments, and results are presented in Section 5.5, however, this activity is not going to be included in the final trial.

### 3.3.6 Network reselection delay

The network reselection process involves different layers of the protocol stack in order to allow MS to select a cell and register to a PLMN. Radio cells are associated with a carrier, which is defined by (i) a carrier center frequency and (ii) a channel bandwidth [23]. To check if a cell is suitable, the MS decodes the advertised system information where a combination of PLMN identity and radio access technology (RAT) are provided. A list of PLMN identities is hold by the MS in priority order: highest priority is given to the H-PLMN, then equivalent PLMNs (E-PLMNs), and finally to other PLMNs, which, when selected, will be simply a visited PLMN. The MS selects a cell which is part of the H-PLMN or of an E-PLMN, to camp on according to well-defined cell selection/reselection criteria based on radio channel quality measurements [24]. If no suitable cell is found on any carrier center frequency, the MS should attempt to find an acceptable cell, that is, a cell that does not belong to the H-PLMN or to an E-PLMN [24]. The explained search process is the origin the service outages which could be in the order of minutes. In this preliminary investigation, we aim at evaluating the gap between the best case and the worst case in terms of network reselection latency $D$, namely:

- **APPROACH #1**: explicit indication - The MS is forced to move from the connected state to the idle state by the Radio Resource Control (RRC) layer of the H-PLMN, and the state transition message provides it with the necessary (a-priori) information for the selection of a suitable cell covering the next tracking area;

- **APPROACH #2**: exhaustive search - The MS recovers from a radio coverage outage, thus it is not aware of any information regarding the surrounding cells. In this case, the MS must scan all the available carrier center frequencies before picking the best suitable/acceptable cell.

Clearly, the former approach minimizes the network reselection latency, while the latter approach provides the upper bound on such latency. Thus, we will show how a simple heuristic provides an intermediate performance between APPROACH #1 and APPROACH #2. The proposed heuristic is defined as follows:

- **APPROACH #3**: search until first success - The MS stops the cell search as soon as it finds the first instance of a suitable cell.

**Characterization of network reselection delay**: For the evaluation of these approaches, we provide a mathematical characterization of the network reselection latency $D$ in the three cases. We start by defining the following parameters:

- $N$ is the overall amount of E-UTRAN absolute RF channel number (EARFCN) that are available to be tested by the MS. We have:

$$N = \sum_{i=1}^{I} n_i$$

where $I$ is the number of considered Evolved Universal Terrestrial Radio Access (E-UTRA) operating bands and $n_i$ is the amount of EARFCN to be tested in the $i$-th band.

- $M$ is the amount of EARFCN indices that are actually allocated to available cells. We have:
\[ M = \sum_{i=1}^{i} m_i \]

Where \( m_i \) is the amount of EARFCN allocated in the \( i \)-th band;

- \( \tau \) is the processing time required by the MS to demodulate and (eventually) decode the system information of an available cell.

For the **APPROACH #1**, the MS must scan just the carrier indicated by the RRC, thus:

\[ D = \tau \]

For the **APPROACH #2**, the MS must scan the entire spectrum, ranking the suitable cells in descending order before actually registering to the best one. The scanning process entails \( N \) frequency scans plus one final scan of the selected cell, yielding:

\[ D = (N + 1) \tau \]

Finally, for **APPROACH #3**, the frequency scanning of duration \( \tau \) must be repeated for a random number of times \( X \). This random variable represents the time before the MS actually finds the first suitable cell. Therefore, \( X \) can be modeled as a truncated Geometric random variable where:

\[ \mathbb{P}[X = k] = \frac{p(1-p)^{k-1}}{1-(1-p)^N}, \quad k = 1,2,\ldots,N, \]

where \( p \) is the probability that the current EARFCN is associated to a suitable cell. Therefore, the network reselection latency becomes, on average,

\[ \mathbb{E}[D] = \mathbb{E}[X \tau] = \frac{1-(N+1)p(1-p)^N-(1-p)^{N+1}}{p[1-(1-p)^N]} \cdot \tau \]

**Analytical expressions of \( N \) and \( p \):** The actual values of \( N \) and \( p \) depend on the specific frequency planning of the spectrum the MS can operate on, i.e., on the allocated carrier center frequencies and channel bandwidths. Each possible carrier center frequency in a given E-UTRA operating band is identified by an EARFCN index \( v_{DL}(j) \in \{0, \ldots, 262143\} \), and it corresponds to integer multiple of 100 kHz. The corresponding downlink carrier frequency (in MHz) can be derived as follows:

\[ F_{DL}(j) = F_{DL,low} + 0.1 \left( v_{DL}(j) - v_{offs-DL} \right), \]

where \( v_{DL}(j) \) is the downlink EARFCN index and \( F_{DL,low} \) and \( v_{offs-DL} \) are given in [23]. A similar equation holds for the uplink carrier frequency. The nominal channel spacing between two adjacent carriers is defined as

\[ \Delta B(B_j, B_{j+1}) = \frac{B_j + B_{j+1}}{2}, \]

where \( B_j \) is the bandwidth of the \( j \)-th carrier expressed in MHz. We remark that the correct value of \( N \) is obtained by subtracting from the total number of candidate EARFCN indices in a given operating band those indices that are actually utilized and the minimum bandwidth occupation after a valid index is detected. Specifically, for each allocated \( v_{DL}(j) \), we have to exclude all of those indices included in the nominal channel spacing between the current carrier and a (presumed) adjacent carrier with minimum bandwidth, that is,

\[ \Delta B_{min}(B_j) = \Delta B(B_j, B_{min}) = \frac{B_j + B_{min}}{2}. \]

Regarding \( p \), in this work we assume that the probability of finding a suitable cell in the operating band is uniform. Therefore, \( p \) can be computed as follows:

\[ p = \mathbb{P}[(\text{current EARFCN hosts a suitable cell})] = \mathbb{P}[(\text{EARFCN hosts a cell}) \cap \{\text{PLMN ID ok}\}] \]
\[
= \Pr \{ \{ \text{PLMN ID ok} \} \cap \{ \text{EARFCN hosts a cell} \} \} \times \Pr \{ \{ \text{EARFCN hosts a cell} \} \}
= \frac{\# \text{suitable cells}}{\# \text{available cells}} \times \frac{M}{N}
\]

Table 6. Considered frequency allocation (based on the Italian scenario) for the performance evaluation.

<table>
<thead>
<tr>
<th>i</th>
<th>E-UTRA Operating band</th>
<th>( F_{DL,\text{low}} ) [MHz]</th>
<th>( \eta_{\text{OB-DL}} )</th>
<th>( v_{\text{DL}} ) range</th>
<th>( m_i )</th>
<th>( v_{DL}^{(j)} ) [MHz]</th>
<th>( n_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1805</td>
<td>1200</td>
<td>{1200, ..., 1949}</td>
<td>5</td>
<td>1225 / 5</td>
<td>295</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>2620</td>
<td>2750</td>
<td>{2750, ..., 3449}</td>
<td>5</td>
<td>2800 / 10</td>
<td>325</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>791</td>
<td>6150</td>
<td>{6150, ..., 6449}</td>
<td>3</td>
<td>6200 / 10</td>
<td>135</td>
</tr>
</tbody>
</table>

**Performance Evaluation:** To provide some numerical results we consider a realistic frequency planning as done in [26]. We thus focus on the Italian channel allocation scenario, where LTE systems are typically deployed in three E-UTRA operating bands, namely #3, #7, and #20, yielding \( f = 3 \). The complete frequency allocation of the various PLMNs in these portions of the spectrum can be derived by exploiting the information about actual carrier allocations provided by [25] and reported in Table 6.

We can see that \( m_1 = m_2 = 5 \), while \( m_3 = 3 \), for an overall \( M = 13 \) allocated EARFCN. Note that we neglect the presence of possible available cells belonging to virtual MNOs, which may be associated to an MNO carrier. The amount of EARFCN indices in the \( i \)-th operating band is

\[
n_i = \left( \max \{ v_{DL}^{(j)} \} - \min \{ v_{DL}^{(j)} \} + 1 \right) - \sum_{B \in B} k_B \left( 10 \cdot \Delta B_{\min}(B) - 2 \right)
\]

where \( B \) is the set of available bandwidths in LTE systems [26] and \( k_B \) is the number of allocated carriers in the \( i \)-th band with bandwidth \( B \). The factor 10 is due to the division between MHz units (10\(^6\)) in which the bandwidths are expressed and the EARFCN spacing of 100 kHz (10\(^3\)).

For example, let us consider the E-UTRA operating band #3 (\( i = 1 \)). We have an overall amount of 1949−1200+1=750 indices in this band, and there are 5 PLMN identity; 3 of them allocated a bandwidth of \( B_j = 20 \) MHz (\( k_{20}=3 \)), 2 of them allocated a bandwidth \( B_j = 10 \) MHz (\( k_{10}=2 \)), and one of them allocated a bandwidth \( B_j = 5 \) MHz (\( k_{5}=1 \)). Therefore, considering that the minimum channel bandwidth is \( B_{\min}=1.4 \) MHz [26],

- each 20-MHz-wide carrier excludes \( \Delta B_{\min}(20) = 21.4/2 = 10.7 \) MHz, that is, 107 - 2 = 105 EARFCN indices;
- each 10-MHz-wide carrier excludes \( \Delta B_{\min}(10) = 11.4/2 = 5.7 \) MHz, that is, 57 - 2 = 55 EARFCN indices;
- the 5-MHz-wide carrier excludes \( \Delta B_{\min}(5) = 6.4/2 = 3.2 \) MHz, that is, 32 - 2 = 30 EARFCN indices.

Therefore, the original set of 750 indices decreases of 3\( \times 105 + 2 \times 55 + 30 = 455 \), yielding an actual amount of EARFCN \( n_1 = 295 \). The values of \( n_i \) for \( i \in \{1, 2, 3\} \) are reported in Table 6. Finally, in order to keep the network reselection delay agnostic of the specific MS hardware [26], we do not provide explicit values for the constant \( \tau \), rather we express the latency in terms of acquisition time units.

\(^7\) Note that we have to exclude 2 indices related to the currently considered EARFCN index and the (presumed) next one.
Figure 52. Network reselection latency $D$ expressed in acquisition time units ($\tau$) versus the number of suitable cells, given 5 available cells.

**Numerical Results** are provided in Figure 52 where the network reselection latency is expressed in $\tau$ units. We can make the following observations.

- The average latency introduced by APPROACH #3 (search until first success) is much closer to the benchmark (APPROACH #1 - explicit indication) than to the worst case (APPROACH #2 - exhaustive search). In particular, APPROACH #3 provides more than 70% latency reduction with respect to APPROACH #2.

- The average latency introduced by APPROACH #3 decreases as the amount of suitable cells increases. The latency reduction between the case of a single suitable cell and the case in which all available cells are suitable is approximately of 60% in terms of $\tau$ units.

It can be noticed that in a typical frequency allocation like the one considered, a large gap between the best case (APPROACH #1) and the worst case (APPROACH #2) for network reselection can arise. The motivation for such a gap is the lack of integration between MNOs, which causes the MS to perform a huge number of attempts to find a suitable/acceptable cell to camp on before registering to the new PLMN, especially in case the MS must scan large spectrum portions.

A tighter integration between MNOs, in terms of extended roaming agreement to provide the MS with a long list of E-PLMN, would allow reducing the network reselection latency. This beneficial effect is clear in our performance evaluation results: if all available cells become suitable (i.e., their PLMN identity is in the list of E-PLMN provided by the H-PLMN), then $p \rightarrow M/N$ and thus it is maximized. We remark that the integration required by APPROACH #3 does not entail the transmission of ad-hoc RRC signalling messages like APPROACH #1, thus resulting in a lighter implementation effort.

### 3.3.7 Practical Network Reselection Acceleration

#### 3.3.7.1 Introduction

The general situation and the underlying complexity concerning cross-border (uninterrupted) connectivity has been described on the joint Whitepaper [27]. Since the political, legal, regulatory and industry-wide business challenges cannot be solved within 5G-Carmen, we focus on a practical and generic technical solution. It is based on approach #1 of the previous chapter: Accelerating the Network Reselection procedure by indicating the foreign cell(s) to connect to. Since we are using standard 3GPP procedures, it is independent of the deployed RAT. This bears several advantages:

- Independence from 5G deployments, the solutions work as well with 4G and 6G
- Independence from network equipment vendor-specific implementations
No delays for a European-wide live network application by any MNO. Our approach circumvents the non-technical challenges, which loom in the Session Continuity itself (customers using different administrative domains during the same session).

For understanding the situation (without having read the above-mentioned whitepaper), we recall that in current cellular networks, not all 3GPP-defined interfaces between different Core Networks are implemented cross-border (between MNOs of different countries and this different jurisdictions). More details are in D2.3 and the 3GPP 5G System Architecture e.g., [28].

![Figure 53. Missing inter-MNO Core Network Interfaces](image)

The consequence is that the cross-border inter-PLMN Session and Service Continuity is currently not possible in live networks (where only the minimal Core Interfaces for Roaming and Home Routing are established), however the network reconnection time can be minimized.

### 3.3.7.2 Solution

Autonomous Vehicles (and any other connected device) are in RRC Connected Mode as long as they have coverage by an MNO. When the cell coverage turns unsuitable, cell (re-)selection procedures are applied, which may require the configuration of neighboring cells (otherwise the previously mentioned RRC Idle Mode frequency scans are executed by the device). At this point, devices can be redirected to other cells. This would typically be the case inside the national cellular network of an MNO (including the Session Continuity), since an MNO has full technical and administrative control over their own national network. A general prerequisite to mention is that source and target cells overlap, which requires aligned and efficient cross-border Radio Planning by all concerned MNOs. More details can be found in the Whitepaper.

The RRC Connection Release-with-Redirect procedure, pointing to a target frequency is applied for the inter-PLMN network reselection. Although the devices pass via the RRC Idle Mode (loss of connectivity), it can immediately reattach to the foreign PLMN, as long as it is declared as Equivalent PLMN (otherwise the device tries to stick to the home PLMN, which corresponds to the current border situation).

Deutsche Telekom assessed alternatives, such as the standard inter-PLMN cell selection procedure (frequency scans) and “blind handovers”. However, the latter requires the 4G inter-MME interface (S10 in the above picture, and the equivalent applies for 5G), since the source MME prepares a handover, but since the target is not known by the source MME, the process stops and the terminal does not receive any RRC reconfiguration to finalize the handover. The standard procedure is not providing a sufficiently fast reconnection to the foreign network, with or without the ePLMN configuration (see also the test results from the VIF live drive tests at the German-Austrian and Austrian-Italian border).
3.3.7.3 Test Setup

A dedicated test environment has been set up in the Deutsche Telekom mobile network lab in Bonn:

- Two independent mobile networks (PLMN)
  - Deutsche Telekom (262 01, Germany)
  - Magenta Austria (232 04, Austria)
- Both networks allow normal roaming traffic (S6a interface used for authentication in roaming scenario and the S8 interface for data roaming connections), but do not have the X2 or S10 interfaces
- Both Core Networks connect respectively to independent LTE cells of different frequencies:
  - Deutsche Telekom (source cell, home PLMN)
    - Vendor: Ericsson, 20.Q2
    - PLMN: 262 01
    - EARFCN: 3750 (LTE 900, B8)
    - PCI: 360
    - TAC: 65321
  - Magenta Austria (target cell, roaming PLMN)
    - Vendor: Huawei, V100R016C10SPC112
    - PLMN: 232 04
    - EARFCN: 1300 (LTE 1800, B3)
    - PCI: 147
    - TAC: 13666
- The test device is a Samsung Galaxy S9, configured to use all RATs to reflect live network scenarios
- In Idle mode tests, the mobile data has been switched off to trigger the idle mode faster
- SIM cards are roaming enabled. Both have Home PLMN 262 01, but only one card has additionally 232 04 (Magenta Telekom) as equivalent PLMN
  1. IMSI: 262015947008743, Home PLMN: 262 01
  2. IMSI: 262015947008796, Home PLMN: 262 01, Equivalent PLMN: 232 04
- Power cycle and flight mode on/off is applied before every test case to ensure that the device does not remember past cells and PLMNs
- Before any new test, the device connects to HPLMN first
- Idle mode is enforced by switching off mobile data

![Figure 54. Deutsche Telekom mobile network lab setup in Bonn](image-url)
Figure 54 depicts the lab environment. At the top of the shelf, a coupling unit receives both radio frequencies of the base stations via coaxial cables. The coupling unit may attenuate these signals and combine them to a dedicated output port. One output port of the coupling unit connects to the input port of a shielded box (lower right).

The shielded box is a metal box with power supply and an antenna inside. An USB interface connects the inside to the outside world. The antenna distributes the radio signal inside the box. The metal box ensures that only radio signals of the test scenario enter the box via the coupling unit. No other frequencies are available in the metal box. The device resides in the shielded environment.

The device connects in the box to the power supply and to the USB port and receives radio signals over the antenna in the box. The Android debugging bridge (adb) allows remote controlling of the device, via the connected laptop. The Laptop connects to the USB port of the shielded box and controls the device via USB interface even when the lid of the box is closed.

During the test, the device is first connected to HPLMN under good radio conditions. In the shielded box, the VPLMN cell is also available but not selected initially. The mobility procedure is started by continuously degrading signal strength of HPLMN cell until predefined thresholds are reached and the device starts to pick an alternative cell (first trigger point). When a suitable cell is selected, the device sends a tracking area update to the network, which is the second trigger point. As the source cell is not known by the visited MME, it rejects the message and the device starts with an Attach message, which is accepted (and a new IP address is attributed to the device). The procedure from the initial TAU message to the final Attach Accept message is also present in live networks and always lasts about 3s in our lab environment.

In all tests, the subscriber moves from the Deutsche Telekom cell towards the Magenta Austria cell and performs an inter-PLMN inter-frequency mobility scenario. However, the results apply vice versa, if optimization is applied in the other network as well. Pure 5G and inter-RAT (e.g. 4G-5G) is not been tested, but similar performance results can be expected.

### 3.3.7.4 Performance Results

In the baseline scenario, representing the state of the art of today’s network (the HPLMN not having any information on the potential target cell, and VPLMN cells are not in list of the equivalent PLMN), the device continues scanning all frequencies and all RATs, and finally picks the VPLMN target cell only as last resort. This time span of about 60s is experienced today, and highly depends on available RATs, PLMNs and their priorities. An essential part of the improvement is the ePLMN configuration, which requires the knowledge of the target PLMN (PLMN IDs are generally known or can be easily found out) and its configuration as ePLMN for a specific subscriber in the HPLMN MME (and thus SIM card). However, the network outage still lasts six seconds on average.

With known target cells and frequencies (considered as confidential MNO data), as well as the configuration of cell Neighbor Relations, event thresholds and redirection procedures between domestic and foreign cells, the whole scanning procedure of the terminal is skipped (The HPLMN sends RRC Connection Release including the foreign target frequency. The device goes into Idle Mode, selects the cell, decodes the SIB and connects to the V(e)PLMN), and in our laboratory conditions the device reconnects to the network within 0.5s on average - a results which renders the network reselection performance suitable (for non-critical operations) for Connected Automated Driving.

Any further improvements require additional cross-border inter-MNO network interfaces to be established, which entail additional efforts in terms of costs and security (along with and the already mentioned different legislative and regulatory conditions in different European countries to be respected). Apart from this, our sister project 5G-Mobix indicates in [29], that the traffic via current international GRX/IPX networks do not meet the required latency and security, whereas 5GCroco states that cross-vendor tests of the S10 interface where the MMEs serve different networks are not common and therefore undetected issues might exist [30].

It must be noted that all measured durations are related to the (ideal) synthetic setup with a limited number of target frequencies and RATs. In reality, with more carriers operating in parallel (several MNOs from at least two countries in border areas), more PLMNs, RATs and frequencies are in use. Beyond this, the
physical topology, base station/cell locations and cell antenna configurations also have a considerable impact on the received cell signal strength. **Since this is different for each border area, network reselection performance results may vary.**

Since 5G-Carmen is devoted to pragmatic solutions for 5G and beyond, the accelerated Network Reselection is practically applicable in the entire live network ecosystem without any dependence on border region 5G NR deployments of all European MNOs. For the necessary foreign RAN data - which is in any case also needed for the inter-PLMN handover with Core Network Interfaces, due to the MNO-internal network management - 5G-Carmen also proposes the solution: This general, automated and secure inter-MNO data exchange and management system, which can be integrated into any MNO OSS/network management systems to assure cross-border Mobility, will be described in further deliverables.
4 Network-based range extension and interworking between communication technologies

4.1 Overview

This section deals with the necessary interworking features that the most demanding, prioritized use cases that 5G-CARMEN has chosen to validate, namely those dealing with automated and cooperative lane changes, to support (i) cross-border operations with a reduced handover time, (ii) fast delivery of messages on the basis of the geographical position of recipients and (iii) interoperability among vehicles equipped with different technologies. Owing to the fact that a prompt and direct communication paradigm is needed, solutions that allow the swift pushing of information from service providers to end users involved in the use cases are preferred. For these reasons, the project has invested in two types of publish-subscribe applications, AMQP and GeoService. Both can operate in the MEC infrastructures responsible for the traffic routing function and enable the network-based range extension and interworking, thus demonstrating possible interoperability also between heterogeneous solutions adopted by different operators. Both can also implement a transparent message-based communication between service providers and end users that is independent of the underlying communication technology. The following subsections,

4.1.1 Interworking via AMQP server

As described in Section 3.1.2.2, the AMQP brokers deployed in the MEC both for the Italian and Austrian side are compliant to C-Roads Platform specification version 1.7.

In Figure 55 is depicted the interworking between two Interchange Nodes according to C-Roads specification for interoperability. In C-Roads an Interchange Node is a specialized SW entity that incorporates an AMQP broker plus additional functionalities.

![Figure 55. Interworking between two Interchange Node in C-Roads](image)

The AMQP broker deployed on a MEC node for the 5G-Carmen project implements only the Basic Interface, on the contrary the Improved Interface is optional, and it is not adopted.
As in Figure 56 the Italian AMQP Broker and the Austrian one are “federated” by means of the Basic Interface, which is each broker acts as server when publishing messages to the other one, and as client when subscribing to the other “federated” broker.

In this manner, cars connected to one broker can receive messages from the other one too. In a cross-border scenario a car e.g., from Italy stays always connected to Italian AMQP broker but it can also receive Austrian messages when it crosses the border.

**4.1.2 Interworking via GeoServices**

GeoService forwards messages received from vehicles or from an application, via the Message Ingestion Interface, to a neighbor GeoService instance if the Area of Relevance (AoR) or the Destination Area (DA) intersects with the neighbor’s Own Service Area (OSA).

On reception of a message e.g. a CAM or DENM, the GeoService disseminates the message to vehicles within the AoR. In addition, GeoService forwards the message to a neighbor if the AoR or DA intersects with the neighbor’s OSA. When the neighbor receives the message, it disseminates the message to vehicles in the AoR.

An example is depicted in the Figure 57. Example of interworking via GeoServices.
GeoService1 has awareness of vehicle1, vehicle2, vehicle3, and vehicle4 whereas GeoService2 has awareness of vehicle5.

GeoService1 is receiving an Infrastructure to Vehicle Information Message (IVIM) that shall be disseminated to vehicles in the specified area (ellipse with green border in the figure above). GeoService1 is sending the IVIM to vehicle4 since it is located within the specified area, and it is forwarding the IVIM to GeoService2 because the specified area intersects with the OSA of GeoService2. When GeoService2 is receiving the IVIM, it is sending the IVIM to vehicle5 since is located within the specified area.

This feature enables the cross-border communication between different GeoService instances.

### 4.2 Implementation and validation of technical enablers

#### 4.2.1 Overview

The aim of this section is to present in-lab testbed implementations that some 5G-CARMEN partners have put together in order to test and provide pre-deployment, pre-integration results of some of the solutions selected for network-based range extension and interworking. First, an evaluation of a MEC-based deployment of an AMQP message broker is presented, showing the measured end-to-end delay (from a producer, hence to the broker, hence to a consumer), experienced under different configurations with and without a MEC deployment. Next, a solution involving a Multi-RAT dual connectivity solution addressing enhanced communication reliability is discussed and investigated using simulation, which highlights different packet reception rates when a Multi-RAT management solution is used versus a case where it is not used.

#### 4.2.2 Joint CNIT-TIM Laboratory

This section aims at describing a laboratory testbed coming from the joint effort of CNIT and TIM, with the goal of testing the deployment of an AMQP message broker (namely, Apache ActiveMQ 5.15) on a MEC platform, as an ETSI MEC service. The testbed is located in the facilities at the CNIT research unit of Politecnico di Torino. As 5G-CARMEN is focused on the development of pilots to showcase the potentialities of 5G in automotive and cross-border scenario, this laboratory activity has been performed to conduct a preliminary and pre-integration testing of an AMQP broker as a technical enabler for range extension and message dissemination, before deploying it in the networks of the MNOs.

The results described below served to validate the effectiveness of this solution and to show how an AMQP 1.0 service on MEC can be suitable to support the project use cases. For instance, the Cooperative and automated lane-change maneuvers use case is relying on AMQP for its Centralized lane change 5G-enabled sub use case. In particular, the S-LDM component will receive all the vehicles’ messages, transmitted through the Uu interface, thanks to the connection to one or more AMQP brokers (in case, for instance, of cross-border scenarios).

As this use case is very latency sensitive and requires the delay to be as low as possible, it shows the importance of analyzing the performance of AMQP 1.0 when a broker is deployed on a MEC platform as a service. The evaluation was based on an open source tool developed by CNIT, called “LaTe” (available on GitHub), which is able to test latency over any AMQP 1.0 server, by relying on the AMQP protocol and by encapsulating a lightweight application layer protocol (called “LaMP”) directly inside AMQP.

This lightweight protocol supports any arbitrary additional payload, allowing us to test with different AMQP message sizes and to focus on the sizes equal or very similar to the ones of actual CAM and DENM messages.

The measurements have also been performed by trying to isolate the different latency contributions, understanding how much the broker processing time is affecting the overall end-of-end delay between a message producer (e.g. for Vehicle Sensor and State Sharing, a roadside sensor) and a message consumer (e.g. for Vehicle Sensor and State Sharing, a vehicle).

The testbed laboratory implementation is depicted in Figure 58.
The testbed is using the FBK LightEdge MEC platform, complying with the latest ETSI standards and which has been integrated in the CNIT-TIM joint laboratory in collaboration with FBK, in the context of 5G-CARMEN.

FBK LightEdge is an open source MEC platform (available at https://lightedge.io/), following the Bump In The Wire (BITW) architecture, which places the MEC host between the RAN and the EPC of a 4G or 5G system.

In order to provide services to the UEs, and let them consume applications on the MEC (as the AMQP broker), LightEdge relies on Kubernetes and containerized applications. Thus, to integrate an AMQP server, CNIT prepared an open source AMQP 1.0 broker container, which has been made available on a Docker Hub repository (francescoraves483/activemq_5-15-11_alpine), and which has been successfully tested and integrated as a LightEdge MEC service. Moreover, as Kubernetes is involved, a dedicated device has been used as a master node, other than the device actually running the vEPC and the MEC platform itself (including the User Plane Function - UPF -, in charge, among its packet routing and forwarding roles, to steer the traffic towards the MEC platform). This allowed CNIT to keep the Kubernetes management logic separated from the nodes running the MEC functionalities.

The RAN built in the CNIT facilities is based on the srsLTE open source cellular network implementation, containing a full 4G stack. A previous version of the testbed was relying on another well-known LTE implementation, namely Open Air Interface (OAI) [41], which has been dropped in favor of srsLTE as the latter was performing better with the selected RF devices (Ettus Research B210 USRP boards) and when integrated with LightEdge.

Although an LTE network is established, due to hardware and software availability, between the UE and the eNB (provided by LightEdge as a containerized version of the srsLTE eNB software), all the components are compliant, as mentioned earlier, with the ETSI MEC standard, thus being ready to be ported to a full 5G architecture. As vEPC, a containerized version of Open5GS [42] has been used.

Focusing on the measured end-to-end delay (from a producer, to the broker, to a consumer), the most relevant results are described below.

The first set of measurements involved the evaluation of the average latency between a LaTe client acting as a producer and another LaTe client acting as a consumer.
Every test (i.e. each point in the plot in Figure 2) has been performed by sending 1200 packets for each analyzed scenario and for each LaMP protocol payload size (taking into account that the actual size of the PDU encapsulated inside the AMQP message is equal to the LaMP payload size, plus 24 B of LaMP header). The periodicity between packets has also been varied between the different scenarios.

The analyzed setups are resumed below:

1. “LTE connectivity with 50 PRB”: test measuring the end-to-end RTT between producer and consumer, with both run on the device acting as UE (i.e. the radio network is traversed twice, as in an actual use case). 50 PRB were set as CNIT found it to be the best tradeoff between stability and performance, as far as the available hardware is concerned. The ActiveMQ broker has been deployed inside LightEdge as a MEC service.

2. “Loopback with AMQP inside K8S container”: test measuring the end-to-end RTT between producer and consumer, with both run on the MEC/UPF device (i.e. excluding the radio network contribution). The AMQP broker has been started inside a Kubernetes container, as part of the LightEdge platform, on a different device in the cluster than the one running the clients (with a Gigabit Ethernet connection and a single switch in between).

3. “Loopback”: pure loopback test with the aim of measuring the impact of the AMQP broker processing time on the total measured RTT. The producer and consumer have been started on the MEC/UPF device, together with a non-containerized version of ActiveMQ (bound to loopback).

The results are depicted in Figure 59.

![Figure 59. Average end-to-end RTT measurements of an AMQP 1.0 broker on the LightEdge platform](image)

The first evident result is the average RTT being always under 50 ms for all the analyzed payload sizes (even much greater than the size of a CAM or DENM), considering an AMQP broker on a MEC platform and, especially, the cellular network implementation (via the USRP B210 boards) which is available in the CNIT-TIM joint laboratory.

In general, it is important to highlight that the results involving the radio part of the network may be highly dependant on the actual network implementation, and, in case open source stacks are used, also on the installed Software Defined Radio software (i.e., srsLTE, in our case).

Nevertheless, from a discussion between CNIT and the MNOs, it was possible to highlight how the obtained results are in line with what could be observed on a real production network, in which, with the adoption of the 5G technologies for the RAN, the average RTT is expected to be noticeably reduced.

The obtained results also show how the key contribution to the total RTT is the one coming from the cellular network, which is always predominant over any delay caused by the broker itself. As a matter of fact, the
loopback tests highlighted a very low average processing contribution due to the broker itself, at most around 1 ms.

Moreover, when placing the broker inside a Kubernetes container and testing inside the LightEdge cluster, all the measured average values proved to be less than 2.5 ms.

Looking at these results, the usage of an AMQP 1.0 server as a message dispatching and efficient range extension tool seems to be the right choice, considering the tight latency requirements of vehicular applications, requiring the server processing time to be as much reduced as possible.

The last remark which can be inferred from the plot in Figure 59 is the decreased measured RTT when a high periodicity is used, starting from around 500 ms. This is, in any case, caused by the radio network itself, and it is not due to the AMQP broker, which proves to be unaffected by the frequency at which it receives and sends new data.

The second set of measurements, instead, involved the evaluation of the maximum RTT during each test, in which 1200 packets were sent from a producer to the broker, and then back to a consumer client. The analyzed scenarios are the same as the ones presented earlier for the average RTT measurements.

The results are depicted in Figure 60.

![Figure 60. Maximum end-to-end RTT measurements of an AMQP 1.0 broker on the LightEdge platform](image)

Before describing the most important results, it should be noted that three outliers were removed from the plot. These points were due to packets that had a much higher latency when going from the producer to the consumer; this situation occurred, however, in three tests only and due to a single packet over 1200 on each of the three tests:

- 750 B - 100 ms - LTE 50 PRB = 270.801 ms (only once over 1200 packets)
- 1000 B - 100 ms - LTE 50 PRB = 262.893 ms (only once over 1200 packets)
- 2000 B - 100 ms - LTE 50 PRB = 142.599 ms (only once over 1200 packets)

Even though, as stated earlier, the full end-to-end RTT, comprising the radio part of the network, is highly dependent on the adopted architecture and implementation, the results reveal how the maximum latency for a packet size similar to the one of CAMs and DENMs (< 300 B) is almost always lower than 50 ms (only one test reported a maximum latency of 52.62 ms).

This, together with the improvement expected when a 5G radio network (either Standalone or Non-Standalone) is deployed, shows how the solution of adopting an AMQP server on a MEC platform can be suitable for all the use cases requiring a message broker for message dissemination.
As a final remark, also the maximum contribution due to the AMQP broker itself is relatively low, being it always less than 10 ms (one outlier only was noticed, at 15.713 ms and when sending packets at a high periodicity).

4.2.3 UPV Laboratory

4.2.3.1 3GPP Rel-16 Multi-RAT V2X

Rel-16 extends the 3GPP 5G specifications with new service functionalities that are useful for the cooperative, connected and automated cross-border mobility aspects studied in 5G-CARMEN. In TS 22.186 [1] Vehicle QoS Support service requirements are placed on the 5GS in its entirety. The goal is a better management of the traffic from V2X services over the Uu interface. This paves the way for introducing solutions with multiple technology interfaces (multi-RAT) addressing one of the KPIs: reliability. In Rel-16, multi-RAT selection is limited, or only concerned, with the sidelink interface, i.e. it must not be confused with “interface selection”, which targets both Uu and sidelink. Note that the coexistence aspects stated by Rel-16 make possible the simultaneous use of multiple 3GPP RATs for direct sidelink transmissions—both NR, and E-UTRA based—but there is no mutual interoperation of NR and LTE sidelink with each other, as of today.

![Diagram showing multi-RAT V2X](image)

**Figure 61. Example of joint Cooperative Manoeuvring and Back-Situation Awareness involving multi-RAT V2X.**

As an example, Figure 61 shows a cross-border scenario with MR-DC, and multi-RAT in place. Here, Cooperative Manoeuvring procedures are expected to begin among road vehicles 2 km ahead (some of them driving on the opposite side of the transnational border) within 1 minute of the reception of a Back-Situation Awareness message concerning the arrival of an emergency vehicle. Assuming that multiple technology interfaces may be potentially involved, NR Uu, NR PC5, LTE Uu, and LTE PC5, the Cooperative Manoeuvring action requires that several vehicles attached to diverse networks would be able to determine, in advance, in a fast way, and at a certain point in time, whether they are in risk of reselecting or switching to another network technology. Besides, unforeseen circumstances, like transient radio coverage fluctuations, etc. reasonably worsen the complexity of predicting in a timeline the likely future onset of such network events. Three possible, coexisting, solutions are shown in Figure 61: a) a dual radio interface approach where vehicles, for example, can use NR PC5 in addition to the NR Uu interface communications to achieve robustness through redundancy (i.e. simultaneous transmissions via PC5 and Uu interface); b) multi-RAT extension of this redundant approach to include LTE V2X sidelink communications too; c) cross-RAT, i.e. coexisting LTE and 5G sidelink. In these
scenarios, it is essential to assess the reliability of the redundant interfaces. Managing this seems also natural because there are potential mechanisms (for example marking the packets as redundant via enhancements in the protocol stack) that allow discarding a redundant packet that no longer serves its purpose.

In addition, when managing such multi-RAT V2X networks, trustworthiness on the available network interfaces impacts on the communication problem. These scenarios imply cooperating with vehicles that can disappear from the local dynamic map of vehicles on the move at any given moment; therefore, considerations must be made concerning how to manage the collaboration with vehicles that disappear from the “local map” at any moment. UPV anticipates the existence of “robust” road areas that will ensure automated driving, for example, where the MEC will be serving the vehicles through the Uu interface uninterruptedly, assisted by a dependable PC5 interface, assuring an up-to-date map of neighbouring vehicles; but also “degraded” areas will exist, where the quality of the redundant communication channels will drop and may trigger lowering a degree of manoeuvring assistance, losing any assistance at all, resorting to on-board sensors, or to manual driving.

4.2.3.2 Cross-RAT in 3GPP Specifications

When operating outside of network coverage, NR V2X sidelink and LTE V2X sidelink connectivity and specific implementation options are not an issue. As a result, this approach allows such UEs to perform dual V2X sidelink communications according to TS 23.285 [3] (using E-UTRA technology) and/or NR sidelink communications according to TS 23.287 [2] with one or more nearby UEs, even when those other UEs may be implementing only one of the sidelink RATs, and independently from the fact of whether those UEs are attached to a LTE or NR cellular network (mainly because those communications are not traversing any network node).

However, if the network needs to control LTE or NR V2X sidelink, then additional functionalities are required for the control of the other sidelink RAT (i.e. cross-RAT⁸). From the sidelink viewpoint, cross-RAT opens the door for an LTE network to participate in the control of the NR sidelink (in fact, this could be actually a prerequisite for the first NR V2X rollouts since LTE Uu coverage is currently wider than NR Uu coverage). For instance, NR mode 1⁹—used for resource allocation by gNBs—may be controlled by the LTE Uu interface if a configured grant Type 1 is made available through LTE RRC signalling. NR mode 2—for UE autonomous resource selection—allows the UE to sense the resources not used by other, higher-priority UE transmissions within a pre-configured resource pool, and to select for particular use the amount of resources that the UE deems necessary. In the LTE Uu RRC the semi-static pre-configuration of the resource pool and other aspects may be provided, which in turn, will be considered by the NR V2X RAT when autonomously choosing the resources for its sidelink transmissions.

Likewise, cross-RAT also clears the way for the control of LTE sidelink by a 5G network via DCI-based activation/deactivation. The control of resource allocation of LTE mode 3—used by eNBs for selecting radio resources—may be performed by NR Uu through the transmission of an NR DCI including the parameters required for the dynamic control of the LTE sidelink. Given enough time, the UE forwards this data to the LTE RAT, and after that, the typical LTE sidelink procedures are followed. For LTE mode 4—for UE autonomous resource selection—the semi-static pre-configuration may be made available via NR Uu RRC, which in turn, will be considered by the LTE V2X RAT when autonomously choosing the resources for its sidelink transmissions.

For the support cross-RAT V2X in Rel-16 TS 23.287 [2], the PC5 Capability for V2X information specifies that the UE is capable of V2X communication over the PC5 reference point and the specific PC5 RAT (LTE and/or NR PC5) in the Registration Request message; additionally, V2X related information may be specified per PC5 RAT. Additionally, the concept of cross-RAT PC5 control

⁸ Cross-RAT is desirable when the frequency spacing between the two RATs is adequate. This may be likely the case as with interface coexistence, where UE RF requirements for NR V2X interfaces are based on the concurrence of the Uu in licensed band and LTE sidelink in ITS band.

⁹ It should be however remarked that current industry trends allow UE autonomous resource selection.
authorization information is introduced, which defines whether LTE Uu controls LTE PC5 and/or NR PC5 from the cellular network, and whether NR Uu controls LTE PC5 and/or NR PC5 from the cellular network. However, note that as of Rel-16, there is no associated explicit IE in the 5GS. Instead, this information should be inferred indirectly from the presence of either one (or both) of the optional V2X Services Authorized IE (renamed to LTE V2X Services Authorized in Rel-16 specifications for S1 and X2) and NR V2X Services Authorized IE respectively.

4.2.3.3 MR-DC architectures for multi-RAT V2X

Some aspects of designing multi-RAT 5G V2X architectures are still an open issue from the state of the art viewpoint, being the intelligent selection among the available communication options one of the most important, pressing and challenging problems still to be solved. A particularly remarkable example of proposal that focuses on the reliability versus latency trade-off is [10], where URLLC is implemented via a novel network slicing solution that covers service and function slicing as well as resource slicing for vehicular networks; however as it is a proposal with V2I in mind (it only addresses RSUs) and NR V2X is not considered, its applicability to MR-DC is not straightforward at best. The topic of multi-RAT schemes motivated by reliability has been met also with some proposals. For example, in [11] a so-called multi-RAT scheme is proposed where the data packet travels through LTE Uu and PC5 to experience diversity gains; however, this is really a dual/multi interface approach that does not brings 5G NR V2X into the equation. Still missing from the literature is a multi-RAT V2X use case-aware approach for improved reliability that has in-built consideration of the performance characteristics motivated by the use of 3GPP MR-DC. It may also be reasoned that being aware (and incorporating into our studies) the underlying 3GPP radio access support for DC UEs could be useful to assure reliability.

When building on the multi-connectivity operation options using E-UTRA and NR radio access technologies proposed by 3GPP TS 37.340 [9], the following MR-DC multi-RAT scenarios may be envisioned, which encompass both LTE V2X sidelink communications and NR sidelink communications (referred to as “sidelink comm.”) (Figure 62):

i) MR-DC: UE configured in NE-DC, sidelink comm. controlled/configured by Uu
ii) MR-DC: UE configured in NGEN-DC, sidelink comm. controlled/configured by Uu
iii) MR-DC: UE configured in EN-DC, sidelink comm. controlled/configured by Uu

![Figure 62. Multi-RAT V2X with MR-DC: NE-DC (left), NGEN-DC (center), or EN-DC (right).](image)
**RRC Reconfiguration.** Similarly, the field `sl-ConfigDedicatedEUTRA-Info` contains the E-UTRA RRC Connection Reconfiguration message inside.

Note that while UE-related RRC messages are transferred over the Uu interface, as of Rel-16, only the MN is allowed to control and configure the UEs performing NR sidelink communications and or LTE V2X sidelink communications [9]. This implies that the SN is not allowed to use (initiate) an E-UTRA RRC Connection Reconfiguration procedure or an NR RRC Reconfiguration with sidelink fields for LTE sidelink or NR sidelink. This restriction does not apply to the Sidelink RRC Reconfiguration procedure, which is initiated by a UE with the purpose of modifying a PC5-RRC connection, (e.g. setting up, changing or freeing to sidelink DRBs, to configure NR sidelink measurement and reporting, to configure sidelink CSI reference signal resources and CSI reporting latency bound); however, it is understood that the MN should be the entity in charge of receiving this control signalling. This constraint reduces the three above mentioned scenarios to the three following ones, respectively (Figure 63):

i) Standalone gNB connected to 5GC: sidelink comm. controlled/configured by the MN (gNB)

ii) Standalone ng-eNB connected to 5GC: sidelink comm. controlled/configured by n-eNB (MN)

iii) Standalone eNB connected to EPC: sidelink comm. controlled/configured by eNB (MN)

![Multi-RAT V2X Standalone](image)

**Figure 63. Multi-RAT V2X Standalone: UE configured in either NE-DC (left), NGEN-DC (center), or EN-DC (right).**

As shown, even though only standalone approaches to sidelink are currently supported by the standard as of Rel-16, non-standalone options are a potential possibility that might be admitted in future releases of the 3GPP specifications. Moreover, 3GPP does not support any forms of joint MR-DC + LTE/NR PC5 in Rel-16, so the LTE Uu + NR Uu is left out of the scope.

**4.2.3.4 Regional multi-RAT management for increased reliability**

All factored, the possible RATs combinations considered in the present MR-DC approach are:

- LTE Uu only

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10 This comes from a RAN2 agreement made in RAN2#106, which stated that Rel-16 NR-V2X does not consider the scenario where the sidelink is controlled/configured by the SN.

11 NR-DC allows a UE connected to two gNBs (acting as MN and SN). This option would require to implement two NR sidelink radio chains in addition to the LTE sidelink radio chain, so it is left out of the scope of this study.
- NR Uu only
- LTE Uu + LTE sidelink
- LTE Uu + NR sidelink (controlled by LTE network)
- LTE Uu + LTE sidelink + NR sidelink (controlled by LTE network)
- NR Uu + NR sidelink
- NR Uu + LTE sidelink (controlled by 5G network)
- NR Uu + LTE sidelink (controlled by 5G network) + NR sidelink

The possible combinations consider the simultaneous use of the communications RATs to provide redundancy, either transmitting the same piece of information, or implementing a scheme for incremental redundancy, aiming at increasing the reliability of the communication and increased robustness against service interruptions.

The proposed regional multi-RAT MR-DC management pursues automatically diversifying multi-RAT selection decisions associated to pre-defined geographical regions. This approach may be justified given that, typically, the reliability experienced by vehicular UEs is spatially correlated. Furthermore, this strategy may be the best one when the data available from specific UEs is scarce but their recent geographical position is known, and it may also be deduced from a priori knowledge about the successive geographical triggering of MR-DC procedures.

For example, Figure 64, shows a UE (green vehicle) along a road covered by a 5G non-standalone deployment. As shown, the UE is expected to experience several MR-DC procedures as it enters the region with 5G coverage, crosses the boundaries between MNs, between SNs and leaves the region with 5G non-standalone coverage. A possible approach to clarify multi-RAT selection decisions is to segment the area into geographical zones according to the overall reliability and range related KPIs experienced for each of the RATs considered, and associate each zone with a specific multi-RAT decision potentially satisfying the QoS requirements (such as the shown in Figure 65 for the previous scenario). For example, we consider that, in case that a RAT has a good reliability, it could be of use for long-range sensitive use cases (e.g. the Cooperative Manoeuvring) where remote alerts and reaching vehicles far ways in a reliable way is a must. According to this rationale, when the Uu interface is always recommended (LTE or NR, depending on the MR-DC procedure), exclusively when “good”, but complemented by LTE sidelink and NR sidelink, when the Uu interface QoS is “average” or “poor”. That is, when the QoS in a certain geographical zone is optimistic enough then reliability sensible service may be exclusively use the Uu interface, so as to free resources in the sidelink for load balancing approaches. Furthermore, the QoS conditions of multi-RAT may be the basis for recommending, e.g. different automation levels according to the expected performance of the 5G communication system for the support of autonomous driving in the different geographical zones.

Figure 64. Multi-RAT vehicle traveling along a road requiring successive MR-DC procedures
When this approach is used, provided that the network is able to track the UE location, it can detect when a UE is crossing the border of the current QoS zone, and then notify a change of recommended multi-RAT management with active initiative, (rather than a reactive one), associating multi-RAT decisions to the QoS that a UE will experience in a geographical area before the UE enters that area, facilitating a smooth transition between automation levels (and warning the driver sufficiently in advance).

The Multi-RAT Manager (MRM) is the proposed multi-RAT management entity for 5G V2X, as shown in Figure 66 co-located at the V2X Applications Server, operating as an AF, and using the AF-based service parameter provisioning for V2X communications to deliver the recommendations to the V2X Application at the UE via V1.

The MRM implements the procedures to allow for multi-RAT management decisions based on a variety of inputs, although the work by UPV simulations is especially focused on geographical segmentation features expected by the use MR-DC. There are five sub-processes, all with their associated signalling:

**Figure 65. Example of geographical division of a motorway scenario according to the perceived reliability of the multi-RAT vehicular communications interfaces.**

**Figure 66. Location of the MRM in the 5GS.**
1. **Providing information to the MRM:** The MRM receives multiple up-to-date information from NG-RAN, SMF, and AMF via a new information element called `InformationForMultiRATManagement`. The MRM is informed about the QoS performance of each RAT via periodical update of this IE by the NG-RAN.

2. **MRM recommendation generation:** With the inputs above, the MRM is in charge of deciding the recommendation for multi-RAT usage. The algorithmic behind this may be focused in the special category of issues to be solved (e.g. the influence of MR-DC on the definition of the geographical areas where the QoS perceived is deemed as homogeneous like in the simulations carried out in this effort); but, in general, would consist of assess potential configurations against previously-trained models or occurrence of past behaviours. Examples of decisions by the MRM could conclude that a new area requires further segmentation or validating that the current poor conditions in all the RATs in a zone require downgrading the automation level.

3. **MRM provides recommendations:** Once the MRM finds out conclusions, e.g. per-region, the decision is sent to the network entity in charge of managing V2X communications (in this approach, the AF acts as this using the C-plane, and the MRM is collocated at the AF), where they are stored in a new MO `MultiRATRecommendation`.

4. **AMF provides UE location predictions to the AF:** When providing per-region multi-RAT management recommendations, the network must be aware of the position of the UE, therefore it is envisioned that the AMF will prompt the AF to update the recommendations because of predicted changes of location.

5. **AF provides recommendations to UE:** The AF informs the UE about the multi-RAT recommendation, the MO exchanged by UE and AF may be the `MultiRATRecommendation` and e.g. trigger changes in the automation level of the self-driving car.

Regarding the multiple up-to-date information, `InformationForMultiRATManagement` could include:

- Mobility-related parameters: speed, direction, UE location.
- Geolocation of the MR-DC procedures being used.
- Status reports about the network resource pools in the LTE and NR sidelink.
- Radio quality measurements: timing advance, channel baseband power.
- Scheduler-related performance indicators, RSSI, CBR, PRR, etc.

A per-region `MultiRATRecommendation` MO has the following structure, which summarizes the recommendation for the V2X application:

- Geographical zone ID
- Geographical polygon definition of the zone.
- Scope: either applies to all, only some services (e.g. cooperative manoeuvring), a specific session or a specific UE.
- Multi-RAT recommendation: either LTE Uu, NR Uu, LTE sidelink, NR sidelink

### 4.2.3.5 Validation

We carried out an initial evaluation of the improvement in reliability when introducing the multi-RAT management proposal. This validation tries to show that a MR-DC aware approach and the definition of recommendation zones benefits the Cooperative Manoeuvring and Back-Situation Awareness in a border corridor. The test environment considered in our simulations corresponds to the Brennero Pass, whose road topology has been generated from Open Street Maps. The selected reference environment corresponds to a 4.5 km-long portion of the A22 highway located at the border between Italy and Austria along with its secondary roads. The preliminary (simplified) approach (via MATLAB simulations)
reproduces the synthetic, proof-of-concept scenario in Figure 64, on the Brennero Pass (Figure 67), in order to elicit the successive MR-DC procedures shown.

**Figure 67. Proof-of-concept deployment scenario (4G brown, 5G blue)**

Regarding the simplified approach, in Figure 67, eNB1, eNB2, and eNB3 are placed in the locations of already existing base stations. Accordingly, eNB5, en-gNB1, en-gNB2, en-gNB3 (inside the tunnel) and en-gNB4 have been heuristically added to match Figure 64. Technical details regarding the road traffic (real traffic flow measurements by Autostrada del Brennero from 2019) and mobility assumptions (i.e. uncongested\(^\text{12}\) average speed of 60-80 km/h, maximum speed of 120km/h) are taken from Section 3.3.3 of 5G-CARMEN Deliverable 6.2. To facilitate the drawing of conclusions, the eNBs are configured with 20 MHz bandwidth centred at 2 GHz, while the channel of the en-gNBs is at 4.5 GHz with 100 MHz bandwidth. The sidelink bandwidth is 10 MHz. The transmit power of base stations (eNB and gNB) is 40 dBm and the antenna height is 25 m, and the antenna gain 17 dB. The UE transmit power is 20 dBm, with an omnidirectional antenna of height 1.6 m, with 2 antennas (cellular and sidelink) full-duplex for transmission and reception. Both the V2V and V2N channels are modelled in the simulation. For the V2V, the sidelink channel model follows 3GPP TR 37.885\cite{18}, simplifying the random distribution of the vehicle blockage loses, that are in our case, fixed to 5 dB and without fast fading. For the V2N, propagation loses are modelled according to the updated guidelines in 3GPP TR 38,901 Rel-16 for a Rural Macro (RMa) model\cite{13}. This model is useful for continuous wide area up to 7 GHz (included both eNBs and en-gNBs), supporting high speed vehicles at least 35 m apart from the base station with macro sites and 3 sectors per site. Although the rural deployment scenario focuses on larger and continuous coverage it includes an NLOS version that is useful to model the obstructions by the terrain. Shadowing is modelled according to\cite{16} with a log-normal distribution with a standard deviation of 7.8 dB as indicated in\cite{13}, and a decorrelation distance of 50 m. The fast fading model is a tapped delay line model according to the Extended Vehicular A power delay profile in\cite{17}.

The en-gNBs in Figure 69, have been placed explicitly outside co-located positions; this unrealistic, for economic reasons, but the goal of this study is prompting MR-DC handover-related procedures. Regarding the mobility management in MR-DC, the simplified approach puts its focus specifically on the standard events that are used by the UEs as described in 3GPP TS 36.331\cite{15}. An example is reporting the presence of other technologies, via events B1 and A2 to assist the “eNB to MN change” and “MN to eNB change” MR-DC procedures. In our scenario, we assume that UEs are always connected to the higher-powered eNB, which acts as a MNs when in MR-DC. The eNBs configure in the UEs the event B1 and a list of en-gNBs to measure. In turn, event B1 is used by UEs to report the signal power, strength and/or quality of neighbouring en-gNBs (i.e. RSRP, RSRQ, and RSSI values), \(^\text{12}\) The vehicle average speed is lowered to 50 km/h to account for a slightly congested situation where Cooperative Manoeuvring and Back-Situation Awareness could be of more critical importance.
when their value exceeds a certain threshold $t_{\text{in}}$. When the report is received, if the vehicular UE has no MR-DC connection, the eNB starts the eNB to MN change procedure to establish a MR-DC connection between the UE and the current eNB (which becomes a MN) and starting a SN addition procedure for the selected en-gNB (the SN). Similarly, event A2 reports when the indicator goes below a configured value $t_{\text{out}}$. In this case the MN to eNB change procedure is triggered and the MN disconnects the UE from the SN it initializes the MR-DC procedure to a fall-back single-connectivity connection between the UE and a eNB. The typical events are also configured to decide other procedures such as SN change, inter-MN handover without SN change, and inter-MN handover with SN change according to [15]. In our case, in the simplified approach all the events are configured for the RSRP, as this is usually only available configuration allowed in the eNBs of real vendors. Values for $t_{\text{in}}, t_{\text{out}}$ etc. have been selected heuristically (-65 to -55 dBW) under the reasonable premise of maximizing the time in which 5G clients are connected to MR-DC. and the Another assumption is that a there is a delay of less than 100 ms for the handover procedure that allows UEs to connect to the best MN in terms of received power, and to the best SN in case the UE makes use of MR-DC. Note however, that we are assuming that the transition from single connectivity to MR-DC is far not perfect, and we assume that its configuration may require up to 500 ms. MR-DC UEs are assumed to consume resources of only the associated SN. This assumption stems from the work in [14], that confirms that MR-DC when configured with split bearers has similar throughput gains to MR-DC configured with data bearers in the SN—this is reasonable, because of the potential capacity offered by 5G in comparison to 4G. As a result, for user plane purposes the vehicular UEs only have a serving node, either a MN in single connectivity or a SN in MR-DC.

Regarding the network traffic, we use a single type of traffic which emulates a periodic transmission of CAMs according to the periodic traffic posited in [18]. An inter-packet arrival time of 100 ms, packet size fixed to low load configuration of 300 bytes [18]. The CAM messages are relevant to all the vehicles within the relevance distance of 2,000 m or coverage range of the initiator. For the sidelink interface, we emulate a pool of RBs divided in five sub-channels, each sub-channel requiring 2 control RBs. It is assumed that each CAM only requires one sub-channel and one sub-frame for its transmission. We emulate the V2X sidelink resource manager behaviour as providing a semi-persistent allocation of resources, in which one sub-channel is allocated with a given periodicity, (without simulating the details). We assume that a network-controlled resource allocation is used; and the central controller knows the position of all the vehicles. The controller maximizes the distance among the vehicles that use the same resources. The resource allocation decision is renewed when the position of the vehicles changes 100 m, which slightly trades off the minimization of allocation decisions for better position accuracy. We assume that the resource manager aims at maximizing the capacity of the system given a maximum E2E latency of 100 ms (again, emulated, because no system-level simulations are performed). The base station uses a unicast single-antenna transmission with maximum ratio combining at the receiver because of its better robustness for vehicular communications. Although latency is not explicitly deal with, we assume that the scheduler tries to prioritize those users with best channel quality in each sub-frame to reduce the transmission latency.

In our simulation the following example is considered: the NG-RAN is sending to the MRM the following useful information: a map with the measured RSRPs delimiting the cell boundaries that trigger different MR-DC procedures, in addition the following reliability-related parameters: the spatial distribution of the average packet reception ratio for the CAMs transmitted by the users with LTE and/or NR sidelink, an average packet reception ratio against distance performance curve for sidelink transmission, and an indication of the coverage range considered for the packet reception ratio (2,000 m). The SMF in turn is sending to the MRM an indication of the minimum desired packet reception ratio (90% in our critical scenario). In addition, the AMF is updating the UE position very often to the MRM so as to achieve a good tracking accuracy.

Using the inputs from the NG-RAN, the MRM may detect which regions have problematic support for the packet reception ratio objective, using only one of the available interfaces, and request the use of multi-RAT. Those regions with insufficient reliability (<99.9%) may elicit an approach by the MRM: recommending in advance to all the vehicle UEs anticipated to arrive to those locations the use of multi-RAT for redundancy purposes, e.g. packet duplication of all transmitted CAMs, transmitting each packet via additional interfaces to push the reliability of the communication above the target. Lastly,
the vehicles receive multi-RAT management decisions whenever they are about to enter or leave a region within a specific multi-RAT category.

In fact, since the CAM must arrive to multiple users, potentially, each CAM, may elicit the generation of an additional sidelink transmission, as well as one uplink V2N transmission followed by many downlink transmissions within the span of the 2,000 m relevance area. (This may also be approached from the viewpoint of selecting only the best interface under anticipated poor radio conditions). Note also that in our simplified simulation, because of the relatively simple nature of CAMs, the MRM only pursues per-region multi-RAT management.

Preliminary improvements on the spatial distribution of the average packet reception ratio for the range 50 to 200 meters have been obtained (Figure 68), that reveal ascertain in advance that the duplication of packet is necessary in certain problematic regions enhances the reliability, thanks to the smarter management of the available paths.

![Figure 68. Packet reception ratio vs distance](image)

Finally, the full (but non-system level) simulation is a currently ongoing task whose results will be included in Deliverable 3.4. As an ongoing work, it is projected a full simulation of the realistic version of the Brennero Pass (Figure 69) matching the deployment of base stations as of Spring 2021, and using both UPV’s Unity pathloss and capacity simulator integration on UPV’s Digital Twin for V2X CCAM work-in-progress. The simulator (Figure 70) implements in a detailed model, the geographical aspects of the Brennero Pass environment. Apart from using SUMO for fine-tuning, it makes use of the Unity Asset *Urban Traffic System 2020* (UTS Pro) for the on-the-fly generation inside the visualization platform of vehicle UEs with the traffic densities required.
Figure 69. Current, real deployment of base Stations (Green sectors).

Figure 70. UPV Simulation and visualization platform in Unity.
5 Positioning Solutions

5.1 Overview

Advanced positioning solutions are key for ADAS level 3+ driving modes. The key requirement is to bring the position accuracy reliably down to a lane-level accuracy, hence it needs to be in the range of centimeters to a few decimeters at maximum. Positioning solutions based on pure Global Navigation Satellite Systems (GNSS), such as GPS, Galileo etc. can currently not achieve such levels of accuracy, although GNSS services and their quality KPIs evolve with new generations of GNSS satellites being launched to gradually replace the legacy satellites currently operating in their respective orbits. In 5G-CARMEN, we look specifically into two approaches to complement and improve the dependability on positioning solutions, i.e. RTK-based positioning and cellular-based positioning.

5.2 RTK-based positioning

The precise positioning service implemented for usage on the 5G-CARMEN corridor and beyond is based on an RTK-PPP approach, where Real-Time Kinematic is combined with a Precise Point Positioning approach.

While in the RTK method corrections are provided for a specific location, the PPP-RTK method broadcasts a correction model to a larger area with slightly lower accuracy. This correction model uses a message format called SSR (Space State Representation) to transmit the GNSS corrections.

PPP-RTK, sometimes also being referred to as SSR, represents the latest generation of GNSS correction services. It combines near-RTK accuracy and quick initialization times with the broadcast approach of PPP. PPP-RTK uses a reference network, with stations in a defined grid across Europe and other geographies (in Europe: co-located with a selection of cellular mobile network sites) and thus known precise locations, for which GNSS data is being collected and both satellite and atmospheric correction models are being computed. Atmospheric corrections are regional, and so a denser reference network is needed than for typical PPP. These corrections are continuously sent to subscribers in the respective area via the mobile network. As the corrections apply to a defined area and are not individual per user/subscriber, they could also be broadcasted in principle. As this is defined only for 3GPP Rel. 16 and beyond, currently individual point-to-point communication between the subscriber and the correction server is being used. Subscribed receivers use the broadcasted correction model to deduce their location-specific corrections for their individual GNSS position, resulting in sub-decimeter accuracy.

The precise positioning service is provided by SwiftNav in partnership with Deutsche Telekom.

5.3 Cellular-based positioning

Given the current dominance of LTE networks besides legacy 2G networks and their almost ubiquitous coverage, cellular-based positioning solutions in 4G had been investigated parallel to the 5G-CARMEN project. Even with multi-lateration approaches, the achievable accuracy is at best in the range of 10+ meters, on average about 30 meters in 4G. In such a dimension, cellular-based positioning could only be used for enhancing position integrity, e.g. against GNSS spoofing, but not for improving GNSS or complementing it in mobility scenarios where no GNSS reception is possible at all (e.g. tunnels).

As 5G offers unprecedented localization performance, network-based positioning is becoming more and more appealing for service providers. Indeed, such players can avoid relying on external parties to retrieve users’ locations and gain additional revenues via ad-hoc services, e.g. targeted advertisement. Moreover, V2X and autonomous driving call for a better accuracy than the one reached by Global Navigation Satellite Systems (GNSSs), which can be improved by leveraging on cellular-network radio link information.

In this regard, we introduce the concept of pseudo-trilateration [20], which combines the canonical approach known as multilateration with the novel capabilities offered by 5G-NR. Multilateration is a positioning method that determines the unknown location of a UE based on range measurements to known anchor points and is the foundation of Observed Time Difference of Arrival (OTDoA), defined by 3GPP in [21]. In particular, OTDoA
performs time-based measurements by means of the Positioning Reference Signal (PRS) from a number of base stations within the UE coverage in order for the UE to infer its own position and propagate it back to the network.

The core idea of pseudo-trilateration is to use a single anchor retrieving multiple distance measurements over a time window moving through different points, namely along some anchor motion trajectory. Such measurements are properly combined to identify the set of positions covered by the target (if moving) within the considered time window. We can prove that such problem admits an ambiguous solution if and only if the anchor moves along a linear trajectory, as graphically hinted in Figure 71.

Hence, to avoid ambiguity, the anchor trajectory must change its direction within a finite time. As this may cause the mobile anchor to get far away from the target UE reducing the receive Signal-to-Noise-Ratio (SNR) and so the accuracy, we rely on a close anchor trajectory (e.g., a circumference).

We can formalize the pseudo-trilateration technique as, e.g., an optimization problem, wherein we aim at minimizing the overall UE trajectory length given that every trajectory point has a specific distance from the moving anchor, i.e. equal to the respective range measurement. Unfortunately, this formulation makes it NP-Hard by reduction to the well-known subset-sum problem, thus not solvable in polynomial time [22]. Moreover, as the optimization-based approach requires finely tuning the initial estimated position in order to define the first path length, its initial configuration greatly affects the overall localization accuracy.

Therefore, we drop the objective of minimizing the overall trajectory length and propose an AI-based localization system that applies the pseudo-trilateration method and learns the UE motion behaviors to return its positions with high accuracy. Our implementation leverages the framework of a regression problem solved by a Convolutional Neural Network (CNN) fed with single-channel images. Indeed, such images are time-based range measurements matrices taken by the moving anchor at subsequent spots along its trajectory. For our experimental evaluation, we make use of a base station moving along a circular trajectory of 50 m radius at a linear speed of 3 m/s, equipped with a Software Defined Radio (SDR) and a mini PC running srsLTE. Specifically, we use the following hardware equipment: National Instruments USRP B210, Intel NUC7i7DNBE, 2 x Mini-Circuits ZX60-V63+ high-gain amplifiers, 2 x Mini-Circuits ZX60-33LNR-S+ low-noise amplifiers, 2 x 10dBi-gain antennas and a Samsung Galaxy Tab S2 as UE.

In Figure 72, we show the performance of our CNN design against the solution obtained via optimization theory using a random initial configuration as well as the true localization value (only for the first point of the solution vector). In addition, we compare the optimization-based solution when noisy or ideal channel conditions are considered. As shown, the CNN outperforms the optimization problem in both channel conditions by a factor 2 and 6, respectively.
Lastly, our results in Figure 73 show that the CNN-based solution is able to achieve an average localization error of 54 meters with a static UE. Such metric would improve dramatically (up to a tenfold improvement) by using a 5G-NR capable SDR due to the tenfold bandwidth enlargement.

We would like to point out that this solution can be straightforwardly applied to any moving anchor with little-to-no modifications. Specifically, in the context of vehicular networks, any vehicle can be equipped with a 5G-NR base station performing range measurements from the UEs. In a more practical view, public transportation vehicles with fixed trajectories (tracked by on-board GNSS receivers) can perform pseudo-trilateration via the above-mentioned AI approach with similar results.

5.4 On-field evaluation results for precise positioning

Test drives with BMW and CRF have demonstrated achieving sub-decimeter level accuracy under ideal conditions, where line-of-sight to the sky was mostly unobstructed, the number of GNSS satellites visible to the GNSS receiver was sufficiently high and cellular coverage was available for receiving the GNSS SSR information from the correction service.

Factors with negative impact on the accuracy have been so far:

- limited number of satellites visible e.g. in narrow valleys
- no GNSS reception e.g. in tunnels and under roofs of toll stations
– lack of mobile network coverage at borders after leaving the last cell of the previously serving network until reselecting the other network.

While the first factor can only be addressed by receiving GNSS signals from multiple GNSS such as GPS, Galileo, etc., the second factor is being mitigated using dead reckoning technologies in the vehicle. The third factor is being addressed by improved network reselection between the networks serving 5G-CARMEN, currently under implementation at the time of the submission of this document.

An additional factor of the achievable accuracy depends on the frequencies supported the GNSS satellites and the respective onboard GNSS receivers. While the legacy GPS L1/L2 combination provides sufficient accuracy for the basic position fixing, the latest GPS L1/L5 combination providing highest accuracy is not yet supported by all GPS satellites in orbit, and not yet in all GNSS receivers. (same as for Galileo and other GNSS). Hence, 5G-CARMEN will rely on the GPS L1/L2 combination and their equivalents in the other GNSS.

### 5.5 Preparatory tests evaluation of RTK-based positioning

Different automotive use cases such as automated overtake, cooperative collision avoidance, or high-density platooning demand high-accuracy positioning, high reliability, and real-time response of the location information [31]. Today, Global Navigation Satellite Systems (GNSS) relying on NRTK (Network Real Time Kinematic) and SSR (Satellite State Space Representation) remains the absolute localization technique.

GNSS is an active area of research for navigation, mapping, positioning, and many other areas that need monitoring and controlling of their location-aware services. Some applications, for instance, autonomous driving and flying, precision agriculture, weather forecasting require precise point positioning [32]. However, the position provided by the GNSS suffers from many limitations. Even though the GNSS satellites are considered as accurate “flying clocks”, they still can experience minute drifts that cause clock errors. In addition, since the satellites provide position and time while they move, their movement is predicted as they orbit the Earth, which results in a prediction error, known as orbit error. While the signal travels from satellites to the receivers on the Earth, the received signal has distortions and delays caused by the ionosphere and troposphere. This error is known as atmospheric error. Moreover, the surrounding environment of the receivers has buildings and tall structures and objects that causes the multipath effect.

All these error types cannot be corrected on the receiver since they are caused by external sources. For this reason, other GNSS technologies are used to eliminate errors and improve positioning accuracy.

The position provided by the GNSS receivers can be corrected using ground-based reference stations known as Differential GNSS (DGNSS) and Real-Time Kinematic (RTK) correction. The idea is to have a reference station which is a GNSS receiver installed at a fixed and precisely known location, which will calculate the GNSS errors and provide these errors to have the required correction.

A group of these interconnected reference receivers spread over an area is known as a reference network, as depicted in Figure 74.

![Figure 74. RTK GNSS positioning](image)
Following the automotive sector demands for precise vehicle localization with a positioning accuracy below one meter, IMEC has investigated the Real-Time Kinematic (RTK) based positioning. To determine the vehicle location coordinates with the required accuracy, GNSS techniques are investigated. Techniques known as Differential GNSS and RTK GNSS are used to have increased localization accuracy by using a network of reference stations.

For testing purposes, we have used the testbed infrastructure deployed on the existing E313 highway in Antwerp, Belgium.

Interconnected hardware including vehicle parts named onboard unit (OBU), base stations, or network sites part named roadside units (RSUs), backbone and testbed management software platform, and the optical fiber ring along the highway are all used to have the field data measurements.

GNSS devises AsteRx-m2/AsteRx-m2a are considered and used to have decimeter and centimeter position accuracy of the OBUs and RSUs. They are used:
- to obtain the positions of RSUs,
- to track the movements of OBUs, and
- to generate position correction messages from RSUs to OBUs.

Septentrio GNSS receivers deliver accurate and reliable positions to different demanding industrial applications. Inertial sensor integration of the AsteRx-i family offers a full attitude solution (heading, pitch, and roll) synchronized with accurate positioning. Their benefits include credit-card size boards with low power consumption, easy-to-integrate into any system, best-in-class RTK performance with true multi-constellation, multi-frequency GNSS technology, Advanced Interference Mitigation (AIM+) anti-jamming and anti-spoofing technology. True multi-frequency multi-constellation technology gives receivers access to every possible signal from all available GNSS satellite constellations: GPS, Galileo, GLONASS, BeiDou, QZSS, and NavIC [33].

**Figure 75. Septentrio GPS / GNSS Rover & Base Receiver AsteRx-m2**

Septentrio receiver AsteRx-m2 is placed and configured in a static base station, which is used to have an accurate determination of the RSU position. For accurate and repetitive absolute positioning, we can provide the accurate coordinates of the ARP (Antenna Reference Point) or let the receiver determine its fixed position autonomously [34].

The OBU AsteRx-m2a receiver can operate as DGPS (Differential GPS) and/or RTK (Real-Time Kinematic) moving base rover mode, while it receives the corresponding RTCM (Radio Technical Commission for Maritime Services) or CMR (Compact Measurement Record) correction messages from a static base station. The supported RTCM and CMR messages are used for position correction to achieve centimeter accuracy [35].

We have investigated two options of having RTK correction on the E313 highway. One option was the use of the Flemish Positioning Service (Flepos) operator from which we received Differential and Real-Time Kinematic correction messages (RTCM), and the second option was the use of the correction messages using AsteRx-m2 unit as a messages generator.

The FLEPOS is a service provided by Information Flanders. It offers the RTK correction signals from navigation satellites and distributes them via the internet. These correction signals make it possible to accurately determine a position anywhere in Flanders, by using the network of GNSS reference stations in the Flemish Region. The

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GNSS receivers are connected to the server and receive the correction data in real-time via the NTRIP protocol (Figure 76) [36].

**Figure 76. Example of a RTK moving-base configuration where the OBU receives RTCM corrections from the Flepos server**

On the second option, we use the AsteRx-m2 receivers to generate and output DGPS and/or RTK corrections in the RTCM formats. In this scenario, we configure and use RSUs as a static base station, which can broadcast the RTK corrections messages (Figure 77).

**Figure 77. Example of the RTK moving-base configuration where the moving base**

**Figure 78. The OBU Roof Unit with the GNSS antennas and the OBU Car Unit placed inside the vehicle**
5.5.1 PolaNt-x MF

PolaNt-x MF is a high-precision antenna for geodetic, survey, and machine control applications. This high-gain antenna incorporates low-noise amplifiers, enabling multi-frequency GNSS signal reception, and is built into a rugged and environmentally sealed housing. It provides multi-constellation tracking of GPS, Galileo, GLONASS, BeiDou, IRSN, and QZSS signals [37].

5.5.2 Communication Protocols

The protocols which are used for the system are NMEA (National Marine Electronics Association) 0183 and RTCM version 3, which are briefly described below.

5.5.3 NMEA

NMEA is a standard used in many industries and multiple applications, such as marine electronics, anemometers, IMUs, autopilots, GNSS receivers, etc. The information is sent in ASCII characters. The receiver can generate a set of approved NMEA sentences. NMEA version 2.30 and version 4.10 are supported. The benefit of the NMEA format is that it is standardized [38].

5.5.4 RTCM Version 3

This protocol is an international standard to publish GNSS data in real-time. All high-precision GNSS receivers support this protocol. It provides a binary message like the UBX protocol, and it is protected by a CRC-24Q checksum (cyclic redundancy verification) with a very low probability of undetected errors [39].

5.5.5 Measurements

The implementations on OBU and RSU, shown in Figure 78 and Figure 79 are used to analyze the accuracy of obtained data, by comparing different OBU drives and checking how accurately they can identify the lane and the position of OBU while driving on the E313 highway. For every planned transmitted/received communication packet between RSU and OBU, RTK GNSS receivers will be used to have the position of OBU and RSU and the timestamp of the tracked position.

For each state of the GNSS position (which has an error of more than 1 meter), we received the correction too, which improves the accuracy within the order submeter.

The data logging in the RSU and OBU is done using General Purpose Compute Unit (GPCU), respectively Intel Nuc 7i7DNKE (NuC) and gpsd tool. Also, a web interface is used to monitor the performance of satellites tracking and correcting messages receiving process.
5.5.6 Results

To perform the RTK GNSS correction validation, using the system explained above we have obtained real data measurements by driving on the E313 highway in Antwerp. We have performed driving on the highway on defined lanes. For this, we have performed 12 drives, from which 6 of them are traveling from point A to point B and 6 of them are coming back from point B to point C, Figure 80. These drives are shown in Figure 81 and Figure 82. These measurements were performed by driving into three different lanes and using two different configurations, one of them using Fleppos operator as RTK message generator and the second one is using RSU base station as the correction station.

In Figure 81 and Figure 82, we have shown the drives of the OBU on the highway, having the transition from latitude and longitude to x, y in meters. It can be noticed how the traffic lanes are defined. RTK GNSS 1.1, 1.2, and 1.3 are samples obtained using Flepos operator as RTK message generator, while the RTK GNSS 2.1, 2.2, and 2.3 is done when using RSU base station as the correction station.

Figure 81. Measurements performed on the first segment on the E313 highway using RTK GNSS provided by Flepos and RTK GNSS provided GNSS devices
Figure 82. Measurements performed on the second segment on the E313 highway using RTK GNSS provided by Flepos and RTK GNSS provided GNSS devices

Further details are shown on a sample of specific segments where it can be noticed the distance between points that are all within the defined lanes. Figure 83 is showing results using Flepos and Figure 84 is showing results when using the RSU correction station. The same scaling was used on the x-axis the y-axis and the changes can be noticed on both axes. In these figures can be noticed the same behavior of drives. While driving on three lanes the coverage of obtained positions is spread on the defined highway positions.

Figure 83. Segment of measurements performed by driving on the E131 highway using RTK GNSS provided by Flepos
The results on the map are shown in Figure 85 a), b), and c). In this figure can be noticed three different drives of the OBU on three different lanes, while the lane was defined with the required accuracy.
Using the previous tests, this information was further used for the Estimated Time of Arrival evaluation, where we developed, implemented, and evaluated the Estimated Time of Arrival algorithm useful for the BSAF implementation on the MEC. We have enhanced the accuracy of the time of arrival estimation with the support of the Kalman filter. In order to showcase the performance, we have compared the outcome from the real measured time of arrival and the calculated time of arrival using a mapping system. The first results are published are found published on the paper in [40].

6 Service-oriented Predictive of Quality of Service

This function will support the manoeuvre-oriented applications in the vehicles with a prediction of key network performance information for the route on the 5G-CARMEN corridor that vehicles will be driving on. It provides predictions for QoS information on waypoints requested by a client in the vehicle for a planned route. Based on these predictions, the applications, such as the automated manoeuvre applications in the vehicle can take either binary decisions on performing or not performing certain manoeuvres involving guidance from applications in the distributed and orchestrated edge cloud or adapting their automated driving functionality accordingly to e.g. cope with lower 5G network throughput or higher latency as it may occur.

![Predictive QoS Scenario ADAS Route](image)

The implementation of Predictive QoS is ongoing. While the pQoS server with API and underlying database with a set of test data has been completed for the network part, the preparation for the implementation of the corresponding pQoS on the client side in the vehicles has been started. Once this will be completed, the end-to-end deployment and evaluation can be completed.

The pQoS server with API and network database has been deployed in a production-grade environment called OTC (Open Telekom Cloud). The preparation and onboarding of initially static network data has been started for the three networks covering the relevant parts of the 5G-CARMEN corridor.

The evaluation procedure will compare the pQoS information provided for the requested route with the measured experienced QoS in the vehicles OBU while driving this route. However, as 5G usage is still rather low especially along transportation corridors (most 5G usage by early adopters and innovation-conscious users occurs in larger cities, while first 5G-enabled production series vehicles are expected to be sold and registered not before the end of 2021), the emphasis of the evaluation procedure will primarily focus on how the ADAS applications in the vehicles will react and adapt to pQoS information received. This can be enforced by providing artificial prediction data suggesting network congestions with limited throughput or higher latency on the route, which does not have to match with the real network load situation.

Results will be made available in an update to this document.
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