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

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5G-CARMEN Final Pilot Report
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<tr>
<td>ADAS</td>
<td>Advanced Driving Assistance System</td>
</tr>
<tr>
<td>AMQP</td>
<td>Advanced Message Queuing Protocol</td>
</tr>
<tr>
<td>AMQP</td>
<td>Advanced Message Queuing Protocol</td>
</tr>
<tr>
<td>API</td>
<td>Application Program Interface</td>
</tr>
<tr>
<td>BSAF</td>
<td>Back situation Awareness Function</td>
</tr>
<tr>
<td>C2X</td>
<td>Car to Everything</td>
</tr>
<tr>
<td>CAD</td>
<td>Connected and Automated Driving</td>
</tr>
<tr>
<td>CCAM</td>
<td>Connected, Cooperative and Automated Mobility</td>
</tr>
<tr>
<td>C-ITS</td>
<td>Cooperative Intelligent Transport Systems</td>
</tr>
<tr>
<td>CLC</td>
<td>Centralized Lane Change</td>
</tr>
<tr>
<td>C-V2X</td>
<td>Cellular Vehicle to Everything</td>
</tr>
<tr>
<td>DSS</td>
<td>Dynamic Spectrum Sharing</td>
</tr>
<tr>
<td>EARFCN</td>
<td>E-UTRA Absolute Radio Frequency Channel Number</td>
</tr>
<tr>
<td>ECON</td>
<td>Edge Controller</td>
</tr>
<tr>
<td>emV</td>
<td>emergency Vehicle</td>
</tr>
<tr>
<td>eNB</td>
<td>Evolved Node B</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
</tr>
<tr>
<td>ePLMN</td>
<td>Equivalent PLMN (Public Land Mobile Network)</td>
</tr>
<tr>
<td>E-PLMN</td>
<td>Equivalent PLMN (Public Land Mobile Network)</td>
</tr>
<tr>
<td>ETA</td>
<td>Estimated time of Arrival</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>ETSI ITS G5</td>
<td>Peer-to-peer Communication Standard based on IEEE802.11p</td>
</tr>
<tr>
<td>E-UTRA</td>
<td>evolved UMTS Terrestrial Radio Access</td>
</tr>
<tr>
<td>FOT</td>
<td>Field Operational Test</td>
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<tr>
<td>gNodeB</td>
<td>5G Base station</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>IMM</td>
<td>Identity Management Module</td>
</tr>
<tr>
<td>IMU</td>
<td>Inertial Measurement Unit</td>
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<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicators</td>
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<tr>
<td>LM</td>
<td>Local Manager</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MANO</td>
<td>Management and Orchestration</td>
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<tr>
<td>MEAO</td>
<td>MEC Application Orchestrator</td>
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<tr>
<td>MEC</td>
<td>Multi-access Edge Computing</td>
</tr>
<tr>
<td>MEC</td>
<td>Multi-Access Edge Computing</td>
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<tr>
<td>MM</td>
<td>Main Manager</td>
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<tr>
<td>MNO</td>
<td>Mobile Network Operator</td>
</tr>
<tr>
<td>MS</td>
<td>Manoeuvering Service</td>
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<tr>
<td>NBI</td>
<td>Northbound Interface</td>
</tr>
<tr>
<td>NFV</td>
<td>Network Function Virtualization</td>
</tr>
<tr>
<td>NFV-LO</td>
<td>NFV Local Orchestrator</td>
</tr>
<tr>
<td>NFV-SO</td>
<td>NFV Service Orchestrator</td>
</tr>
<tr>
<td>NS3</td>
<td>Simulation Tool Used in Telecommunications</td>
</tr>
<tr>
<td>NSA</td>
<td>Non-standalone</td>
</tr>
<tr>
<td>OBU</td>
<td>On Board Unit</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>PCS5</td>
<td>Peer-to-peer Communication standard interface in LTE-V2X/5G</td>
</tr>
<tr>
<td>c</td>
<td>Packet inter-arrival time</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>PLMN</td>
<td>Public Land Mobile Network</td>
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<tr>
<td>PPP</td>
<td>Public-Private Partnership</td>
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<tr>
<td>PRR</td>
<td>Packet Reception Rate</td>
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<tr>
<td>RAN</td>
<td>Radio Access Network</td>
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<tr>
<td>RNIS</td>
<td>Radio Network Information Service</td>
</tr>
<tr>
<td>RR</td>
<td>Response Router</td>
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<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>RSRP</td>
<td>Reference Signal Received Power</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinematics</td>
</tr>
<tr>
<td>RTT</td>
<td>Round-trip-time</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>S-LDM</td>
<td>Server Local Dynamic Map</td>
</tr>
<tr>
<td>UE</td>
<td>User equipment</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>V2N</td>
<td>Vehicle to Network</td>
</tr>
<tr>
<td>V-LDM</td>
<td>Vehicle Local Dynamic Map</td>
</tr>
<tr>
<td>VNFs</td>
<td>Virtual Network Functions</td>
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<tr>
<td>VS</td>
<td>Video Streaming</td>
</tr>
<tr>
<td>VSSS</td>
<td>Vehicle Sensors and State Sharing</td>
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<td>WP</td>
<td>Work Package</td>
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Executive Summary

The 5GCARMEN project objective is to test 5G communication for highly automated driving, focussing on cross-border aspects. Based on the collaboration among vehicle manufacturers, equipment and service providers, network operators and research institutes, 5G-CARMEN has demonstrated challenging use cases of cooperative and automated lane-change and in-lane manoeuvres, supported by a novel 5G-ecosystem along the highway Corridor Munich-Bologna.

The project Work Package 5 (WP5) is dedicated to the pilot deployment, execution, data analysis and technical evaluation. The vehicle and infrastructure components and platforms developed in WP3 and WP4 have been deployed, integrated, and tested in Italy, Austria and Germany. The experimental campaign started in-country and then achieved its final target, namely the system evaluation across Austria-Italy and Austria-Germany borders, which is the main subject of this final pilot report D5.3.

To plan the experiments and analyse the results, a set of Key Performance Indicators were defined by WP5 jointly with WP3 and WP4, to evaluate the suitability to Cooperative, Connected and Automated Mobility (CCAM) of the following features deployed along the corridor: 5G Network, cross-border Network Reselection Improvements, Local Break Out, Orchestrated Platform based on MEC enabling seamless service provision, low-latency Message dispatching and storing in Local Dynamic Map, Precise Positioning and robust C-V2X link exploiting 5G Uu and Direct Communication for SAE Level 4 manoeuvres.

This document reports the final pilot status, details the experiments carried out, and provides a preliminary analysis of results focussing on the collected data. A further discussion of the KPI achievements and a comparison with simulations, is reported in deliverable D5.4 [1].

Chapter 1 introduces the 5G-CARMEN pilot, referring to its location and main components.
Chapter 2 reports on the 5G deployment in the corridor and the measurements by Mobile Network Operators.
Chapter 3 reports on the measurements from cross-border transitions using a 5G Modem.
Chapter 4 presents deployment Orchestrated platform for CCAM, taken from WP4 deliverables.
Chapter 5 reports the results of tests with vehicle prototypes connected to CCAM services along the corridor.
1 5G CARMEN pilot overview

The 5G-CARMEN project has piloted Connected and Automated in-lane and lane change manoeuvres in the two in-country locations – near Munich and north of Trento – and two cross-border locations – Brenner pass and Kufstein.

Figure 1: 5G-CARMEN Pilots

Figure 2: Austria-Italy (left) and Austria-Germany border (right)
The target 5G-CARMEN Use Cases currently addressed are:

1. Cooperative and automated lane-change manoeuvres
2. Cooperative and automated in-lane manoeuvres

The system deployed in the pilot reflects as much as possible the reference architecture of WP2 (Figure 3 [2]). The cross-border system was deployed in the second half of 2021 and was the focus of 2022 pilot activity.

In particular the 5G-CARMEN pilot has developed all the subsystems and features of Table 1. With respect to the status presented in D5.2 preliminary pilot report [3], we have the following changes: the Fast network reselection from Italy to Austria was implemented, but not on time for the pilot; the AMQP sync cross-border (initially not planned) was introduced.

Table 1: Subsystems and features developed by 5G-CARMEN partners for the 5G pilot

<table>
<thead>
<tr>
<th>Subsystems and features</th>
<th>Partner(s)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Breakout</td>
<td>TIM, MTA, DTAG</td>
<td>Network feature</td>
</tr>
<tr>
<td>Fast network reselection</td>
<td>TIM, MTA, DTAG</td>
<td>Network feature</td>
</tr>
<tr>
<td>Predictive QoS (static due to NSA)</td>
<td>DTAG</td>
<td>Network feature</td>
</tr>
<tr>
<td>RNIS (lab only)</td>
<td>CMA</td>
<td>Enabler, network</td>
</tr>
<tr>
<td>Precise Positioning</td>
<td>DTAG</td>
<td>Enabler, vehicle &amp; net.</td>
</tr>
<tr>
<td>S-LDM</td>
<td>CNIT-BMW</td>
<td>Enabler, MEC service</td>
</tr>
<tr>
<td>AMQP</td>
<td>SWM-TIM</td>
<td>Enabler, MEC service</td>
</tr>
<tr>
<td>GeoService</td>
<td>NOKIA</td>
<td>Enabler, MEC service</td>
</tr>
<tr>
<td>Maneuvering service</td>
<td>BMW</td>
<td>Enabler, MEC service</td>
</tr>
<tr>
<td>MEC service orchestration</td>
<td>NEC, IMEC, FBK, CNIT, WINGS</td>
<td>Enabler, MEC platform</td>
</tr>
</tbody>
</table>
During the experiments, the interested components were operational, and data were recorded for post-processing analysis. Data management was not done centrally, rather, dedicated data logs were collected and analysed by each component owner, in agreement with partners. Specifically, the following kind of experiments were performed:

1. Network measurements by DTAG, MTA, TIM at the borders
2. 5G on-board unit (OBU) measurements, focussing on cross-border transitions by QCGER
3. In country and cross-border tests on vehicles by BMW and CRF; with the involvement of MEC platform and service components, experimented by CNIT, FBK, IMEC, NEC, NOKIA, SWM, TIM
4. Parallel laboratory testing by CMA, IMEC, WINGS

From the tests, KPI’s were calculated. The pilot focussed on selected Use Case (UC) KPI and addressed some of the network KPI within the network and 5G OBU measurements, namely network throughput, latency and availability. Hereafter, the full list of UC KPI as in D5.1 pilot plan is reported.

- UC.01 - Position Accuracy
- UC.02 - Position Refresh Time
- UC.03 - Throughput
- UC.04 - Predictive QoS for take over time
- UC.05 - Service Level Reliability
- UC.06 - Communication range /geo-cast area
- UC.07 - Data refresh rate
- UC.08 - Service Level Latency

All these KPI were addressed, excluding Predictive QoS for take over time which was only partially addressed in terms of current QoS, as the pQoS values were given by a proof-of-concept service which provided only static data, not correlated with the real data. Measurements on pQoS and some inferences for a future predictive service are discussed in D5.4 [1].

The following sections report on the experiments conducted in the pilot activity.
2 5G deployment in the pilot

Hereafter, 5G deployment in the pilot sections of the 5G CARMEN Corridor is reported.

In Italy (TIM), 5G Non-Stand Alone (NSA) is installed and operational in the in-country section North of Trento and in the Italy-Austria section at Brenner.

In Austria (MTA), 5G NSA is installed and operational in the Italy-Austria cross-border section at Brenner and in the Germany-Austria border section near Kufstein.

In Germany (DTAG), 5G NSA is installed and operational in the in-country section near Munich and on the Germany-Austria section.

Fast network reselection is composed of configuration of equivalent PLMN (ePLMN) and Radio Resource Control (RRC) connection release before the border (based on RF level/quality criteria of this cell) with information about the neighbour cell on the other side of the border. ePLMN is configured and available in the networks of DTAG and Magenta, showing all the three networks Magenta, DTAG and TIM as ePLMNs in the Attach Accept. The second part of the feature, RRC connection release, has been implemented and verified working only from Germany to Austria (DTAG to MTA), and implemented without verification from Italy to Austria (TIM to MTA), as lack of 4G/5G coverage in the northbound motorway tunnel does not help exploiting this feature for fast network reselection.

“Local” Breakout to the MEC in the respective home network is of course available using TIM SIM cards in Italy, MTA SIM cards in Austria and the DTAG SIM cards in Germany. Local breakout to the MEC in Austria in the visited network of MTA is available for TIM SIM cards crossing the border between Italy and Austria, and for DTAG SIM cards crossing the border between Germany and Austria, respectively.

In the next sections, network measurements along the corridor (and in other places when needed for comparison) are reported, as performed by TIM, MTA, DTAG, QCGER and VIF.

2.1 TIM network measurements

This Section describes the performance tests related to the mobile network infrastructure, both for 4G and 5G technologies.

Preliminary tests, fully reported in Deliverable D5.2 [3] were carried out in Turin and Trento, to verify the proper operation of the network and the communication among the functional elements in 5G-CARMEN architecture developed by the different partners of the project. In the second part of the project, measurements were repeated at the cross-border, between Italy and Austria, to assess network coverage and KPIs in the target location of the pilots. Moreover, specific measurements were carried out to verify the correct implementation of the network features deployed to address the cross-border challenges, namely Fast Network Reselection (FNR) and Local Break Out (LBO).

2.1.1 Summary of preliminary tests in national coverage

The testing objectives in report D5.2 were related to in-country test on TIM MEC for the following KPIs:

- NW.01 Network throughput
- NW.02 RTT network latency

The Round-Trip Time (RTT) was measured through the PING tool and the throughput with the help of the IPERF3 tool. In particular, the Iperf server ran on the User Equipment (UE) and the Iperf client was launched on the AMQP Broker Virtual Machine (VM) terminal located in the MEC platform.

As shown in Figure 4, the testing environment was composed of a TIM SIM card used in a commercial device. The smartphone can be:
• Connected through USB tethering to a Linux terminal;
• Used to send/receive commands through a dedicated terminal emulator application directly installed on the smartphone.

Figure 4: Testing environment

The following schema (Figure 5) summarizes the overall network setup that has been realized in Italy to support the Use Cases of the project (as detailed in Deliverable D3.3 [4]). It includes the 5G communication network, the connectivity towards external servers and the Magenta MEC platform, the client-to-LAN VPNs used to grant access to the MEC for the different partners involved in the development of all the functional elements of the project, and the NOKIA MEC platform based on Openstack.

Figure 5: Network setup in Italy

Reachability and latency tests were executed by using ICMP messages (i.e., Ping) with an interval between packets under 200 ms, varying the packet size and the time interval between them, with the aim of stressing the
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network and analyse the variation on the measured KPIs. Instead, the throughput tests were executed with the help of the IPERF3 tool.

The measurements, both for 4G and 5G, took place in:
- Turin metropolitan area;
- Trento.

Hereafter we summarize the results collected in Turin, while the complete set of measurements are available in Deliverable D5.2.

4G measurements were performed using TIM commercial network to set up a baseline that could be used to appreciate the improvement achieved exploiting 5G connectivity in both throughput and latency.

4G coverage in Turin is obtained through different frequency layers, including a base layer at 800 MHz with 10 MHz of available bandwidth, an 1800 MHz layer with up to 20 MHz of bandwidth, and a third layer granting extra capacity in certain areas using a 2600 MHz carrier with 15 MHz of bandwidth. In the area considered for the tests the 1800 MHz carrier was available, with a total bandwidth of 20MHz.

Latency tests were performed through ping with varying packet size, ranging from a minimum of 50 Bytes to a maximum of 2000 Bytes. The obtained average, maximum and minimum values are reported in Table 2. Note that increasing the packet size leads in general to higher latency values, as it might be expected.

<table>
<thead>
<tr>
<th>Packet size → Measure ↓</th>
<th>50 Bytes</th>
<th>500 Bytes</th>
<th>2000 Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>30.4 ms</td>
<td>38.7 ms</td>
<td>40.6 ms</td>
</tr>
<tr>
<td>Max</td>
<td>39.3 ms</td>
<td>48.0 ms</td>
<td>48.0 ms</td>
</tr>
<tr>
<td>Min</td>
<td>27.1 ms</td>
<td>34.7 ms</td>
<td>36.2 ms</td>
</tr>
</tbody>
</table>

Table 2: Round Trip Time Latency [ms] measured on 4G connection in Turin

Throughput tests were carried out using the IPERF tool, generating a UDP stream with very high data rate and measuring the amount of data that could actually be transmitted through the channel. The measured values are reported in the following Table 3.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>61.3 Mbit/s</td>
</tr>
<tr>
<td>Uplink</td>
<td>33.2 Mbit/s</td>
</tr>
</tbody>
</table>

Table 3: Measured throughput on 4G connection in Turin

Similar measurements were performed with a 5G connection. As shown in Table 4, latency measured in this case is in general lower than those achieved with 4G, as expected. While the full set of features that could improve latency and fully support Ultra Reliable Low Latency Communication (URLLC) are still not available on commercial networks, the reduced slot duration available for 5G at 3.7 GHz with a subcarrier spacing of 30 kHz (which leads to a time slot of 0.5 ms for scheduling resources in 5G, against the 1 ms in LTE) and the more stringent processing time for scheduling resources can overall speed up the exchange of data over the radio access. It should be stressed that nowadays deployment of 5G networks, based on a Non-Standalone architecture defined in the early drop of 3GPP Release 15 specification for 5G, are mainly designed to support enhanced Mobile Broad Band (eMBB) services. As discussed in Deliverable D3.2[9], a set of tools to further improve
latency have been defined in Release 15 specification and extended in Release 16, including exploiting higher subcarrier spacing (in particular for millimetre wave communication), enabling mini-slot support (using shorter slot composed of only 2, 4 or 7 OFDM symbols instead of a full slot of 14 symbols), supporting increased PDCCH monitoring capability to minimize scheduling block/delay, supporting configured-grant which allows the UE to autonomously transmit uplink data without having to send a scheduling request and wait for the uplink grant, and supporting different TDD patterns to better balance uplink and downlink transmission. However commercial solutions still do not support these features, thus limiting the actual gain that can be achieved in terms of latency.

Table 4: Round Trip Time Latency [ms] measured on 5G connection in Turin

<table>
<thead>
<tr>
<th>Packet size → Measure ↓</th>
<th>50 Bytes</th>
<th>500 Bytes</th>
<th>2000 Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>23.30</td>
<td>27.20</td>
<td>44.10</td>
</tr>
<tr>
<td>Max</td>
<td>31.4</td>
<td>43.1</td>
<td>58.9</td>
</tr>
<tr>
<td>Min</td>
<td>18.5</td>
<td>21.3</td>
<td>25.7</td>
</tr>
</tbody>
</table>

As shown in Table 5, the throughput measured exploiting 5G connectivity is approximately four times larger than that achieved with 4G, which is reasonable considering that the bandwidth available for 5G at 3.7 GHz is 80 MHz, thus four times larger than the 20 MHz of bandwidth available at 1800MHz with 4G.

While it is known that 5G New Radio physical layer is slightly more spectral efficient than 4G, the usage of a TDD pattern (with a schema, in Italy, DDDSU) and the higher carrier frequency used in 5G compensate the improvement that one could expect, leading to similar overall spectral efficiency in the measurement here performed, with the gain of 5G basically given by the larger available bandwidth.

Table 5: Measured throughput on 5G connection in Turin

<table>
<thead>
<tr>
<th>Direction</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>311 Mbit/s</td>
</tr>
<tr>
<td>Uplink</td>
<td>126 Mbit/s</td>
</tr>
</tbody>
</table>

2.1.2 Final tests at Brenner cross-border

After the preliminary measures in Turin and Trento, a new test campaign was carried out at the Brenner Pass, at the border between Italy and Austria. In 2021, both TIM and Magenta installed a 5G node in the border area, which cover both the statal road and the highway. The information of the 4G and 5G nodes of both TIM and MTA are reported in Table 6. The goals of these measurements were again (i) the assessment of the network coverage quality, (ii) latency, and (iii) throughput. Furthermore, we also evaluated the advantages brought by the specific features introduced in the project, i.e., FNR, LBO and the use of a dedicated APN (Access Point Name). Both measurements of radio parameters and latency were collected in a “dynamic” way, i.e., moving on a vehicle from Italy to Austria (and vice-versa).

The tests presented in this section were carried out with a dedicated 5G-CARMEN TIM SIM card, connecting to the architecture shown in Figure 5. The radio parameters were captured with a Samsung S21 Ultra 5G, connected to a laptop running XCAL by Accuver. The latter traced any signalling and radio parameter every
second. In order to associate each sample collected by XCAL to a geographic position, we used a GPS module connected to the PC running XCAL. For what concerns the latency and throughput evaluations, we used again the IPERF and the PING tool, running them on the Samsung terminal with the Android App Termux (a Linux terminal emulator for Android). The terminal and the laptop with XCAL were time-synchronized: in this way, by using the date time, it was possible to associate each sample collected by Termux with a GPS position. Several Python-based post-process scripts were developed to parse the measurement files and generate the plot reported in the following subsections. The list of the main Python libraries used include Pandas, Numpy and Folium.

Table 6: TIM and MTA 4G and 5G nodes details

<table>
<thead>
<tr>
<th>RAT</th>
<th>EARFCN</th>
<th>Carrier [MHz]</th>
<th>Band</th>
<th>PCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM Site</td>
<td>5G</td>
<td>650666</td>
<td>3759.99</td>
<td>n78</td>
</tr>
<tr>
<td></td>
<td>5G</td>
<td>650666</td>
<td>3759.99</td>
<td>n78</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>6300</td>
<td>806.00 DL + 847.00 UL</td>
<td>B20</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>6300</td>
<td>806.00 DL + 847.00 UL</td>
<td>B20</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>1350</td>
<td>1820.00 DL + 1725.00 UL</td>
<td>B3</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>1350</td>
<td>1820.00 DL + 1725.00 UL</td>
<td>B3</td>
</tr>
<tr>
<td>MTA Site</td>
<td>5G</td>
<td>650000</td>
<td>3750</td>
<td>n78</td>
</tr>
<tr>
<td></td>
<td>5G</td>
<td>650000</td>
<td>3750</td>
<td>n78</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>6400</td>
<td>816.00 DL + 857.00 UL</td>
<td>B20</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>6400</td>
<td>816.00 DL + 857.00 UL</td>
<td>B20</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>1300</td>
<td>1815.00 DL + 1720.00 UL</td>
<td>B3</td>
</tr>
<tr>
<td></td>
<td>4G</td>
<td>1300</td>
<td>1815.00 DL + 1720.00 UL</td>
<td>B3</td>
</tr>
</tbody>
</table>

2.1.2.1 Network Radio KPIs: Coverage, RSRP and SINR

Network coverage

In this section we present the radio parameters measurements, in particular the analysis of the network coverage and the assessment of the Reference Signal Receive Power (RSRP) and the Signal to Interference and Noise Ratio (SINR). The measurements were performed on a vehicle, moving from south of the border to north (i.e., Italy to Austria, IT→AT) and vice-versa (i.e., Austria to Italy, AT→IT). The measurements involved both the statal road and the highway, and were performed while exchanging data with the MEC (i.e., in connected mode).
Figure 6: TIM and MTA coverage on statal road, moving from IT→AT (a) and AT→IT (b)
Figure 6 shows the network coverage on the state road, while Figure 7 refers to the highway. Darker colors are used to highlight areas where 5G technology is available, while blue and magenta rhombus show the location of TIM and MTA base stations respectively. Black lines correspond to areas where the terminal had no connectivity while performing network reselection.

Note that Figure 6(a) refers to measurements collected before the enabling of FNR, while the other figures have the feature enabled. This allows to appreciate the advantages of the feature since, as it can be seen, the out of coverage area is significantly reduced. In fact when moving from Italy to Austria the terminal is initially connected to TIM network and it stays connected to TIM until the signal is lost and the traditional network reselection procedure is triggered. On the other hand, when moving in the other direction, the terminal starts under the coverage of MTA network and it switches to TIM again when MTA signal is too weak to sustain the connection. However, in this case, since ePLMN is enabled from MTA to TIM, the reselection procedure is significantly faster (see Section 2.1.2.3 for further details).

In general, the 5G nodes offer good coverage of the whole region, in particular in the highway which is the main target for the pilots. It is worth pointing out that also in part of the tunnel of the highway it is possible to have 5G connectivity.

**LTE Reference Signal Receive Power (RSRP)**

The following Figure 8 and Figure 9 report the evaluation of LTE RSRP on the state road and highway. RSRP is a measure of the power received by the terminal on the reference signals transmitted by the 4G base station. It is used to have an indication about the signal strength of the serving cell. Green shades correspond to areas with high signal strength, while red regions have lower coverage. As it can be expected, the signal is stronger
close to base stations, and becomes weaker at cell edge. Note that in the highway the RSRP falls abruptly when the signal enters the tunnel. However, in general, highway coverage outside of the tunnel is better than on the statal road. This is particularly evident from the overall statistics collected in Table 7, where both the RSRP mean and all percentile values are significantly higher in the highway case. This is reasonable since the highway has a better visibility of the deployed sites.

Figure 8: TIM (a) and MTA (b) 4G serving cell RSRP measured on statal road, moving from IT→AT (a) and AT→IT (b)
Figure 9: TIM (a) and MTA (b) 4G serving cell RSRP measured on highway, moving from IT→AT (a) and AT→IT (b).

Table 7: Measured 4G RSRP statistics.

<table>
<thead>
<tr>
<th>4G RSRP [dBm] Statistics</th>
<th>Statal road</th>
<th>Highway road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IT → AT</td>
<td>AT → IT</td>
</tr>
<tr>
<td><strong>Samples</strong></td>
<td>431</td>
<td>504</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>-100.00</td>
<td>-101.86</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>8.73</td>
<td>13.42</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>-141.00</td>
<td>-135.00</td>
</tr>
<tr>
<td></td>
<td>25-Percentile</td>
<td>50-Percentile</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>SINR</td>
<td>-107.00</td>
<td>-111.00</td>
</tr>
<tr>
<td>50-Percentile</td>
<td>-100.00</td>
<td>-102.00</td>
</tr>
<tr>
<td>75-Percentile</td>
<td>-93.00</td>
<td>-92.00</td>
</tr>
<tr>
<td>Max</td>
<td>-76.00</td>
<td>-66.00</td>
</tr>
</tbody>
</table>

**LTE Signal to Interference and Noise Ratio (SINR)**

Figure 10 and Figure 11 show the LTE Signal to Interference and Noise Ratio (SINR) measured in the statal road and highway respectively. While RSRP only reports the signal strength coming from the serving base station, SINR also takes into account the presence of interference that can impact the overall service quality. Again, green shades correspond to areas with high SINR, while red regions have lower SINR, which can be due to either reduced signal strength or the presence of other interfering signals. In general, SINR is higher close to base stations, and becomes weaker at cell edge. However, in the proximity of base stations the SINR can drop due the presence of interference. This is clearly visible in Figure 10(a) where the SINR becomes lower when the user is close to the TIM base station (the blue rhombus), due to the interference generated by the two sectors of the base station itself (which has one sector pointing to the north and one to the south). As shown in the RSRP analysis, also SINR falls abruptly in the highway when the signal enters the tunnel, and also in this case the highway SINR outside of the tunnel is significantly better than on the statal road, as can be appreciated from Table 8.

![Maps showing LTE Signal to Interference and Noise Ratio (SINR)](image-url)
Figure 10: TIM and MTA 4G SINR measured on statal road, moving from IT→AT (a) and AT→IT (b)

Figure 11: TIM and MTA 4G SINR measured on highway, moving from IT→AT (a) and AT→IT (b)

Table 8: Measured 4G SINR statistics

<table>
<thead>
<tr>
<th>4G SINR [dB] Statistics</th>
<th>Statal road</th>
<th>Highway road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IT → AT</td>
<td>AT → IT</td>
</tr>
<tr>
<td>Samples</td>
<td>431</td>
<td>504</td>
</tr>
</tbody>
</table>
5G Reference Signal Receive Power (RSRP)

Similarly to what was previously shown for 4G, Figure 12: TIM and MTA 5G RSRP measured on statal road, moving from IT→AT (a) and AT→IT (b) Figure 12 and Figure 13 show the measured RSRP for the 5G signal covering the Brenner area on both statal road and highway. Also in this case the RSRP is higher in the highway, as it can be observed from the statistics collected in Table 9.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>STD</th>
<th>Min</th>
<th>25-Percentile</th>
<th>50-Percentile</th>
<th>75-Percentile</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>9.90</td>
<td>8.23</td>
<td>17.80</td>
<td>12.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STD</td>
<td>12.60</td>
<td>7.78</td>
<td>7.63</td>
<td>6.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>-30.00</td>
<td>-10.00</td>
<td>-12.00</td>
<td>13.00</td>
<td>18.00</td>
<td>24.00</td>
<td>30.00</td>
</tr>
</tbody>
</table>

1 RSRP in 5G is measured on the Synchronization Signal (SS), while in 4G on the Reference Signal, they can be subject to different power offsets, and in 5G the SS is beamformed with its own beams; thus, they are different in nature. Still, the two measurements are usually considered as an indication of the general signal strength that can be received in a certain area for the respective technology.
Figure 12: TIM and MTA 5G RSRP measured on statal road, moving from IT→AT (a) and AT→IT (b)
Figure 13: TIM and MTA 5G RSRP measured on highway, moving from IT→AT (a) and AT→IT (b)

Table 9: Measured 5G RSRP statistics

<table>
<thead>
<tr>
<th>5G RSRP [dBm]</th>
<th>Statal road</th>
<th>Highway road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IT → AT</td>
<td>AT → IT</td>
</tr>
<tr>
<td>Samples</td>
<td>240</td>
<td>289</td>
</tr>
<tr>
<td>Mean</td>
<td>-99.27</td>
<td>-97.63</td>
</tr>
<tr>
<td>STD</td>
<td>15.39</td>
<td>14.72</td>
</tr>
<tr>
<td>Min</td>
<td>-123.48</td>
<td>-121.60</td>
</tr>
<tr>
<td>25-Percetile</td>
<td>-113.99</td>
<td>-112.27</td>
</tr>
</tbody>
</table>
5G SINR

Figure 14 and Figure 15 report the measured SINR for the 5G signal covering the Brenner area on the stateal road and highway respectively, as it was measured moving from Italy to Austria, and backwards. Also in this case it is possible to observe the effect of the two sectors, particularly on the Italian site, on both Figure 14(a) and Figure 15(a). Once again, the SINR is significantly higher on the highway when compared to what has been measured on the stateal road (see Table 10).

![Figure 14: TIM and MTA 5G SINR measured on stateal road, moving from IT→AT (a) and AT→IT (b)](image-url)
Figure 15: TIM and MTA 5G SINR measured on highway, moving from IT→AT (a) and AT→IT (b)

Table 10: Measured 5G SINR statistics

<table>
<thead>
<tr>
<th>5G SINR [dBm]</th>
<th>Statal road</th>
<th>Highway road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IT→AT</td>
<td>AT→IT</td>
</tr>
<tr>
<td><strong>Samples</strong></td>
<td>254</td>
<td>292</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>14.06</td>
<td>14.58</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>8.07</td>
<td>7.26</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td><strong>25-Percentile</strong></td>
<td>6.14</td>
<td>7.77</td>
</tr>
</tbody>
</table>
2.1.2.2 Latency and Throughput

Besides the radio level KPIs previously shown, in this subsection we present network testing, which focused on the assessment of network performances in terms of latency and throughput.

![Figure 16: TIM and MTA RTT latency measured on statal road, moving from IT→AT (a) and AT→IT (b)](image)

As previously explained, Round Trip Time (RTT) latency has been measured with the PING tool, running it on the device with the Android Linux terminal emulator Termux, and exploiting a simple script that allowed to add a timestamp to each generated ping message. In this way the measured ping value has been matched with the position of the vehicle during the measurement, so that ping statistic could be georeferenced and measured while...
moving along the road. RTT measurements have been collected by pinging the Italian MEC server when under the coverage of TIM, and the Austrian MEC server when under the coverage of MTA. Ping packets had the default size of 56 bytes, and periodicity was set to 200ms.

The measured values when traveling along the state road are reported in Figure 15. In particular, Figure 15(a) refers to the samples collected when moving from Italy to Austria under the coverage of the TIM network, and in Figure 15(b) when moving back from Austria to Italy while being under the coverage of the MTA network. The overall distribution of the measured RTT values on the state road is provided in Figure 16. Similar measurements have been performed on the highway (which is the final target of the pilots) and are reported in Figure 17 and Figure 18. A comparison between the RTT statistics collected in the state road and on the highway is provided in Table 11. As it can be seen, the RTT statistics measured on the highway are better. This is however reasonable because, as previously discussed, the overall radio level KPIs are better on the highway than on the state road. Moreover, 5G coverage on the highway is larger when compared to the state road. As show in Figure 20, 5G is in general associated with lower latency, and it is more stable, also considering lower RSRP, while 4G provides higher latency and has a higher level of variability (which might be due to 4G networks being more loaded than 5G).

Figure 17: Probability density function of RTT latency measured on state road
Figure 18: TIM and MTA RTT latency measured on highway, moving from IT→AT (a) and AT→IT (b)
Figure 19: Probability density function of RTT latency measured on highway

Table 11: Measured RTT latency statistics

<table>
<thead>
<tr>
<th></th>
<th>RTT Latencies [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statal Road</td>
</tr>
<tr>
<td><strong>Samples</strong></td>
<td>824</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>169.01</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>407.79</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>15.10</td>
</tr>
<tr>
<td><strong>25-Percentile</strong></td>
<td>23.80</td>
</tr>
<tr>
<td><strong>50-Percentile</strong></td>
<td>34.20</td>
</tr>
<tr>
<td><strong>75-Percentile</strong></td>
<td>58.37</td>
</tr>
<tr>
<td><strong>Max</strong></td>
<td>4255.00</td>
</tr>
</tbody>
</table>
Throughput

In this section we present the analysis on another important network KPI, i.e., the throughput. Unlike the previous measurements which were performed on a running vehicle, here the samples were collected in specific positions in the Italian territory. Our Samsung smartphone acted as Iperf client whereas the TIM MEC platform as Iperf server. We did not perform a “dynamic” measure since it was not possible to add a precise timestamp to the throughput samples measured by the IPERF tool. As a result, without time-related references, it is not possible to link any throughput sample to the specific GPS coordinate in which the sample was measured. For this reason, we identified 4 points north of the TIM BS and 4 points south, in which measuring the throughput offered by the 5G connectivity at Brenner pass.
Figure 21: TIM Downlink throughput measured on statal road.

Figure 21 shows the results obtained by the Iperf test in download. As expected, the closer the user is to the BS, the higher the throughput that is achieved. The highest measured sample is 532.01 Mbps, a throughput value impossible to achieve with the legacy 4G connectivity. It is worth emphasizing that also the lowest value measured (i.e., 76.46 Mbps) is however significantly higher than the 4G downlink throughput (i.e., 61.3 Mbit/s) measured in Turin (as reported in Table 3).

Table 12 reports the measured downlink throughput values depicted in Figure 21 and the corresponding values of 5G SINR and RSRP averaged during the Iperf test (which lasted 100 s). As shown in the table, the worst point in which performing the measurement is the first to the north in which the SINR is 14.42 dB (however a quite high value) but a RSRP well below -100 dBm which causes the worst performance among the ones observed.

Table 12: Measured 5G Downlink Throughput vs 5G radio KPIs.

<table>
<thead>
<tr>
<th>Position</th>
<th>SINR [dB]</th>
<th>RSRP [dBm]</th>
<th>DL Throughput [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>14.42</td>
<td>-109.20</td>
<td>76.46</td>
</tr>
<tr>
<td>Position 2</td>
<td>21.50</td>
<td>-97.53</td>
<td>331.73</td>
</tr>
<tr>
<td>Position 3</td>
<td>21.75</td>
<td>-79.90</td>
<td>532.01</td>
</tr>
<tr>
<td>Position 4</td>
<td>21.83</td>
<td>-69.41</td>
<td>438.27</td>
</tr>
<tr>
<td>Position 5</td>
<td>19.56</td>
<td>-90.97</td>
<td>453.41</td>
</tr>
</tbody>
</table>
For what concerns the uplink throughput measurements, the results achieved are shown in Figure 22. As expected, the performance in uplink is much lower than what observed in downlink. This is due to the 5G TDD schema adopted, in which the number of slots for uplink transmissions are much less than the slots dedicated to the downlink. As a result, the two highest values achieved are 68.77 Mbps and 70.22 Mbps which correspond to the two measurements taken closer to the BS. Again, the correlation between the uplink throughput and the radio parameters SINR and RSRP are reported in Table 13.

![Figure 22: TIM Uplink throughput measured on statal road.](image)

### Table 13: Measured 5G Uplink Throughput vs 5G radio KPIs.

<table>
<thead>
<tr>
<th></th>
<th>NR SINR [dB]</th>
<th>NR RSRP [dBm]</th>
<th>UL Throughput [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>14.42</td>
<td>-109.20</td>
<td>10.91</td>
</tr>
<tr>
<td>Position 2</td>
<td>21.50</td>
<td>-97.53</td>
<td>14.92</td>
</tr>
</tbody>
</table>
### 2.1.2.3 5G-CARMEN specific features: FNR, LBO, Dedicated APN

In this section we analyse the impact of some specific features that have been deployed to address the challenges posed by providing connectivity to CCAM users in a cross-border scenario, namely Fast Network Reselection, Local Break Out and Dedicated APN.

**Fast Network Reselection**

It is well known that when a user leaves its home network (i.e., its own Home PLMN) and moves under the coverage of a different network operator (thus, after having crossed a national border), it experiences a connectivity gap. Indeed, the modem first starts scanning all available frequencies to identify a suitable foreign PLMN to connect to, then it synchronizes with the selected new network to setup a new connection. Preliminary measurements at the borders showed connectivity interruptions between 11 to 96 sec (see Deliverable D5.2), which are not acceptable for the use cases considered in the project.

To reduce this connectivity gap, 5G-Carmen introduced the Fast Network Reselection, which is achieved by:

- Setting the Foreign PLMN as “equivalent PLMN” so that the UE does not stick to the home network and can be swiftly moved to the indicated foreign PLMN.
- Setting cell neighbour relations within “foreign cells” at the border.
- Implementing the “Release with Redirect” procedure in the radio access of the operators to indicate the (preferred) foreign carrier to select directly to the user equipment when it approaches the border, discarding the lengthy frequency scan.

A more detailed analysis will be provided in section 3.3. Hereafter, we report a set of measurements performed travelling from Austria to Italy and performing network reselection from MTA to TIM network. In this section of the corridor, the Equivalent PLMN was available, and cell neighbour relations within foreign cells at the border has been implemented; whereas, the Release with Redirect procedure was not available. However, also with this setup, a significant reduction on the transmission gap can be observed. The transmission gap at radio layer has been measured observing the timestamp of signalling messages exchanged by the user equipment with the network and computing the difference between the timestamp of the last message received by the MTA network, and the Attach Complete message received by TIM network after successful reselection (see Figure 23). Figure 24 reports the measured transmission gaps observed in a series of tests performed at the border, while Table 14 summarizes the corresponding statistics. Overall, the gap ranges between 1.82 sec to 2.91 sec, with an average of 2.5 sec.

#### Table 14: Transmission Gap Measurements

<table>
<thead>
<tr>
<th>Position</th>
<th>Time Gap (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>21.75</td>
</tr>
<tr>
<td>4</td>
<td>21.83</td>
</tr>
<tr>
<td>5</td>
<td>19.56</td>
</tr>
<tr>
<td>6</td>
<td>19.98</td>
</tr>
<tr>
<td>7</td>
<td>10.65</td>
</tr>
<tr>
<td>8</td>
<td>7.08</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>Time Gap (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>-79.90</td>
</tr>
<tr>
<td>4</td>
<td>-69.41</td>
</tr>
<tr>
<td>5</td>
<td>-90.97</td>
</tr>
<tr>
<td>6</td>
<td>-94.57</td>
</tr>
<tr>
<td>7</td>
<td>-111.99</td>
</tr>
<tr>
<td>8</td>
<td>-113.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>Time Gap (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>68.77</td>
</tr>
<tr>
<td>4</td>
<td>70.22</td>
</tr>
<tr>
<td>5</td>
<td>6.02</td>
</tr>
<tr>
<td>6</td>
<td>48.06</td>
</tr>
<tr>
<td>7</td>
<td>1.76</td>
</tr>
<tr>
<td>8</td>
<td>15.83</td>
</tr>
</tbody>
</table>
Figure 23: Main signalling messages captured during network reselection.

Figure 24: Time spent for network reselection at radio access layer (MTA→TIM).

Table 14: Measured FNR gap statistics.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Fast NW reselection gap [sec]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>10</td>
</tr>
<tr>
<td>Mean</td>
<td>2.50</td>
</tr>
</tbody>
</table>
Local Break Out

It is well known that latency for the traffic of users in roaming is strongly affected by the Home Routing problem: user traffic needs to be routed back from the visited country, where it is generated, to the core network of the operator of the used SIM. As a result, if the user is contacting a server located on the same visited country, the traffic will have to travel from the visited country to the home country, and back, thus adding extra latency to the communication (a phenomenon usually referred to as the “trombone” effect).

Local Break Out (LBO) eliminates the Home Routing problem by delegating routing directly to the visited Packet Gateway (PGW), so that traffic generated in a country can be routed to the visited PGW which forwards it directly to the MEC of the visited country, thus avoiding the trombone effect. Although defined at the 3GPP level, it is currently not yet present in commercial roaming agreements as many of the following aspects are not defined, that is:

- Charging
- Lawful Intercept
- APN harmonization

In the scope of the 5G-CARMEN project, LBO in roaming was implemented for TIM SIM in Magenta network but with limitations in terms of APN, charging and scalability (being limited to a few subscribers).

Figure 25 shows the important gain that can be achieved through the activation of LBO. RTT latency was measured using a 5G-CARMEN TIM SIM card, with LBO activated, and pinging the Austrian MEC server in Vienna while being in a good position close to the MTA site in Brenner. At the same time, a second TIM SIM, with a regular commercial subscription, has been used to ping a server in Vienna. Since this second SIM was in roaming without the advantage of LBO, the measured latency were significantly worse, as can be seen comparing the blue line (with LBO) and the green line (without LBO) in Figure 25, or the RTT latency distribution in Figure 26, and by observing the statistical values reported in Table 15.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>STD</td>
<td>0.36</td>
</tr>
<tr>
<td>Min</td>
<td>1.82</td>
</tr>
<tr>
<td>25-Percentile</td>
<td>2.37</td>
</tr>
<tr>
<td>50-Percentile</td>
<td>2.54</td>
</tr>
<tr>
<td>75-Percentile</td>
<td>2.79</td>
</tr>
<tr>
<td>Max</td>
<td>2.91</td>
</tr>
</tbody>
</table>
Figure 25: RTT latency comparison with and without LBO feature enabled.

Figure 26: RTT latency distribution with and without LBO feature enabled.
Table 15: Measured RTT latency statistics with and without LBO.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Latency without LBO [ms]</th>
<th>Latency with LBO [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Mean</td>
<td>97.72</td>
<td>19.12</td>
</tr>
<tr>
<td>STD</td>
<td>1.89</td>
<td>1.90</td>
</tr>
<tr>
<td>Min</td>
<td>93.70</td>
<td>14.50</td>
</tr>
<tr>
<td>25-Percentile</td>
<td>96.50</td>
<td>17.80</td>
</tr>
<tr>
<td>50-Percentile</td>
<td>97.60</td>
<td>19.10</td>
</tr>
<tr>
<td>75-Percentile</td>
<td>98.90</td>
<td>20.30</td>
</tr>
<tr>
<td>Max</td>
<td>108.00</td>
<td>36.10</td>
</tr>
</tbody>
</table>

Dedicated APN

The last analysis of this subsection is the comparison, in terms of RTT latency, experienced by users with and without the use of a dedicated APN. The use of a dedicated APN by a SIM card allows a better control on the routing of packets that travel through the mobile operator’s network, ensuring that data are forwarded toward the final destination (in this case the MEC platform) following the shortest possible path.

![Figure 27: RTT latency comparison with and without Dedicated APN.](image)
The advantage in using a dedicated APN is reported in Figure 28. The blue bars report the latency values obtained with a 5G-CARMEN TIM SIM card when using the dedicated APN. On the contrary, the green bars refer to the samples collected with a commercial TIM SIM card when using the default TIM APN. In the first case, the target of our ping was the MEC platform in Turin, whereas, in the second case, we considered a public server (located in Turin as well). The measurement was performed close to the cross-border while the terminal was connected to the 4G TIM network. We performed 300 ping values, 5 per second. As can be seen in Figure 28, the use of the dedicated APN brings a gain in the order of 10 ms.

![Figure 28: RTT latency distribution with and without Dedicated APN.](image)

Table 16 reports an accurate list of the main statistics. It is interesting to point out that in both cases the 25-, 50-, and 75- percentile are very close (e.g., 31.50, 33.70, 34.20) but the difference between the two cases is always greater than 10 ms (e.g., 45.90 ms vs. 34.20 in the case 50-percentile).

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Latency without dedicated APN [ms]</th>
<th>Latency with dedicated APN [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>46.57</td>
<td>35.11</td>
</tr>
<tr>
<td><strong>STD</strong></td>
<td>2.39</td>
<td>2.81</td>
</tr>
<tr>
<td><strong>Min</strong></td>
<td>43.40</td>
<td>31.50</td>
</tr>
<tr>
<td><strong>25-Percentile</strong></td>
<td>45.30</td>
<td>33.70</td>
</tr>
<tr>
<td><strong>50-Percentile</strong></td>
<td>45.90</td>
<td>34.20</td>
</tr>
</tbody>
</table>


### 2.2 DTAG Network Measurements

The measurements in this section are reported for the 4G baseline and for 5G NR (limited to the 3.x GHz carrier, excluding the DSS 2.1GHz carrier) on the German section of the 5G-CARMEN corridor, with a focus on in the border section between Germany and Austria. The tests were carried out during daytime 10-17 CEST of last week of July 2021 for the 4G baseline, and for 5G NSA during daytime 9-18 CEST of the first week of July 2022.

#### 2.2.1 Test setup

The setup chosen in this test is the setup of the 5G-CARMEN system for CCAM manoeuvring services, with the same 4G / 5G NSA RAN, EPC, local breakout and MEC path.

| Description |  
| --- | --- | --- |
| **Measurement System** | Windows 10 ping and sftp tool |  
| **Used Mobile** | Netgear MR5200 / Nokia G50 |  
| **Forced Mobile (locked on a specific band or technology)** | 4G LTE: 800/1800/2600 MHz (5G NSA LTE anchor band: 1800 MHz) 5G NR: TDD 3.x GHz |  
| **Type of test** | ICMP, 5 pings per sec, 500bytes |  
| **Target Server** | 80.159.227.34 (MEC Geoservice) 80.159.227.2 (MEC FTP) |  
| **Mobile Position** | 4 glass-mounted multiband antennas 700-6000 MHz, 5G modem/router inside the vehicle, all connections via cable (Coax/Ethernet) / 5G Smartphone inside the vehicle, dashboard-mounted |  
| **Routes** | Corridor Munich: A9 south of intersection 13 (A99/A9) Munich-North, average driving speed ~80km/h  
Border DE: A93 south of intersection 101/56 (A8/A93) Inntal Triangle to border Kiefersfelden/Kufstein, average driving speed 80km/h |  

#### 2.2.2 Test results

The results of the latency and throughput measurements are shown below for two sections of the German part of the 5G-CARMEN corridor.

##### 2.2.2.1 Corridor section Munich

This part of the corridor is the motorway A9 from the intersection A9/A99 – the A99 connects to the A8 direction to Austria – in the northern part of Munich. It represents an urban and partially dense urban environment with 5G NR deployment (NSA mode) in the 3.6 GHz band.
The 4G / LTE measurements represent the baseline for a comparison with 5G NSA.

Table 18: Latency 4G drive tests on A9 in Munich

<table>
<thead>
<tr>
<th>Measure</th>
<th>Latency [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>33</td>
</tr>
<tr>
<td>Max</td>
<td>69</td>
</tr>
<tr>
<td>Min</td>
<td>21</td>
</tr>
</tbody>
</table>

Table 19: Average throughput 4G drive tests on A9 in Munich

<table>
<thead>
<tr>
<th>Direction</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>73.8 Mbit/s</td>
</tr>
</tbody>
</table>
The 5G NR NSA measurements on the A9 in Munich indicate what can be expected on the 5G-CARMEN corridor in sections with high-density population and usage, both CCAM-related and other eMBB data traffic.

### Table 20: Latency 5G drive test on A9 in Munich

<table>
<thead>
<tr>
<th>Measure</th>
<th>Latency [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>29</td>
</tr>
<tr>
<td>Max</td>
<td>65</td>
</tr>
<tr>
<td>Min</td>
<td>18</td>
</tr>
</tbody>
</table>

### Table 21: Average throughput 5G drive tests on A9 in Munich

<table>
<thead>
<tr>
<th>Direction</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>362.1 Mbit/s</td>
</tr>
<tr>
<td>Uplink</td>
<td>61.6 Mbit/s</td>
</tr>
</tbody>
</table>

The 5G results show relatively minor improvements regarding latency, which is related to the NSA mode with all signalling running via LTE and rather small LTE cells in the urban / dense urban environment in Munich, which are causing frequent inter-cell/inter-site handovers at higher UE mobility. Average throughput rates are significantly improved with NR compared to LTE, however, it is fair to assume that utilisation of LTE is still significantly higher than utilisation of NR.
2.2.2.2 Corridor section border DE/AT

This is the corridor section crossing the border between Germany and Austria. It focuses on motorway A93 between exit Kiefersfelden on the German and the border across the Inn river close to Kufstein in Austria, where the motorway continues as A12.

Table 22: Latency 4G drive test on A93, to/from border DE/AT

<table>
<thead>
<tr>
<th>Measure</th>
<th>Latency [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>37</td>
</tr>
<tr>
<td>Max</td>
<td>83</td>
</tr>
<tr>
<td>Min</td>
<td>24</td>
</tr>
</tbody>
</table>
Table 23: Average throughput 4G drive test on A93, to/from border DE/AT

<table>
<thead>
<tr>
<th>Direction</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>67.9 Mbit/s</td>
</tr>
<tr>
<td>Uplink</td>
<td>29.6 Mbit/s</td>
</tr>
</tbody>
</table>

4G Latency at the border is slightly higher by 4ms on average than latency observed in the Munich area, which can be attributed to the significantly higher distance to LBO and MEC located in Munich and the number of routing hops which IP data has to take on the aggregation network. Average 4G throughput is approximately in the same range compared to Munich, although 4G capacity is significantly higher in Munich, using carrier aggregation with 2 / up to 3 carriers, of course in line with significantly higher network utilisation in Munich.

The 5G NR NSA measurements on the German side of the cross-border section DE-MI yielded the following results:

Table 24: Latency 5G drive test on A94 at the border to Austria

<table>
<thead>
<tr>
<th>Measure</th>
<th>Latency [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>32</td>
</tr>
<tr>
<td>Max</td>
<td>74</td>
</tr>
<tr>
<td>Min</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 25: Average throughput 5G drive tests on A94 at the border to Austria

<table>
<thead>
<tr>
<th>Direction</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>348.7 Mbit/s</td>
</tr>
<tr>
<td>Uplink</td>
<td>57.3 Mbit/s</td>
</tr>
</tbody>
</table>

Again, the 5G results show relatively minor improvements regarding latency. Average throughput rates are significantly improved with NR compared to LTE.

### 2.3 Magenta Network Measurements

This section reports the outcome of Magenta’s network performance tests that were performed close and cross the borders with Italy (Brenner) as well as with Germany (Kufstein).

The tests were performed by own Magenta’s drive test teams on 6th and 7th of July 2021 and complemented by tests of the 5G NR performance at the AT-MI border at Kufstein on the 7th and 8th of July 2022 by the Technical Manager of 5G-CARMEN.
2.3.1 Test setup

The measurement setup has been decided to reflect as much as possible the end-to-end network performance including the radio layer but also the integration of the MEC platform that has been used to host the different CCAM applications.

The overall setup is summarized in Table 26.

<table>
<thead>
<tr>
<th>Description</th>
<th>Measurement System</th>
<th>Used Mobile</th>
<th>Forced Mobile (locked on a specific band or technology)</th>
<th>Type of test/Duration</th>
<th>Target Server</th>
<th>Mobile Position</th>
<th>Other active elements in the car</th>
<th>Scanner</th>
<th>Network</th>
<th>Type of Car</th>
<th>Routes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement System</td>
<td>Qualipoc Rohde &amp; Schwarz / Windows 10 PC with ICMP and sftp for additional 5G tests at Kufstein</td>
<td>Samsung S20 / Nokia G50 for additional 5G tests at Kufstein</td>
<td>No</td>
<td>FTP DL 60 sec, FTP UL 60 sec, 30 PINGS per sec</td>
<td>188.125.17.140</td>
<td>NO EXTERNAL Antenna, Mobile Mounting on Car Dashboard</td>
<td>NO</td>
<td></td>
<td>Magenta AT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Used Mobile</td>
<td></td>
<td></td>
<td></td>
<td>In Brenner Tunnel: FTP DL 5 sec PAUSE 2 sec, FTP UL 5 sec PAUSE 2 sec, 5 times PING</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forced Mobile (locked on a specific band or technology)</td>
<td>No</td>
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</tr>
<tr>
<td>Type of test/Duration</td>
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<tr>
<td>Target Server</td>
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<tr>
<td>Mobile Position</td>
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<tr>
<td>Other active elements in the car</td>
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<tr>
<td>Scanner</td>
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<tr>
<td>Network</td>
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<td></td>
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<tr>
<td>Type of Car</td>
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</tr>
<tr>
<td>Routes</td>
<td>Border DE: Highway 1x both directions</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stationary tests: 2 different locations</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Border IT: Highway Tunnel: 2x both directions Stationary tests: 4 different locations National Road: 1x both directions</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The tests were performed at the borders as illustrated in Figure 30 and Figure 31.
2.3.2 Test outcome

2.3.2.1 Border Austria – Italy: Brenner Area
The measurements on the radio conditions show that the whole route was covered by Magenta network, we did not manage to attach to the Italian network. In the Brenner tunnel, the radio coverage remains weak (no 5G coverage at all and very low 4G signal strengths and quality).

As illustrated in Figure 32, Figure 33, and Figure 34, A12 is principally covered by both sectors of TIIL-BRENNER N01 with a good level and quality before the tunnel.

In 5G, the signal is completely lost in the tunnel and we did not recover it again. Whilst the 4G signal is degrading (to the limit of retainability) without dropping, we recover it again after the tunnel. We did not drive far enough to reselect the Italian network.

The measurements in the road B182 shows obviously continuous and better coverage for both 4G and 5G without interruption of low signal levels (absence of a tunnel on B182)

![Figure 32: Best Server: Cells serving the route](image-url)
We could also notice from Figure 35 that over B182 road, the mobile is principally connected over 5G, the rest of the time it uses LTE network (in single or two carrier modes), whilst through the highway, and because of the tunnel, most of the connection is done through LTE and only a small part is using 5G.
Regarding the end-to-end performance reflected by FTP UL throughput, FTP DL throughput and RTT measurements, they have been performed in a “mobile mode”: driving over the highway A13 as well as the B182 road. A second bench of measurements have been done in a “static” mode and this time only on B182 (Obviously no possibility to have static tests on the highway).

As in the below figures, the results show the following:

- **“Drive Tests or mobile tests”:**

  The FTP DL throughput in both highway A13 and B182 shows overall pretty good values. However, as illustrated in Figure 36, despite of the low throughput points especially in the tunnel due to the loss or very weak coverage, we still have some cases that would require further investigation (especially when the RSRP and SINR don’t match the throughput behaviour). Outside of the tunnel in B182, the overall performance remains better than on the highway with an average value of 95.7 Mbps vs 7.9Mbps on the highway A13. 10% of the samples on the B182 reached more than 229.4Mbps instead of 181.2Mbps on the highway (see Figure 37)
Unlike in DL, the FTP UL throughput shows significant fluctuations in both B182 as well as in the highway A13. As seen in Figure 38, several samples show less than 10Mbps in both areas (Highway A13 and B182) which definitely requires a deeper investigation. The UL throughput distribution confirms the behaviour as in both cases (Highway A13 and B182), the UL throughput values are pretty similar and low: Median in the highway and B182 respectively at 2.3Mbps and 2.6Mbps with only 10% of the samples above 26.5Mbps and 24.6Mbps as shown in Figure 39. Further and deeper investigation would be required; however, it looks like the low throughput might be due to LTE900 as this is where most of the “low throughput” samples are occurring.

The RTT testing shows good RTT values (20ms – 70ms) in most of B182 as well as on the highway right before the tunnel. Everywhere else, we are experiencing long RTT exceeding even 2s in few cases even on B182 (as shown in Figure 40 and Figure 41).
- **Stationary testing:**

  Static tests were done here in 4 locations over the B182.

  The measurements of radio conditions on both 5G and LTE show very good conditions on all measured locations as shown in Figure 42 and Figure 43. The coverage in all location is ensured by the site TIIL BRENNER sector 1 and 2. For LTE, it is mainly covered by LTE 1800 band (see Figure 44).
The coverage in all location is ensured by the site TIIL BRENNER sector 1 and 2. For LTE, it is mainly covered by LTE 1800 band (see Figure 44).

During performance measurements including throughput and RTT, the mobile is mostly connected over 5G network for all four locations (see Figure 45).

Regarding the FTP DL throughput, except one specific sample, all points show a throughput higher than 100Mbps with an average value between 114Mbps and 120Mbps.
When it comes to FTP UL Throughput, most of the values are between 10Mbps and 30Mbps (few samples only have exceeded the 40Mbps).

The UL throughput distribution shows that in 2 locations (Einfahrt_Verladest and Ortsschild_Brenner), the UL throughput is pretty stable with no big fluctuation, the average value is respectively 24.2Mbps and 25.7Mbps,
whilst the two other locations (Grenze and Ortsmitte_Brenner) have a slightly higher fluctuation with significantly lower average not exceeding 10.5Mbps. Further analysis in required.

![Figure 49: FTP UL Throughput Distribution in static mode](image)

The RTT Ping measurements still show high RTT values (compared to what is expected from a CCAM application) over most of the samples.

![Figure 50: RTT Ping in static mode](image)

Most of the values are located between 40ms and 60ms. Only few samples below 40ms. We can also notice less fluctuations in (Einfahrt_Verladest and Ortsschild_Brenner) compared to (Grenze and Ortsmitte_Brenner) with less samples in the high RTT range (above 60ms)

![Figure 51: RTT Ping distribution in static mode](image)

2.3.2.2 Border Austria – Italy: Kufstein Area
The measurements on the radio conditions show that the whole route was covered by the Magenta network, and we did not manage to attach to the German network because of the SIM cards used were not configured for the German network being an ePLMN, in combination with the fact that the border between Austria and Germany continues running parallel to the motorway on the German side in both close proximity and for more than 10 kilometres, hence the modem will continue being attached to the Magenta network as the home network. The whole route is covered with LTE; as the 5G site went on air in October 2021, additional tests were carried out in early July 2022 to provide complementing results for 5G NR.

Several cells from different bands (LTE900, LTE1800 and LTE2100) are covering the route:

![Image](image.png)

**Figure 52: Best Server: Cells serving the route**

There is almost a balanced split of LTE technologies used (LTE 3CA, LTE 2CA and LTE PCC “One serving cell only) along the route as shown in Figure 53.

<table>
<thead>
<tr>
<th>Tech</th>
<th>LTE 3CA</th>
<th>LTE 2CA</th>
<th>LTE PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Share</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Image](image.png)

**Figure 53: Used technologies in drive test mode**

As illustrated in Figure 54, the RSRP (signal strength) is in a good range in general, there is a part of the route where it drops down significantly (probably due to some terrain profile) after the border in Germany before recovering again. In the Austrian side (south of the river), the signal reaches very good level as we are close to the base station.
Figure 54: RSRP Level during drive test mode

Unlike the RSRP, the SINR shows mediocre values right after the border (After the river). In the Austrian side, the SINR values are in a decent to good range.

Figure 55: SINR values during drive test mode

The performance tests including FTP DL throughput as well as FTP UL throughput and Ping RTT have also been done here in both drive test and static mode.

- **Drive test mode:**

In the Austrian side (south of the river) the DL throughput values fluctuate mainly between 30Mbps and 70Mbps with few samples even below 20Mbps. Right after the border, most of the measurements show very low DL throughput values (less than 20Mbps and even 10Mbps) after it gets better close to Niederndorf. The DL throughput seems to have a quite accurate correlation with the RSRP as well as the SINR.
The throughput’s distribution here below show a median value around 30.82Mbps

Figure 56: FTP DL Throughput in drive test mode

Figure 57: FTP DL Throughput Distribution in drive test mode

It is a decent performance for a pure LTE connectivity, however, considering that 2/3 of the drive test was whether on LTE 2CA or even LTE 3CA, a better performance could be expected. One reason for this can be attributed to the higher network utilisation be vehicles and passengers not only during the day, as this section of the corridor is impacted by slowed down traffic (down to 30-60 km/h towards Austria and down to 10 km/h towards Germany due to intermitting inspections of vehicles.

Regarding the UL throughput, the values hardly reach 30Mbps (only few samples on the German side close to Niederndorf). We can still see several samples even below 10Mbps (especially right after the border) which can probably be explained by the radio conditions. In the Austrian side, there are still some samples below 10Mbps but it is mostly between 20Mbps-30Mbps.
The throughput’s distribution below confirms the previous comment and shows a median value around 11.37Mbps. Only 10% of the samples exceeded 28.44Mbps with only handful of points above 60Mbps.

A deeper analysis and traces troubleshooting are probably needed to understand and draw a conclusion including the related actions to be taken.

The RTT values seem to be uniformly spread in the range of 35ms – 60ms. This remains pretty high for what is expected from a CCAM application, however, it can also be explained by the fact that the whole measurement happened on a LTE network only. The activation of 5G would definitely improve the overall performances (UL, DL and RTT).
- **Static mode:**

The same performance tests (FTP DL throughput, FTP UL throughput as well as Ping RTT) have been repeated in a static mode in two different locations:

1. Kufstein Mc Donalds (in the city of Kufstein Austria)
2. Grenz Kiefersfelden (on the German side but still attached to the Austrian network)

As it can be seen from Figure 61, the first point (Kufstein Mc Donalds) is served by TIKU Hugo Petterstr whilst the second one is served by TIKU Oberndorf. Both cells are LTE 1800.

![Figure 61: Best Server in static mode](image1)

Their point in Kufstein Mc Donalds has a much better RSRP (Figure 62) as well as SINR (Figure 63) compared to the one in Kiefersfelden. The second one seems to suffer from pretty mediocre radio conditions.

![Figure 62: RSRP Level in static mode](image2)
The throughput performances seem to be in line with the level of the reported radio conditions. Indeed, the FTP DL throughput in Mc Donalds has much better values (between 70Mbps and 80Mbps) than the one in Kiefersfelden (less than 10Mbps) as shown in Figure 64.

The throughput’s distribution gets this difference even more explicit as the median throughput in Mc Donalds is around 60Mbps with less than 10% of the samples below 33Mbps. The measurement in Kiefersfelden has a median of 6.5Mbps with no sample exceeding the 20Mbps.
The same conclusion can be made for the FTP UL throughput results with maybe less difference than in the DL. The mean value in Mc Donalds measurements is 20.7Mbps vs 11.1Mbps for the Kiefersfelden points. The other contrast between both could also be the fact that only couple of samples in the Mc Donalds points are below 10Mbps whilst we have much more samples in that range for the Kiefersfelden ones.

The Ping RTT values for both points are close to each other. Most of them located in the range of 40ms- 50ms. Despite of the overall better conditions and performance of the Mc Donalds points, we notice that unlike in Kiefersfelden, we didn’t have any sample of RTT below 40ms (in Kiefersfelden there are couple of sample below 40ms).
Additional testing of the 5G NR network of Magenta was carried out, using the LTE1800 anchor and the NR3700 layer provided by the site set up in Eichelwand/Ebbs on the eastern side of the Inn river in close proximity to the border crossing of the motorway A12/A93. These measurements were recorded during the first week of July.

Table 27: Latency 5G drive test on A12 at the border to Germany

<table>
<thead>
<tr>
<th>Measure</th>
<th>Latency [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>(33)</td>
</tr>
<tr>
<td>Max</td>
<td>(72)</td>
</tr>
<tr>
<td>Min</td>
<td>(20)</td>
</tr>
</tbody>
</table>

Table 28: Average throughput 5G drive tests on A94 at the border to Austria

<table>
<thead>
<tr>
<th>Direction</th>
<th>Throughput [Mbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink</td>
<td>(322.5)</td>
</tr>
<tr>
<td>Uplink</td>
<td>(61.8)</td>
</tr>
</tbody>
</table>

The 5G results show relatively minor improvements regarding latency compared to LTE. Average throughput rates are significantly improved with NR compared to LTE.

2.3.2.3 Action Points / For Further Study

At the Italian border (Brenner Area), despite of the existence of 5G and although a big portion of the measurements have been done over the 5G network, parts of the network performances remain mediocre especially in UL (incl. RTT) and would require extensive further investigations. One potential reason could be the difference in TDD slotting times between Austria and Italy: although both countries have adopted the 8:2 ratio (DL:UL) to protect Fixed-Wireless Access legacy networks, the start timing of the slots has a shift by one slot, causing one UL slot being de facto cancelled by interference of DL transmissions on the other side of the border. This is not necessarily limited to interference on the same channel(s).
While Austria and Germany have different TDD patterns (Austria: 8:2; Germany 4:1/4:1), no issues comparable to the situation at the Brennerpass/Brennero border were observed. One reason is that the 3.7 GHz section assigned to MTA is not used by PLMNs in Germany but assigned to private 5G campus networks which are limited to indoor operation. The other reason is that no 3.x GHz TDD deployments (any MNO and any private campus network) side have been done so far in Germany anywhere close to this border with the exception of the German 5G-CARMEN deployment.

### 3 Cross-border transition measurements using automotive 5G-modem

This chapter describes the 5G NSA measurements performed mainly in 2022 after more features have been activated in the mobile Networks, as well as all planned 5G cells at the borders were installed. Most of the measurements were thus repeated compared to what was reported in D5.2. Focus of the measurements were the determination of border transition procedures and related data interruptions, as well as basic performance tests for latency in stationary conditions in a 5G cell, which was measured with means of PING round trip time. This means that the respective results comprise mainly the radio interface and basic core components. In this regard, for actual use cases additional delays related to application processing sum up the values measured here.

#### 3.1 Test Equipment

For the setup, a Qualcomm 5GCC device was used, which consists of a modem supporting 5G NSA on all the relevant bands and with the needed LTE anchor combinations. For 5G, this is band n78 used in TDD as configured in all the networks of the project. The device is the same, which is used as 4G/5G modem in the BMW and CRF cars for this project.

The device was connected to a laptop for tracing with the Qualcomm QXDM tool and providing access via the Android Debug Bridge (adb). Utilizing this connection, tools like PING could be directly used inside the Android operation system of the device.

The QXDM tracing e.g. enables the evaluation of all RRC and NAS layer messages exchanged, which gives a deeper understanding of the procedures happening during the cross-border transitions, including the data interruption times. It also provides information of the other layers like MAC, PDCP and Physical layer.

#### 3.2 Measurement Locations and Procedures

The cross-border measurements were performed with 5G-enabled SIM cards from Deutsche Telekom for Austria – Germany, and from Telecom Italia for Austria - Italy. The device had a continuous PING running to have an ongoing data connection (staying in RRC connected mode). Partly two parallel PING sessions were prepared, since in the case of Italy an internal MEC server was supposed to be the target of the PING, which is not reachable when in Austria.

The tests were done at the defined border crossings of the 5G-CARMEN corridor, i.e. Kiefersfelden/Kufstein for Germany-Austria, and Brenner for Austria-Italy. The driving speed was determined by the overall traffic situation, i.e. down to about 10 km/h and less for Germany-Austria due to some border control activities, and about 60 km/h for Austria-Italy, where constructions were ongoing in the border tunnel.
To access the latency performance of the networks, stationary near cell tests have been conducted at locations that get 5G service from the involved cross-border sites in line-of-sight conditions: for Germany the service station parking of Inntal West (Kiefersfelden), for Austria Ebbs-Eichelwang (Kufstein), and for Italy the parking of Eurospin supermarket in Brennero. Figure 69 gives an overview of the test locations along the 5G-CARMEN corridor.

![Figure 69: 5G-CARMEN corridor and measurement locations](image)

**Figure 69: 5G-CARMEN corridor and measurement locations**

**Picture source: OpenStreetMaps © OpenStreetMaps Contributors**

### 3.3 Test results

#### 3.3.1 Inter PLMN transitions at border crossings

**3.3.1.1 General background and interworking**

As outlined in Deliverable D3.2, in current networks the Inter PLMN transitions are not supported in the most seamless way that the 3GPP standard defines, which would be an Inter PLMN handover, which means a call or data connection simply continues without packet losses or interruptions, similar to a handover inside the PLMN. In contrast to this the strategy of the operators so far was to keep their subscriber as long as possible in their network including some spill over areas to the neighbour countries, which is e.g. avoiding “ping-pong”-effects for subscribers who live close to the border and whose devices would else potentially move back and forth between the own and the neighbour PLMN due to fluctuating RF conditions.

When indeed moving to the neighbour PLMN this approach means, that the UE has to stick to the old registered PLMN until it completely loses coverage on the serving cell and does as the next step try to find another cell of
this PLMN, checking all Radio Access Technologies (RATs) it is supporting (like 4G, 3G, 2G). Only after this, the UE is allowed to search for a new PLMN to register at and try to re-establish the data connection.

A major improvement can be expected with the configuration of equivalent PLMNs (ePLMNs): it is possible to define other networks as ePLMNs, which is transferred to the UE within the ATTACH ACCEPT message when registering to a network, as well as in the TRACKING AREA UPDATE ACCEPT, which is received when the UE is moving through the network, reporting the change of the tracking area broadcast by the serving cell it is entering. Figure 70 shows the Information Element that is included in these messages, here for the actual PLMNs involved in 5G-CARMEN.

![Magenta](image1)

![TIM](image2)

Figure 70: Information Element to list equivalent PLMNs

The UE is then treating cells belonging to an ePLMN the same way as if they would belong to the PLMN it is registered to. This already impacts radiolink layer procedures like failure recoveries. E.g. in case of a radiolink failure in connected mode, the recovery procedure would be an RRC Connection Reestablishment and with the ePLMN setting also cells from the other PLMN would be seen as candidates, and the procedure will be attempted. This procedure cannot be carried out successfully since there are no interconnections of network elements like eNode Bs over the PLMN borders, however the transition to this cell can happen very fast (guard timers are typically in the hundreds of milliseconds range; can be configured by the operator).

The UE will stay on this new cell to carry out the next steps to get the data connection back, which is sending a TRACKING AREA UPDATE REQUEST to the MME. For this purpose, a new RRC connection is established with the eNode B. If the MMEs would be interconnected over the PLMN borders (S10 interface in a roaming configuration), the Tracking Area Update procedure would move the UE context in the core network and do the needed switches in the user plane, and the data flow could continue at this point.

Since this is not the case for our networks, the MME is sending a TRACKING AREA UPDATE REJECT message (since it has no connectivity to the last MME the UE was connected to and cannot derive the UE context). This is per 3GPP standard triggering an immediate ATTACH procedure from the UE, similar to an initial registration, when a device is powered on. This includes the setup of the data connection, and finally the data can continue to flow, now utilizing the new network. Note, that additional needed procedures like AUTHENTICATION and SECURITY that happen within the ATTACH procedure are further delaying this. For an NSA network all these procedures are carried out on the LTE/EPC part. 5G is not involved at this point, however the steps needed for the activation of the Secondary NR Cell can be started while the interworking is ongoing in the new PLMN. This is normally the configuration of measurements for the 5G cell followed by the reporting of the UE (in case it found it). Depending on the RF conditions for the NR cell and the LTE carrier, it is possible that at the time when the data connectivity is re-established, also the 5G secondary cell was added.
and can be used for the actual data transfer. In case of a smaller coverage of 5G (or potentially not co-located deployment), the 5G part activation might also be carried out at a later step.

A further improvement is the “Fast Network Reselection”, which means that when the UE is about to leave the network and the coverage or RF signal strength degrades under a certain limit, the eNode B would send a RRC Connection Release which contains the frequency information of the target cell in the new PLMN. In combination with the ePLMN configured, the UE would then immediately try to acquire the target cell and do an RRC Connection Request for the TRACKING AREA UPDATE REQUEST. This means there is no attempt of a RRC Connection Reestablishment saving some message exchange. Also the transition is supposed to be smoother since the trigger is coming earlier (i.e. in better RF conditions) compared to hitting a radiolink failure due to too weak RF plus there is no guard timer involved that needs to elapse, and the data connection is continuing until the RRC Connection Release is sent. (For the other case it is lost at some point when the synchronisation to the old cell is not possible anymore). This improvement was implemented for the transition from Germany to Austria. The details will be explained in the respective section below.

3.3.1.2 Result Austria - Germany

Figure 71 shows the results for the transition between Austria and Germany. The most important parts of the interworking are shown including the timestamps for the different messages. These timestamps are taken at the UE, i.e. when a certain message appears in the UE stack. There would be some slight differences if someone would trace at a RAN or core network element due to the transmission times over the air.

The Austrian PLMN had the German PLMN configured as ePLMN, so this transition can happen fast, and in this example the UE accesses the German NW with a RRC Connection Reestablishment caused by a Handover failure. This is also a possibility when by chance the serving eNode B tried to handover the UE to another cell, which is failing due to the worsening RF conditions, and the UE cannot get successfully onto the target cell. Instead, it finds the cell of the new PLMN, trying the recovery there. One can see the fast rejection and following new RRC Connection Request for the TRACKING AREA UPDATE REQUEST – all this happens within 400 ms.
The TRACKING AREA UPDATE REQUEST is immediately rejected by the MME (within about 260 ms), which triggers the new ATTACH procedure. As mentioned above, further procedures with the network have to be carried out in this step (Authentication and Security), which results in an overall duration of about 1 s between ATTACH REQUEST and ATTACH COMPLETE. The latter can be seen as the point when the data connection is up again. The overall interruption seen here is 2.6 s.

### 3.3.1.3 Result Austria- Italy

Also, here the interworking is quite similar to the Austria – Germany case (see Figure 72) – in this example the actual change to the cell in the TIM PLMN is happening when trying to re-establish the connection after a radiolink failure (the last message seen in Austria is a measurement report, that did not trigger any action from the old eNode B anymore). As mentioned, TIM is an ePLMN for the subscriber coming from Austria, which enables this smooth move to the Italian cell.
In the tests reported in D5.2, the oddity of an extensively long duration between TAU REQUEST and TAU REJECT of 9 s was seen. This could meanwhile be debugged and solved: the reason was that the Italian MME tried to resolve the IP address of the Austrian MME by querying the Magenta DNS server (it is possible to derive the URL from the MME identifiers given in the TAU REQUEST). The server was responding with the address, which caused the Italian MME to start the UE CONTEXT REQUEST procedure. Since there is indeed no S10 interface setup between these MMEs, there is no response from the Austrian MME, however the procedure continues as defined with 3 s wait time for an answer and overall three attempts, which adds up to the seen 9 s extra delay. After this the Italian MME declared the procedure as not successful and was thus finally sending the TAU REJECT. To solve this problem, Magenta was able to configure their DNS server in a way, that it does not return the IP address of the Austrian MME, thus the Italian MME was not attempting the UE CONTEXT REQUEST procedure. Since there is indeed no S10 interface setup between these MMEs, there is no response from the Austrian MME, however the procedure continues as defined with 3 s wait time for an answer and overall three attempts, which adds up to the seen 9 s extra delay. After this the Italian MME declared the procedure as not successful and was thus finally sending the TAU REJECT. To solve this problem, Magenta was able to configure their DNS server in a way, that it does not return the IP address of the Austrian MME, thus the Italian MME was not attempting the UE CONTEXT REQUEST procedure, but instead is also now immediately rejecting the TAU REQUEST. As a result, one can now see the TAU REJECT about 230 ms after the TAU REQUEST. The cause value of the TAU REJECT is “UE identity can not be derived by the Network”, which means that the following ATTACH REQUEST contains the IMSI, and thus there is no need for the IDENTIFICATION procedure.

In the shown example, the overall interruption between the last message seen in Austria and the successful end of the ATTACH procedure is in average 2.7 s, for different runs values in the range from 2.2 s to 3.7 s were measured.

3.3.1.1 Result Germany – Austria

The difference between Germany – Austria and the reverse direction is the additional implementation of the “Fast Network Reselection”: when the signal strength and quality of the serving cell in Germany is degrading (since the UE is moving towards the border and that way out of coverage), the EUTRAN is configuring a
specific Measurement Report for an Event A3, which means “Neighbour Cell becomes offset better than primary serving cell”. For the neighbour cell the frequency (EARFCN) of an Austrian cell is given, and for offset the NW uses 0 dB, which means that the event is fulfilled as soon as the Neighbour Cell is as strong as the serving cell. This triggers a Measurement Report Message from the UE, which includes the PCI of the detected cell. Note, that in the case that the same EARFCNs are used for the two different NWs (which is possible since they are in different countries), the NW would look up if this is indeed a PCI from a cross-border cell and is then triggering the RRC Connection Release. This means also, that there is a need for some coordination and exchange of site data between the MNOs in the neighbouring country to populate such information properly. In

Germany - Austria (DTAG SIM)

![Diagram of interworking](image)

- **09:58:08.416**: Meas. Report (Event A2) (i.e. weak serving cell)
- **09:58:08.917**: RRC Con. Reconfig (Setup of Event A3, 6400)
- **09:58:09.473**: Meas. Report (Event A3)
- **09:58:09.491**: RRC Con. Release (EARFCN: 6400)
- **09:58:09.935**: RRC Con. Request [TRACKING AREA UPDATE REQUEST]
- **09:58:10.022**: TRACKING AREA UPDATE REJECT
- **09:58:10.074**: RRC Con. Request [ATTACH REQUEST]
- **09:58:11.874**: ATTACH ACCEPT (Activate default EPS bearer context request)
- **09:58:11.877**: ATTACH COMPLETE (Activate default EPS bearer context accept)

Note: for simplicity, not all messages shown. Time stamps based on UE log

Figure 73: Interworking with timestamps for the border crossing Germany - Austria

case that a PCI from the own NW would be reported, the RAN should do a Handover to that cell instead. The RRC Connection Release message does per standard only contain the EARFCN of the target cell (not the PCI), however since this was the strongest cell measured just before, a smooth acquisition is very likely, and could also be confirmed by the testing that was executed. The rest of the interworking is quite similar, i.e. the UE sends a TRACKING AREA UPDATE REQUEST, which is rejected, followed by the ATTACH procedure. A small difference in the interworking compared to the reverse direction is the cause value of the TRACKING AREA UPDATE REJECT, which is here “Implicitly Detached”. This triggers the UE to use still the GUTI (Global Unique Temporary UE Identity) in the following ATTACH REQUEST which is followed by an IDENTIFICATION procedure from the MME asking for the IMSI (since it cannot get this information from the last MME, that issued the GUTI). In the Austria – Germany case, the TAU REJECT has in most cases the cause value “UE Identity cannot be derived by the Network”, thus the UE is per 3GPP standard directly including its IMSI as identity in the ATTACH REQUEST and therefore the IDENTIFICATION procedure is not needed, which saves some signalling and this way time. This might be an optimization opportunity (also
checking the reason of the seen inconsistency in the Austria – Germany direction). Evaluating the field measurements done, one can see that the time between TAU Request and TAU reject is very small mostly - under 100 ms. The overall service interruption here between the RRC Connection Release and the ATTACH COMPLETE is in average 2.3 s, with the observation that the ATTACH procedure takes 1.6 s to 1.8 s, which is significantly longer than what is seen for the reverse direction (there < 1 s).

The mobility procedures are happening on the LTE anchor frequency used (also called primary serving cell). Since modern 4G networks use a combination of different LTE bands, the actual used anchor frequency can vary depending on the actual RF conditions that the UE was experiencing, and this also applies to the target neighbour cell in the cross-border country.

For the tests performed we mainly see 1800 MHz as band of the LTE anchor cell in Germany, followed by the configuration to measure the 800 MHz band and the RRC Connection Release to this band (this is also shown in Figure 73: ARFCN 6400 belongs to the 800 MHz band). In some occasions additional measurements for the 2.6 GHz band were also configured. However, the target of the RRC connection Release was always the 800 MHz band. The actual parameter settings and target frequency band strategy etc. could be an area of optimization, however this was not attempted within the project.

### 3.3.1.2 Result Italy - Austria

The situation is different for the case of the transition from Italy to Austria (see Figure 74): the TIM Network was not configured to declare the Magenta Network as ePLMN, thus the transition here can be seen as the legacy situation. This means the actual registration on the new network is only happening after the extended search for cells of the old PLMN after the serving cell was lost due to too weak RF conditions (since the UE moves away from it). The 3GPP standard gives only an upper limit for the time when the UE is finally considering to register on the new PLMN (very high value of 300 s), thus the actual value is implementation dependent. Looking at the UE trace, one can see a last Measurement Report Message (MRM) on the old cell, after which the border crossing is happening. Afterwards the attempts of the UE to find another cell are visible: it is reading System Information Broadcast Type 1 messages, which carry the PLMN information of the cell which is broadcasting this. Here already 1.8 seconds after the MRM the UE is able to acquire a cell from the Magenta network. However, it is not yet allowed to register.
It takes nearly another 17 s until the UE is allowed to attempt the registration on the new PLMN cell. The rest of the interworking is like seen in the other tests: TAU REQUEST being rejected quickly by the Austrian MME (about 160 ms), which is followed by the ATTACH procedure. As seen before for the Austrian MME/CN and the transitions from Germany, this is done within about 1.7 s. The overall duration of the data outage amounts to 20 s for this test (remember that this might vary with the UE implementation as mentioned above).

Since there were restrictions in the TIM NW which did not make it possible to configure the ePLMNs in the MME to get the respective IE added in the ATTACH ACCEPT/TAU ACCEPT, TIM was pursuing another way: it is also possible to have this information on the SIM card, which is then referred to as eHPLMN. The actual configuration would be sent over-the-air updating the SIM information, when the user first attaches to the TIM network, and would be stored. Related configuration and first field verification was attempted by TIM; however this was not successful yet. The expectation is that the SIM based and MME based approaches for giving the ePLMN information to the UE achieve the same, so the cross-border behaviour shall be identical.

### 3.3.1.3 Result Summary

The table below summarizes the test results for the seen over all data interruption times when crossing the borders, and the areas for potential optimization to reduce these times. Note, that Germany – Austria with the complete implementation of Fast NW Reselection also shows very consistent results with small variations. This is according to the expectation since the move to the new PLMN is steered here by the RRC Connection Release
command. For the other cases, the move is happening more randomly due to the actual radiolink or handover failure experienced.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Overall Data Interruption</th>
<th>Optimization Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany - Austria</td>
<td>2.3 s</td>
<td>Check ATTACH procedure (1.8 s instead of 1.0 s in reverse direction)</td>
</tr>
<tr>
<td>Austria - Germany</td>
<td>2.6 s</td>
<td>Add Fast NW Reselection</td>
</tr>
<tr>
<td>Austria - Italy</td>
<td>2.7 s</td>
<td>Add Fast NW Reselection</td>
</tr>
<tr>
<td>Italy - Austria</td>
<td>20 s</td>
<td>Add ePLMN + Fast NW Reselection (currently legacy situation)</td>
</tr>
</tbody>
</table>

Figure 75 summarizes the different implementations of the cross-border transitions including some durations of the related sub-procedures. The values are estimates from the field testing results. There are run to run variations, but also systematic differences, e.g. the TAU REJECT of the Magenta MME is below 100 ms, while for TIM more than 200 ms are seen. However, the aim of this figure is rather to give an overview, especially for the stepwise improvements of the features. A further improvement would be brought in if the S10 interface between the involved MME in the neighbour countries could be established. In that case the interworking would end with the TAU procedure, which should then be successful, i.e. lead to a TAU ACCEPT, the ATTACH procedure would not be executed. Note, that the successful TAU procedure likely will take a bit more time than the rejection since further procedures in the core network will be needed to switch the data connection accordingly. It can be assumed that it should be faster than the ATTACH procedure, so less than 1 s can be expected.

Figure 75: Summary of different implemented cross-border transitions and related time durations

However, the introduction of S10 as roaming interface is seen as not feasible by mobile network operators, keeping in mind the multitude of neighbour countries and different operators in each country that then would need to be interconnected and the reluctance to expose network elements like MMEs to external parties.

3.3.1.4 Results for 5G Interruptions
As mentioned, the cross-border transition is based on procedures happening on LTE anchor. Here a closer look on the handling of 5G after the borders shall be provided (before the borders, the data connections were running with NR Secondary Cell Group (SCG) active in all cases). Apart from the implementation which is dependent on the choice of the infrastructure vendor, also the actual deployment of the 5G cells which effect the RF conditions seen have an impact. Thus, the performance is only valid for the actual location and road driven.

**Germany – Austria** (Kiefersfelden – Kufstein on motorway A93/A12):

In Austria there is some additional time needed after the ATTACH procedure is completed: within 30 ms Measurements for an Event B1 for NR cells are setup (Event B1: “Inter RAT Neighbour becomes better than threshold”). The NR cell is reported after further ~160 ms, which leads to the addition of the NR SCG after about 250 ms. So after the data connection is up again Austria, additional 460 ms are needed to have the call back in 5G. An additional observation here is, that the activation of the NR SCG includes also an inter-band handover of the LTE anchor cell from the 800 MHz band to 1800 MHz.

**Austria – Germany** (Kufstein - Kiefersfelden on motorway A12/A93):

The B1 Measurement for NR is configured in the same message that carries the ATTACH ACCEPT, the cell is reported after 230 ms to 440 ms in the different runs analysed, and the NR SCG addition happens about 80 ms after the Measurement Report was sent. This gives an overall duration of 320 ms to 520 ms, mainly dependent on the actual RF conditions.

**Austria – Italy** (Brennero Tunnel, A22):

Also, here the B1 Measurement configuration is carried in the same RRC message as the ATTACH ACCEPT, but here in some cases the UE is only able to report the NR cell after a couple of seconds (there is a big variation between different runs). This can be attributed to the fact, that the changing of the PLMN is happening inside the tunnel, where the LTE anchor provides some coverage. However, the 5G cell is not visible there. From the drive tests, this is only the case after the tunnel was left and a curve to the left, close to the Plessi Museum, where then also the 5G SCG addition is happening (the log shows 80 ms after the reporting of the 5G cell). So for this location the additional time needed to have again a 5G data connection depends on where exactly the PLMN transition is happening within the tunnel – if it happened early, the delay is bigger and vice versa. There might be impacts by shadowing from trucks in certain runs, which can influence the location of the transition. In the best cases the time is with about 500 ms similar to the other border.

The table below summarizes the overall 5G interruption times.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Interruption of 5G</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany - Austria</td>
<td>2.8 s</td>
<td></td>
</tr>
<tr>
<td>Austria - Germany</td>
<td>2.9 s – 3.1 s</td>
<td>Some variations in reporting the 5G cell</td>
</tr>
<tr>
<td>Austria - Italy</td>
<td>3.2 s (best case)</td>
<td>Big variations due to tunnel and 5G site location</td>
</tr>
</tbody>
</table>

### 3.3.2 Latency Results in Stationary Conditions

The end-to-end latency was assessed using PING from the device operation system (via adb) to suitable servers depending on the country. For the tests shown here the SIM cards which were also used for the cross-border scenarios, which were selected in the way that also Local Breakout could be enjoyed e.g. using a DTAG SIM card in Austria. As PING payload size, the default android value of 64 bytes was used and a time between consecutive PINGs of 200 ms to provide a certain activity level and stay for sure in RRC connected state. Near cell conditions with one dominant serving cell were selected to avoid handovers during the tests as well as a potential influence from weak RF (e.g. needed re-transmissions). Note, that the latency derived from PING might be lower than what will be experienced on application layer for the actual use case implementations since needed time for processing on higher layers is excluded.

#### 3.3.2.1 Results Austria
The stationary tests were performed in Ebbs-Eichelwang, which is the location of the Magenta site covering the motorway at the border. The target server for the PINGs was the provided testserver (tmatest.at). The performance was very good with an average PING RTT value of 19 ms and a very low variation (see PDF in Figure 76). This is the NW with the best performance seen.

![PING RTT - Austria](image)

**Figure 76: PING RTT in Stationary Conditions for Magenta Austria**

### 3.3.2.2 Results Germany

For Germany the tests were executed on the parking lot of service station Inntal-West in close vicinity of the site. Here the measured average of the RTT was 28 ms for a call in 5G, which is nearly 10 ms more than for the Austrian case. A comparison with 4G was done here as well (disabling the 5G capabilities of the device by a SW change, but keeping the rest of the conditions identical, like exact position etc.). This led to an average RTT of 37 ms, which means 9 ms more than for 5G. The PDF of the RTTs can be seen in Figure 77 – for the 5G case the values are less spread and the overall shift of about 10 ms can be observed as well.
3.3.2.3 Results Italy

The stationary tests were performed on the parking lot of a supermarket in Brennero being served by TIM 5G site installed on one of the motorway parkings there. Here a TIM SIM card was used and the MEC server as target of the PINGs. However, the measured average RTT was with 39.8 ms quite high for 5G. A comparison test for 4G only resulted in an average RTT of 41.1 ms. Looking at the PDFs for these tests (see Figure 78), one can see an a bit smaller distribution of values for 5G. A deeper analysis of the UE logs showed, that during the PING activities, the network configured the connection in a way that 4G had to be used in the uplink, while the downlink went via 5G (more details below). C-DRX (connected mode discontinuous reception) was deactivated, which was in earlier tests last year impacting the performance due to quite aggressive settings rather trying to optimize battery life (see D3.2 for details). Note that around 40 ms RTT for 5G had also been estimated from the testing in Laghetti last summer, however there one could see an about 10 ms advantage compared to LTE. Since TIM was performing some optimization activities, they might have measured better results with a better setting compared to what was available at the time of our testing.

As indicated, there are different configurations possible for an NSA system in terms of which technology is used in the uplink, even when the 5G SCG is activated. During the latter tests within 5G-CARMEN, it was noticed that the uplink allocation on TIM network switches between NR and LTE in both stationary and mobility conditions. After SCG addition, uplink traffic is configured on NR and is then moved to LTE and toggled back to NR and so on. This is done with the change of cellGroup ID for the uplink path in the RRC message sent to the UE (RRC Connection Reconfiguration). It also includes the buffer threshold, which was then set to infinity (ul-DataSplitThreshold “infinity”). The threshold determines a size in bytes to which the traffic would be split between NR and LTE once it is exceeded, and since the configuration is “infinity” it means there is no split. If there is indeed the strategy to change between an NR and LTE configuration for the uplink, it is seen as an optimization point for TIM to configure the threshold accordingly once NR is brought up and therefore obtain the advantages of both RATs and therefore avoid signalling to perform leg switch. Another point would be to review the criteria for uplink switch (e.g. buffer size, uplink SNR, BLER) to make sure the ping pong is avoided. The uplink leg switch could be expected to occur specially in mobility as the NR cell strength degrades and the

![Figure 77: PING RTT in Stationary Conditions for Deutsche Telekom](image-url)
traffic would then be moved to LTE, considering it has bigger footprint, but for the stationary PING tests it revealed some area of improvement or investigation for TIM. Also for the tests in mobility, rather a periodic toggling was seen then something connected to the actual conditions experienced.

Figure 78: PING RTT in Stationary Conditions for TIM

3.4 Summary

The main focus of the tests was the investigation of the cross-border service interruption times, and how the different available features that could be deployed do significantly reduce these times compared to the legacy situation: from 20 s the interruption could be reduced to 2.3 s with the implementation of ePLMN and fast NW reselection by RRC connection Release. However, keeping the intended CCAM related applications in mind, which require continuous service without significant outages (like smaller than 50 ms), this reduced value is still magnitudes too high. Such a reduction might be possible in case the different MNOs would implement inter PLMN handover, which is judged as not feasible due to the needed deep integration and connection between the networks.

This leads to the conclusion that C-V2X direct communication using the PC5 interface plays an important role, which can be used as a complementary link ensuring uninterrupted service across PLMNs and country borders. It is also well suited to deliver latency-critical applications like basic safety. Even though the outlook is promising for Uu interface with the introduction of 5G Standalone, the current values measured for the different networks show, that even in the currently unloaded scenario, 5G did not yield a major improvement in latency (as was actually expected from a Non-Stand Alone deployment). The following sections, as well as D5.4, show the application/service processing delays which need to be added (although we do have good examples - Geoservice southbound interface, S-LDM – where processing latencies have proven negligible with respect to the total delay budget).
4 Federated and Orchestrated MNO Edges - Final Deployment and Use for CCAM

This section describes the final deployment of the Orchestrated Edges and associated edge services for CCAM in the local cloud premises of the project’s MNOs, i.e., DTAG, MTA, and TIM. The final deployment serves the project’s WP5 for trialing, testing, and demonstration of CCAM use cases per this document’s Section 0 at and across borders. Furthermore, the final deployment of the Orchestrated Edges in the MNOs’ production network complements early laboratory deployments for testing, validation, and evaluation of Orchestrated Edges enablers per WP4, going beyond features required by the demonstrated use cases, thus enabling future CCAM services by means of low-latency cross-border service continuity. This includes features of smart edge applications to boost orchestration decisions and of a programmable edge data plane for transparent edge bridging (TEB) between different MNO edge networks. Detailed evaluation results based on the deployed Orchestrated Edges can be found in D4.3 [5].

4.1 Deployment and Connectivity between Orchestrated Edges – High-Level View

As reported and described in D4.2 [6], the Orchestrated 5G Edges platform has been deployed stepwise on the MNOs’ edge network premises in all three countries (i.e., Italy, Austria, and Germany). Thus, Figure 79 illustrates the deployment of the high-level architecture of the Orchestrated 5G Edges platform using the MNOs’ infrastructure (i.e., TIM, Magenta, and DTAG), thereby showing the main components that enable federation and cross-border management and orchestration operations for the Connected, Cooperative, and Automated Mobility (CCAM) services that correspond to the 5G-CARMEN use cases.

The colour code in Figure 79 is described below:

- Red circle – interfaces for the communication between applications of distributed orchestrated edges (service mesh). This type of interface enables sharing MEC application specific metadata (e.g., UE location, speed, destination, etc.) for the state migration and service continuity.
- Blue circle – interfaces for the communication between orchestration components. In particular, Lo-Lo reference points are between edge-level orchestrators from different domains, and Or-Or reference points are between top-level orchestrators from different MNOs.
- 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. This type of interface represents the interaction between orchestration layer and the Edge Controller’s Northbound Interface (NBI).

The deployment of the Orchestrated Edges set-up in all three countries consists of two orchestration layers and is based on the principles of Network Function Virtualization (NFV) and Software Defined Networking (SDN). The orchestration layers are:i) the top-level service orchestrator NFV Service Orchestrator (NFV-SO), and ii) the edge-level orchestrators, i.e., NFV Local Orchestrator (NFV-LO) and MEC Application Orchestrator (MEAO). The edge-level orchestration system connects with the NFV-SO via the newly defined Mv1’ reference point, through the Adaptation layer, which is an extended version of the standard Mv1 reference point, as described in D4.2.

With reference to Figure 79, two boxes shown in each MNO’s setup represent two Kubernetes (K8s) clusters. One of these clusters (the top one) hosts the software components of the NFV-LO, MEAO, and Adaptation Layer, i.e., Mv1’ (cluster 1), while the second cluster (the bottom one) hosts the components of Edge Controller (ECON) and the MEC platform (cluster 2), which represents Network Function Virtualization Infrastructure (NFVI) resources that can be used for the instantiation of edge services associated with the project’s Back Situation Awareness (BSA) and Centralized Cooperative Lane Change (CLC) use cases.
4.2 Deployment and testing methodology

As reported in D4.2, the evaluation of the Orchestrated 5G Edges platform is being performed both in partners’ lab premises and in a field pilot trial, where lab-based evaluations focus mainly on the concepts that cannot be evaluated in the pilot due to the limitations and constraints in the production network (e.g., no 5G-Core available yet and related coupling with MEC, MEC host selection, etc.).

We deployed all platform components (i.e., NFV-LO, MEAO, adaptation layer, and ECON) on the sites of TIM, MTA, and DTAG, except for the NFV-SO, which is hosted in a private cloud network. Three instances of the NFV-SO are deployed in the private cloud, mimicking the centralized deployment of each MNO’s service orchestrator, whereas the Or-Or reference point applies as local interface between the NFV-SO instances of TIM and MTA, as well as of MTA and DTAG. After the deployment has been successfully finalized, we started the initial functional, operational, and integration testing of management and orchestration operations of the distributed service deployments. Besides the orchestration components that constitute the Orchestrated 5G Edges, we have also deployed BSA application service, as well as the Server Local Dynamic Map (S-LDM), to test the orchestration operations (e.g., application on-boarding, instantiation, termination). In particular, to test the connectivity of BSA application service with the client application running in a vehicle, a testing application has been developed, thereby mimicking the traffic sent from a vehicle to the BSA application in the upstream direction. This client application has been used for early testing BSA application and reception of the Cooperative Awareness Message (CAM), followed by tests with real vehicles on the road, which connect to the infrastructure through MNOs’ cellular network. In case of S-LDM, the application running on the Orchestrated edges platform retrieves real-time information from the AMQP broker on the MEC platform, while the broker collects messages from a vehicle. The last services, that has been packaged to suit automated deployment on the Kubernetes-based edges and on-boarded in the networks of DTAG and MTA, was the Manoeuvring Services (MS), which collaborates with the S-LDM and Response Router edge services as well as with the AMQP broker to enable the CLC use case.

In this report, we enclose the final status of integration and functional tests, while the detailed presentation of all tests, including the operational tests and results have been presented in D4.3 [5]. The deployment is also
depicted in Figure 80, with the color code described in scope of the figure. Some functions have been deployed and tested only with coverage on one border and not on both borders. Local tests have been performed for all deployed functions. For a few functions, cross-border operations could only be tested partially with connected and driving vehicles.

In Table 29, we present the status of the integration and deployment tests. These tests are defined to confirm the status of platform deployment on different MEC platforms that belong to respective MNOs, and to report the connectivity of a particular platform component with other components. The success of an integration and deployment test is measured in terms of i) testing the connectivity of a particular platform component with other platform components, i.e., via testing the reference points through which this particular component interfaces with the remaining part of the platform (e.g., performing REpresentational State Transfer (REST) request and receiving a valid response), and ii) checking the status of the deployed K8s Pod inside the K8s Cluster.

In Table 30, the functional tests as well as their status are reported. Functional tests indicate the feasibility of a particular orchestration/service operation, e.g., the in-country service instantiation is successful as an intended operation of deploying service in the platform resulted in service availability. In addition, the operational tests that correspond to the functional tests result in the measured KPIs.

Note: The list of functional tests provided in Table 30 is not exhaustive, but comprise selected tests being of key relevance for the WP5 trials and demonstration. The complete set of tests have been reported in the final deliverable of WP4, D4.3 [5].
Figure 80: Final status of integration, deployment and functional tests of the Orchestrated 5G Edges platform
4.3 Result of selected tests

The following tables present the results of the integration and deployment as well as of selected functional tests. For complete figures on the testing and validation results status of all designed cross-border CCAM enablers of the Orchestrated Edges, please refer to D4.3 [D4.3].

Note: The following tables update the status that has been presented in D5.2 [3]. Updated status carries a green status symbol.

Table 29: Integration and deployment (ID) tests

<table>
<thead>
<tr>
<th>Label</th>
<th>Test</th>
<th>MNO site (MEC platform)</th>
<th>Status</th>
<th>Status description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID-T1</td>
<td>Deployment of NFV-LO</td>
<td>DTAG</td>
<td>✔</td>
<td>Connectivity with Adaptation Layer, MEAO, and ECON, tested via registration procedure performed via REST requests (response to POST request is 200 OK in all cases, connectivity ensured). NFV-LO Pod running in K8s cluster (cluster 1).</td>
</tr>
<tr>
<td>ID-T2</td>
<td>Deployment of MEAO</td>
<td>DTAG</td>
<td>✔</td>
<td>Connectivity with NFV-LO tested via registration procedure performed via REST requests (response to POST request is 200 OK, connectivity ensured). MEAO Pod running in K8s cluster (cluster 1).</td>
</tr>
<tr>
<td>ID-T3</td>
<td>Deployment of Adaptation Layer</td>
<td>DTAG</td>
<td>✔</td>
<td>Connectivity with NFV-LO and NFV-SO tested via registration procedure performed via REST requests (response to POST request is 200 OK, connectivity ensured). Adaptation Layer Pod running in K8s cluster (cluster 1).</td>
</tr>
<tr>
<td>ID-T4</td>
<td>Deployment of ECON</td>
<td>DTAG</td>
<td>✔</td>
<td>Connectivity with NFV-LO tested via registration procedure performed via REST requests (response to POST request is 200 OK, connectivity ensured). ECON Pod running in K8s cluster (cluster 2).</td>
</tr>
<tr>
<td>ID-T5</td>
<td>Deployment of NFV-SO</td>
<td>Private Data center</td>
<td>✔</td>
<td>Connectivity with Adaptation Layer tested via registration procedure performed via REST requests to DTAG’s orchestrated edge deployment (response to POST request is 200 OK). Since three instances of an NFV-SO are running in a private data center, one for each MNO, the same validation tests have been performed for the NFV-SO instances dedicated to TIM and MTA, including the connectivity to the Adaptation Layer associated with the orchestrated edge deployment in TIM and MTA networks, respectively.</td>
</tr>
<tr>
<td>ID-T6</td>
<td>Deployment of NFV-LO</td>
<td>MTA</td>
<td>✔</td>
<td>Same as ID-T1.</td>
</tr>
<tr>
<td>ID-T7</td>
<td>Deployment of MEAO</td>
<td>MTA</td>
<td>✓</td>
<td>Same as ID-T2.</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------</td>
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<td>----------------</td>
</tr>
<tr>
<td>ID-T8</td>
<td>Deployment of Adaptation Layer</td>
<td>MTA</td>
<td>✓</td>
<td>Same as ID-T3.</td>
</tr>
<tr>
<td>ID-T9</td>
<td>Deployment of ECON</td>
<td>MTA</td>
<td>✓</td>
<td>Same as ID-T4.</td>
</tr>
<tr>
<td>ID-T10</td>
<td>Deployment of NFV-LO</td>
<td>TIM</td>
<td>✓</td>
<td>Same as ID-T1 &amp; ID-T6.</td>
</tr>
<tr>
<td>ID-T11</td>
<td>Deployment of MEAO</td>
<td>TIM</td>
<td>✓</td>
<td>Same as ID-T2 &amp; ID-T7.</td>
</tr>
<tr>
<td>ID-T12</td>
<td>Deployment of Adaptation Layer</td>
<td>TIM</td>
<td>✓</td>
<td>Same as ID-T3 &amp; ID-T8.</td>
</tr>
<tr>
<td>ID-T13</td>
<td>Deployment of ECON</td>
<td>TIM</td>
<td>✓</td>
<td>Same as ID-T4 &amp; ID-T9.</td>
</tr>
</tbody>
</table>

Table 30: Functional (F) tests

<table>
<thead>
<tr>
<th>Number</th>
<th>Test</th>
<th>MNO site (MEC platform)</th>
<th>Status</th>
<th>Status description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-T1</td>
<td>In-country instantiation</td>
<td>service</td>
<td>DTAG</td>
<td>✓</td>
</tr>
<tr>
<td>F-T2</td>
<td>In-country termination service</td>
<td>DTAG</td>
<td>The REST requests exchanged between NFV-SO, Adaptation Layer, NFV-LO, and ECON. All responses resulted in 200 OK, and application service deleted from K8s cluster 2. Application not reachable anymore on the designated IP address and port.</td>
<td></td>
</tr>
<tr>
<td>F-T3</td>
<td>In-country instantiation service</td>
<td>MTA</td>
<td>Same as F-T1.</td>
<td></td>
</tr>
<tr>
<td>F-T4</td>
<td>In-country termination service</td>
<td>MTA</td>
<td>Same as F-T2.</td>
<td></td>
</tr>
<tr>
<td>F-T5</td>
<td>In-country instantiation service</td>
<td>TIM</td>
<td>Same as F-T1 &amp; F-T3.</td>
<td></td>
</tr>
<tr>
<td>F-T6</td>
<td>In-country termination service</td>
<td>TIM</td>
<td>Same as F-T2 &amp; F-T4.</td>
<td></td>
</tr>
<tr>
<td>F-T7</td>
<td>Cross-border service instantiation via Or-Or</td>
<td>DTAG &amp; MTA</td>
<td>Same as F-T1, except that the instantiation of BSA application includes two MEC platforms, i.e., two countries. The corresponding REST requests sent from NFV-SO 1 to NFV-SO 2 via Or-Or interface. Both NFV-SOs perform instantiation procedure in their respective domains (K8s clusters in DTAG, and K8s clusters in MTA) as described in F-T1. As a result, BSA application available in two countries, and these two application instances are reachable on the designated IP addressed and ports (dashboards available, and CAM traffic successfully received and parsed).</td>
<td></td>
</tr>
<tr>
<td>F-T8</td>
<td>Cross-border service termination via Or-Or</td>
<td>DTAG &amp; MTA</td>
<td>Same as F-T2, except that the termination procedure includes two MEC platforms. The corresponding REST requests sent from NFV-SO 1 to NFV-SO 2 via Or-Or interface. As a result, either application instance in DTAG, or instance in MTA, or both (depending on the type of termination request and passed parameters in the message body), is/are deleted from cluster 2 (DTAG and/or MTA).</td>
<td></td>
</tr>
<tr>
<td>F-T9</td>
<td>Cross-border service instantiation via Or-Or</td>
<td>MTA &amp; TIM</td>
<td>Same as F-T7.</td>
<td></td>
</tr>
<tr>
<td>Case</td>
<td>Description</td>
<td>Corresponding Line</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------------------------</td>
<td>--------------------</td>
<td>----------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>F-T10</td>
<td>Cross-border service termination via Or-Or</td>
<td>MTA &amp; TIM</td>
<td>Same as F-T8.</td>
<td></td>
</tr>
<tr>
<td>F-T11</td>
<td>Cross-border service instantiation via Lo-Lo</td>
<td>DTAG &amp; MTA</td>
<td>Same as F-T7, except that the corresponding REST requests are directly exchanged between NFV-LO in DTAG, and NFV-LO in MTA, via Lo-Lo reference point.</td>
<td></td>
</tr>
<tr>
<td>F-T12</td>
<td>Cross-border service termination via Lo-Lo</td>
<td>DTAG &amp; MTA</td>
<td>Same as F-T8, except that the corresponding REST requests are directly exchanged between NFV-LO in DTAG, and NFV-LO in MTA, via Lo-Lo reference point.</td>
<td></td>
</tr>
<tr>
<td>F-T13</td>
<td>Cross-border service instantiation via Lo-Lo</td>
<td>MTA &amp; TIM</td>
<td>Same as F-T11.</td>
<td></td>
</tr>
<tr>
<td>F-T14</td>
<td>Cross-border service termination via Lo-Lo</td>
<td>MTA &amp; TIM</td>
<td>Same as F-T12.</td>
<td></td>
</tr>
<tr>
<td>F-T15</td>
<td>Deployment of BSA service</td>
<td>DTAG</td>
<td>The application dashboard is reachable, and upstream CAM traffic received from a testing client application. BSA service successfully receives CAM traffic via UDP listener. BSA Pod is running in cluster 2. Application reachable on the designated IP address and port. Upon reception of CAM from a client application, BSA successfully performed CAM decoding, ETA calculation and definition of dissemination areas, DENM encoding, and message preparation for GeoService.</td>
<td></td>
</tr>
<tr>
<td>F-T16</td>
<td>Deployment of BSA service</td>
<td>MTA</td>
<td>Same as F-T15.</td>
<td></td>
</tr>
<tr>
<td>F-T17</td>
<td>Deployment of BSA service</td>
<td>TIM</td>
<td>Same as F-T15 &amp; F-T16.</td>
<td></td>
</tr>
<tr>
<td>F-T18</td>
<td>Deployment of S-LDM</td>
<td>DTAG</td>
<td>The application dashboard is reachable, and application updates the map dynamically based on the notifications received from the AMQP broker, based on the CAM traffic sent from a vehicle to the broker. This test has been performed from an emulated vehicle as well as with real vehicles on the road. S-LDM Pod is running in cluster 2. Application reachable on the designated IP address and port.</td>
<td></td>
</tr>
<tr>
<td>F-T19</td>
<td>Deployment of S-LDM</td>
<td>MTA</td>
<td>✔️</td>
<td>Same as F-T18.</td>
</tr>
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</tr>
<tr>
<td>F-T20</td>
<td>Deployment of -S-LDM</td>
<td>TIM</td>
<td>✔️</td>
<td>Same as F-T18, with addition that this test included also the vehicle. S-LDM Pod is running in cluster 2. Application reachable on the designated IP address and port. More information about the S-LDM tests available in S-LDM (Section 5.2.5).</td>
</tr>
<tr>
<td>F-T21</td>
<td>Deployment of CLC components</td>
<td>DTAG</td>
<td>✔️</td>
<td>CLC service leverages on several platform-deployed components interacting: S-LDM, Manoeuvring Service, Main Manager, Local Manager, Response Router. These components are deployed by the Orchestrated 5G Edges platform by leveraging on a dedicated set of script files, each one providing the needed references to software repositories and configurations specific to the component type, the other components configuration and the environment where it is going to be deployed.</td>
</tr>
<tr>
<td>F-T22</td>
<td>Deployment of CLC components</td>
<td>MTA</td>
<td>✔️</td>
<td>Same as F-T21.</td>
</tr>
<tr>
<td>F-T23</td>
<td>Deployment of S-LDM components for Increased Perception service</td>
<td>TIM</td>
<td>✔️</td>
<td>Same as F-T21 &amp; F-T22, but without Maneuvering Service (MS) and Response Router (RR), since CLC service is deployed only on the German-Austrian border and in the networks of DTAG and MTA accordingly.</td>
</tr>
<tr>
<td>F-T24</td>
<td>CLC components: Integration between deployed components</td>
<td>DTAG</td>
<td>✔️</td>
<td>Once deployed, the deployable components interact with each other in different ways: all these interactions have been tested and verified, in particular if they leverage on some information passed through the Orchestrated 5G Edges platform during deployment. Components include the Manoeuvring Service (MS), the Response Router (RR), and the S-LDM regarding instances deployed on the orchestrated edge. Connectivity enablers of the orchestrated edges have been validated during this test, ensuring proper operation between these components, which in some cases include an AMQP broker, which is deployed on a different platform, different from the orchestrated edge (refer to F-T27).</td>
</tr>
<tr>
<td>F-T25</td>
<td>CLC components: Integration between deployed components</td>
<td>MTA</td>
<td>Same as F-T24.</td>
<td></td>
</tr>
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<td></td>
</tr>
<tr>
<td>F-T26</td>
<td>S-LDM for increased perception service: Integration between deployed components</td>
<td>TIM</td>
<td>Same as F-T24 &amp; F-T25, but without Manoeuvring Service (MS) and Response Router (RR), since CLC service is deployed only on the German-Austrian border and in the networks of DTAG and MTA accordingly.</td>
<td></td>
</tr>
<tr>
<td>F-T27</td>
<td>CLC components: Integration with components, which are locally available but not deployed on the orchestrated Edges</td>
<td>DTAG</td>
<td>This test validates the connectivity and operation of the CLC components with the AMQP broker, leveraging the orchestrated edge’s connectivity enablers to operate with components, which are not deployed on the orchestrated edge, but on a different platform in the same network or in a different network, such as on the vehicle.</td>
<td></td>
</tr>
<tr>
<td>F-T28</td>
<td>CLC: Integration with components, which are locally available but not deployed on the orchestrated Edges</td>
<td>MTA</td>
<td>Same as F-T27.</td>
<td></td>
</tr>
<tr>
<td>F-T29</td>
<td>S-LDM for Increased Perception service: Integration with components, which are locally available but not deployed on the orchestrated Edges</td>
<td>TIM</td>
<td>Same as F-T27 &amp; F-T28, but without Manoeuvring Service (MS) and Response Router (RR), since CLC service is deployed only on the German-Austrian border and in the networks of DTAG and MTA accordingly.</td>
<td></td>
</tr>
<tr>
<td>F-T30</td>
<td>Inter-service communication (BSA)</td>
<td>DTAG &amp; MTA</td>
<td>Two BSA application instances, one running in the cluster 2 of the DTAG MEC platform, and the other running in the cluster 2 of the MTA MEC platform, share application metadata via the data plane communication. Application metadata includes the current location of EmV, as well as its speed and destination, all extracted from the received CAM. This metadata is successfully sent from BSA instance in Germany (DTAG MEC) to BSA instance in Austria (MTA MEC) via REST-based communication.</td>
<td></td>
</tr>
<tr>
<td>F-T31</td>
<td>Inter-service communication (BSA)</td>
<td>MTA &amp; TIM</td>
<td>Same as F-T30.</td>
<td></td>
</tr>
<tr>
<td>F-T32</td>
<td>Internal notification delivery via message broker</td>
<td>DTAG</td>
<td>Internal message broker deployed as a containerized application server in the K8s cluster 1. The components in cluster 1 (i.e., MEAO and Adaptation Layer) able to receive notifications on the topics to which they are subscribed, by running corresponding subscriber scripts. The ECON from cluster 2 publishes updates on the resource consumption in K8s cluster 2, consumed by applications (such as BSA and S-LDM).</td>
<td></td>
</tr>
<tr>
<td>F-T33</td>
<td>Internal notification delivery via message broker</td>
<td>MTA</td>
<td>Same as F-T32.</td>
<td></td>
</tr>
<tr>
<td>F-T34</td>
<td>Internal notification delivery via message broker</td>
<td>TIM</td>
<td>Same as F-T32 &amp; F-T33.</td>
<td></td>
</tr>
<tr>
<td>F-T35</td>
<td>Communication between BSA service and Geoservice</td>
<td>DTAG</td>
<td>The BSA application sends DENMs packed into Avro messages to the Geoservice running on the DTAG MEC. Avro messages are ingested to the Geoservice Kafka REST Proxy, and response that BSA application received is 200 OK.</td>
<td></td>
</tr>
<tr>
<td>F-T36</td>
<td>Communication between BSA service and Geoservice</td>
<td>MTA</td>
<td>Same as F-T35.</td>
<td></td>
</tr>
<tr>
<td>F-T37</td>
<td>Communication between BSA service and Geoservice</td>
<td>TIM</td>
<td>Same as F-T35 &amp; F-T36.</td>
<td></td>
</tr>
<tr>
<td>F-T38</td>
<td>Inter-edge mobile data plane indirection and forwarding on N6/SGi reference point</td>
<td>DTAG &amp; MTA</td>
<td>Mobile data plane traffic between vehicle and edge service in DTAG is forwarded to the corresponding peer component (service or vehicle) in the MTA edge network. Test has been performed also for data plane indirection and forwarding from MTA edge network to DTAG edge network.</td>
<td></td>
</tr>
</tbody>
</table>
5 Connected and Automated Driving pilot

The 5G-CARMEN concept deployed in the pilot is summarized hereafter, referring to Figure 81 which is a simplified picture of the architecture (Figure 3).

**Figure 81: Basic concept of the 5G-CARMEN system deployed in the pilot**

**On-Board Components**

A vehicle with SAE L4 automated functionality can perform full automated driving tasks in specific Operational Design Domains, and handle emergency situations without requesting the driver intervention. In 5G-CARMEN project, the 5G and C-V2X support to L4 perception are addressed. For this purpose the vehicle (Figure 81) needs:

- Precise positioning
- Uu and PC5 redundant connectivity with monitored and predictive QoS
- Onboard extended perception
- Low-latency message brokers
- Local Dynamic Maps
- Manoeuvre Recommendation Service on MEC
- Back Situation Awareness Function (BSAF) Service on MEC
- Use Case application

*Precise positioning* - The L4 vehicle, but also the cooperative vehicles, need to share very precise positioning data (10-20 cm). Positioning results are presented in sections 5.1.4 and 5.2.2.

*Uu and PC5 redundant connectivity with monitored and predictive QoS* – High-rate sensor sharing needs 5G connectivity on Uu to get an extended perception. PC5 is used for redundancy for L4 Automated Driving (see Table 35: L4 Operational Design Domain assumption of CRF prototype in 5G-CARMEN). On top of the facility layers of the C-V2X stack, two main application components have been developed: a software module taking care of reconnecting the system to MEC service in cross-border transition and a QoS on board system has been implemented, which takes into account positioning and communication to assess the L4 Operational Design domain. The cross-border connectivity tests is treated in section 5.2.2 whereas the QoS is treated in 5.2.7.

*Onboard extended perception (enhanced Cooperative Awareness) and Vehicle Local Dynamic Map* - vehicles need to be aware of other vehicles and also of the objects sensed from the other vehicles, with a performance comparable with their own sensors. The vehicle in front shares not only its position but also sensed information at 20Hz. Results are given in Section 5.2.4.
Applications performing the use cases

The onboard applications, through the combination of C-V2X, sensors perception and vehicle dynamics, and utilizing prototype AD functionalities, enable the 5G-CARMEN Use Cases, namely:

1. Cooperative and automated lane-change manoeuvres
   a. **Lane change as planned**, centralized (manoeuvring service)
   b. **Lane change as planned**, decentralized (no manoeuvring service)
   c. **Lane clearance for emergency vehicle** based on estimated time of arrival

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

All 7 scenarios have been developed and tested functionally on-board, with success.

Data collection and analysis for KPI extraction have focussed on

- 1.a Lane change as planned, centralized (section 5.1.3).
- 1.b Lane change as planned, decentralized (section 5.2.7)
- 2.a In-lane manoeuvres based on forward detection (section 5.2.7)

Several tests were performed for 2.d (Back Situation Awareness Functionality) but due to the testing complexity, results have regarded mostly the MEC services KPI (5.2.6.3).

MEC Services

*Message brokers* ensure the casting of messages to interested vehicles among all the vehicles in the corridor.

5G-CARMEN piloted two components: GeoService and AMQP.

The AMQP broker sends messages to the Server Local Dynamic Map and sends back advisory from the manoeuvring service (via the Response Router) to the vehicles in the centralized lane change approach. The usage of AMQP broker within the centralized lane change approach is illustrated in section 5.1. The functionality and performance of AMQP broker is addressed in 5.2.6.1.

The GeoService is used for exchanging cooperative awareness and sensor sharing messages among vehicles over Uu in the Extended perception, and for sending Estimated Time of Arrival messages from the BSAF service to the in-vehicle system. Results on Geoservice cross-border are presented in section 5.2.6.2.

Local Dynamic Maps on Vehicle and on MEC - The vehicle receives information via 5G and updates its Vehicle Local Dynamic Map (V-LDM), in order to have a full picture of 5G-equipped Vehicles as well as non-equipped vehicles, accessible by onboard applications. There is a supervising entity on the MEC (Server Local Dynamic Map or S-LDM) aggregating and reconstructing a Local Dynamic Map from coming information (uplink), to be an input in the cars (downlink) intended for the automation perception layer, or to be used by third parties to generate warnings and recommendations (manoeuvre advisors). S-LDM results are shown in 5.2.5.

**Manoeuvre Recommendation Service on MEC** - A dedicated service gets context information from the S-LDM, for example an automated vehicle planning to change lane, merging between two other vehicles. The service understands the context and based on algorithms, provides manoeuvre recommendations to the vehicles concerned, thus enabling a safer and more efficient traffic situation. Results on Manoeuvring Service are presented in section 5.1.3.

**Back Situation Awareness Function (BSAF) Service on MEC** - This service provides the estimated time of arrival of an emergency vehicle. Emergency vehicles fast approaches may require sudden manoeuvres, e.g. sudden lane clearance) and thus are “at the border” of the Automated Driving Operational Design Domain (AD ODD). Such events have to be detected with sufficient advance to clear the lane or keep safely in lane. This service is illustrated in 5.2.6.3.
Use Cases

5.1 Connected and Automated Driving: connected and automated lane-change manoeuvres (centralized)

5.1.1 BMW Prototype Overview

The centralized lane-change manoeuvres are based on a novel Edge Computing system demonstrated by BMW: a dedicated Manoeuvring service gets information from a Server Local Dynamic Map (S-LDM) and provides response to the vehicles through a response router. Information between the aforementioned services and vehicles is dispatched through the AMQP message broker.

BMW counts with three prototype vehicles which are equipped with 4G and 5G communication modules, external cellular and GNSS antennas, screens, and the necessary ECUs to perform the computation required for 5G-CARMEN use cases. The following pictures (from Figure 82 to Figure 84) show snapshots of the integration tests performed in the German-Austrian border, for the connected and automated lane-change use case.

![Figure 82: BMW prototype vehicle at Kiefersfelden (German-Austrian border)](image-url)
The setup for this use case consists of a manoeuvring management application running in the vehicle. This application is in charge of encoding and decoding ITS messages such as CAMs and DENMs exchanged with the network via Uu interface, interfacing the vehicle ACC and ECU's so that the driving recommendations from the network can be performed, and finally interfacing the central display so that the recommendations are shown in case a human driver performs these instructions.
The onboard software loads the json file, writes the data into the respective fields and afterwards the json file is converted into the binary CAM file.

This application is assisted by a precise positioning system provided by DTAG. More detailed information on both the functional view and the deployment of the in-vehicle components are provided in Figure 85.

**Figure 85: Functional view and deployment of the in-vehicle components for the CLC use case**

**Qualcomm Roadrunner** - it enables C-V2X 3GPP Release 14 V2V/V2I/V2P short range communications via PC5 interface. In this use case, it will be used as an interface for CAM exchange among the vehicles (V2V).

**Qualcomm 5GCC** - it enables 3GPP Release 15 5G NR radio communications for high throughput and low latency. It provides Uu interface for V2N communication also via LTE. In this use case, it will be used as an interface for CAM/DENM provisioning to vehicles by leveraging on the radio connectivity established between the vehicle’s OBU and the network components.

**Connectivity OBU** - it is a prototype on which the CLM manoeuvre management application runs. ITS messages (CAM, DENM) are generated using the vehicle’s network information provided via the Controller Area Network (CAN) interface and encoded using ASN.1 with Basic Encoding Rules (BER).

The onboard software encodes its information into CAM messages which are then sent via AMQP to the S-LDM. We created json templates with the C++ code which is shipped with the V2X library. This makes it easy to set default values and to observe the data which is sent. The manoeuvring service encodes the velocity suggestion as well as the merging-possible flag into a DENM message. Analogously to CAM, we created a template json, set the values and use the V2X library to create the encoded binary. Note: since we send the data via REST to the response router first, we encode the message as a b64-string. When the onboard-software receives the AMQP message from the response-router, it decodes the b64-string again before passing the data into the V2X-library to transform the information in json format.

**Driver Assistance/ADAS prototype unit** - if available on the vehicle, the driver assistance system supports the driver of the driving task, hence offering more comfort and increasing safety for the driver. In this use case, the vehicle’s speed could be adapted automatically via the ACC in case the CLC manoeuvre application management requires it. In vehicles with higher levels of automation, the lane merge action could be done in an automated manner.
**Head Unit** - human interface to the vehicle’s central screen, where the warnings and messages for this use case are displayed, if necessary.

**DTAG’s Precise Positioning** -- it provides high accuracy information on the vehicle’s current geographical location, through network correction information. In this use case, the CLC manoeuvre management application in each vehicle will combine this input with the vehicle’s own GNSS data in order to improve location information.

### 5.1.2 Onboard Software Architecture

The requirements to be fulfilled by the Onboard software architecture (Figure 86) are the following:

- Gather vehicle information: vehicle ID, speed, heading, position, blinker status, and lane position (when available) utilizing a CAN PCIe interface (Vector VN7572)
- ID should be configurable by the user
- Gather high precision GNSS (if available) or onboard GNSS otherwise
- Format data as a Cooperative Awareness Message (CAM)
- Encode using ASN.1
- Receive data as a Decentralized Environmental Notification Message (DENM) and decode using ASN.1
- Reactions on received data:
  - display recommendations/notifications on Central Information Display (e.g. “reduce speed up to x km”, “lane merge allowed”, etc.)
  - automatic speed modifications on the automated cruise control (ACC)
5.1.3 BMW Manoeuvring Service

The Manoeuvring 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 manoeuvre can be done safely and efficiently; and generate recommendations for vehicles to follow if possible. It is located in the MEC.

To allow flexible recommendations and be as close to the State of the Art as possible, a Model-Based Control Approach was chosen [8]. 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.

Figure 87 shows a complete system diagram.
The operational layer controller is implemented as a python class which initializes the controller on its first call, setting the sequence of merging vehicles based on the situation and parameters set in the opc_config.toml file.

The control actions are calculated using model predictive control (MPC) [9] and the controller settings can be changed using a deployed tuner webpage (Figure 88)
The Controller operation, with its inputs and outputs can be monitored using Grafana-based dashboards as shown below:

Figure 89: Broker Demonstration Dashboard

Figure 90: Positions and Velocity Dashboard

In addition, there is a visualization that shows the current status of the manoeuvre at first glance. The size of the animation has been optimized for iPads. You can see the three vehicles with their respective distance, note that the distance is not to scale. In addition, the current speed can be seen under the vehicles and the arrows above the vehicle indicate whether the vehicle should increase or decrease the speed.
5.1.3.1 Simulation Tests

As a first step, the algorithm was tested by simulating lane change sequences with three vehicles. The goal was to evaluate the system with ideal conditions and compare them to real drive tests later on. The following assumptions where considered:

1. In the simulation, we assume that the vehicle ACC is controlled automatically, and the driving instructions are followed, as expected in future vehicles with higher levels of automated driving. In lower levels of automated driving where vehicles are controlled by humans, the instructions are sometimes neglected.

2. We assume a stable cellular connection in the simulation, which can provide update rate of control signals every 5 seconds and update rate of vehicle location every 100 milliseconds (10Hz). During the next steps of the project, a higher position refresh rate (20Hz) was implemented. In the real world this depends on the quality of the connection.

3. We assume, that the algorithm is used in the controlled environment and no other cars are involved while performing the manoeuvre.

The main objective was to determine the time it took for a lane change manoeuvre to take place under different initial vehicle distances and speeds. Additionally, the reaction time of the vehicle to reach the recommended speed at each step of the manoeuvre was also tested. Each simulation ends after a lane change manoeuvre is successfully performed. The figures show the speed of vehicles compared to target speed given by the manoeuvring service.

The following simulated sequences were then replicated during our drive tests. The drive test counterpart will be shown in Section 5.1.3.2.
Figure 92: CLC System Simulation: Scenario 1

Figure 93: CLC System Simulation: Scenario 2
5.1.3.2 Drive Tests
As mentioned in Section 5.1.3, drive tests were performed with three vehicles, with the same initial parameters as each simulated scenario, but with real-life conditions, including the communication channel between the vehicle and the manoeuvring service in the network, and human drivers performing the driving instructions. For the first trials of the system, in order to have a controlled environment, BMW Test Track in Munich was chosen as the test location. The results are shown below. Compared to the simulation, we can observe a higher difference between the actual speed and the recommended speed, and also a delay between recommendation and speed change. This is due to having human drivers controlling the cars.

![Graph](CLC_Data_Recordings.png)

**Figure 96: CLC Drive Test: Scenario 1**

**Figure 97: CLC Drive Test: Scenario 2**
The final pilot drive tests were performed with three vehicles on the Kufstein border between Germany and Austria on the 23rd of June, 2022. The manoeuvre chosen for the pilot was the Lane Merge and all components and parameters were as in tested in the previous weeks in Munich.
Only modification was the usage of BMW private SIM cards instead of DT/Magenta cards. The decision of swapping the SIMs was taken after two days of using DT 5G-CARMEN SIMs, where use cases could not be tested since the communication between the vehicle and the network was unstable at best and non-existent most of the time for the cross-border setup specific to 5G-CARMEN.

The first graph shows the relative distances between the vehicles. The vehicle that activates the turn signal is the reference car and therefore has a distance of 0 m. As soon as the distances are large enough in relation to the speed, the controller gives the green light for merging.

The second graph shows the current speed (solid line) and the control speed calculated by the controller for each vehicle (dashed line).

**Run 1: 23.06.2022 Kufstein**

In this scenario, the middle car (green) in the left lane activated the scenario, and the controller adjusted the speeds of the cars in front (yellow) and behind (blue) to increase the gap. After the gap was large enough, it enabled merging.

![Relative Vehicle Location](image.png)

**Figure 100 Relative vehicle location (Run 1)**

Since the gap only had to be widened slightly, only minimal changes to the speed are necessary, which were implemented by the drivers with a slight delay. When setting the controller, the delay due to human reaction time was taken into account, and therefore the recommendations are divided into larger blocks.
Run 2: 23.06.2022 Kufstein

In this scenario, the rear vehicle (green) has started the maneuver. After the rear vehicle has positioned itself in between the other two cars and the controller has created enough space, merging is possible.
Figure 103 Velocity of each vehicle (Run 2)

Run 3: 23.06.2022 Kufstein

In this run, the middle vehicle initiated the merging manoeuvre. As the manoeuvre was progressing, the front vehicle (yellow) had a network outage for about 10 seconds, resulting in wrong relative distances being sent to the manoeuvring service (cached distances for the yellow vehicle were being used while other cars progressed in distance). The reaction of the controller can be seen in the velocity graph, because it tries to put the yellow vehicle to the front by accelerating it. After the connection was re-established, the manoeuvre continued as expected.

Figure 104 Relative vehicle location (Run 3)
5.1.3.3 Final Results

Results show that the algorithm developed for the Manoeuvring Service is successfully able to send the necessary instructions to the vehicles so a lane change manoeuvre can be executed. The average time for successful execution depends on the initial distance and speed of each vehicle at the time when the manoeuvre is initiated. The average time goes from 20 seconds (close proximity) to 150 seconds (vehicles further apart).

Finally, the centralized lane change manoeuvre was executed in a cross-border scenario on the highway located at the German-Austrian border. Since traffic conditions on the highway cannot be controlled and other vehicles were present on the highway, the results could not be compared one to one. In the final pilot, the plots show a good performance of the controller. In order to be adapted to the real-life scenario, the manoeuvring service algorithm implemented faster update rates. It managed to calculate a sensible manoeuvre and also gave the green light at the right moment (i.e. when humans would merge too).

The difference between reaction times of a human driver compared to an automated system is also something to highlight. For complex manoeuvres to be executed in a more efficient manner, higher levels of automation are required. This can be seen in the plots, where a deviation and delay from the recommendations is due to the speeds being controlled by drivers.

For the Manoeuvring Service to provide more accurate instructions in such challenging scenarios, besides a faster update rate, a complete view of the traffic situation would be required. This could be achieved either by having all vehicles on the road share their location information, sensor sharing to the network or with the help of the infrastructure components.

5.1.4 Precise Positioning Tests

Precise Positioning Tests were performed by BMW, using DTAG’s precise positioning modules in one of the vehicles. As follow-up, two more vehicles will be equipped and the manoeuvre performance, which is expected to increase, will be evaluated.

The two main objectives were:

1. To evaluate the system performance in the corridor along the German-Austrian border
2. To evaluate the system performance in the context of a Centralized Lane Change manoeuvre, and compare it with a standard GNSS solution, which normally offers less precision.

5.1.4.1 Location
Drive tests were performed along the corridor in the German – Austrian border.

5.1.4.1 Point Perfect Location system

A new Precise Positioning System was installed in the three vehicles to allow smaller positioning error in the complete manoeuvre. The installed GNSS is based on the U-Blox ZED F9P [10].

The firmware was configured using U-Center, provided by U-Blox. The GNSS outputs NMEA messages at a frequency of 10 Hz on the serial port. Any other output messages were deactivated to minimize the board's effort and buffer usage. To receive a correction stream, a UART input was configured with the baud rate equal to the correction stream provider.

The setup uses the included U-Blox Antenna ANN-MB-00-00 (Multi-band Active GNSS Antenna).

Two USB cables need to be connected to the host system:

- The USB C port can be referred as the main connection, which supplies the GNSS board with power. This connection provides NMEA messages containing GNSS data (like latitude, longitude, altitude, time, connection mode, visible satellites, etc). In summary, this port is used to collect data provided by the board.
- The dongle USB connection is needed for correction data. In summary, this port is used by a host pc to feed GNSS correction information to the board.

The board was configured in a way that it does not need any software (nor U-Center). As soon as the main USB connection is attached properly, the board is powered and provides NMEA messages via a serial port.
However, to get precise positioning and an RTK fix, correction data is necessary. After testing with RTK Lib used in combination with the SAPOS [11] service, it was decided to use Thingstream Point Perfect as a correction message provider.

![Diagram of Point Perfect Location system](image)

**Figure 107: 2.1.4.1 Point Perfect Location system**

In order to use PointPerfect as a correction source, a Location Thing on thingstream.io was created. Every device requiring a correction stream, needed to have its own Location Thing.

The biggest advantage of using PointPerfect compared to SAPOS is the increased coverage, while only a single USB port is required for both, correction stream and corrected positions. Furthermore, an MQTT client makes it easier to create dedicated applications using Python instead of relying on RTK Lib.

### 5.1.4.2 Point Perfect vs Ground Truth

The Point Perfect Positioning system provided high accuracy for the Cooperative Driving application, as shown by the diagrams below. To assess the quality of the used GNSS, a comparison with the logs provided by a Ground Truth System (installed in the CARMEN G05) was done. For the evaluation, we used the Woodpecker tool by Swift Navigation.

Drive 1 (22.06.2022, morning):
Figure 108: LLH map of entire ride

Figure 109: LLH map: detailed view on 2 curves
Figure 110: Latitude offset

Figure 111: Longitude offset

Figure 112: Timing offset
Figure 113: Number of connected satellites

Figure 114: Position Modes of the GNSS during the test drive

Drive 2 (23.06.2022):
Figure 115: LLH map of entire ride

Figure 116: LLH map: detailed view of a turn

Figure 117: Latitude offset
Figure 118: Latitude offset detailed view

Figure 119: Longitude offset

Figure 120: Longitude offset detailed view
Figure 121: Timing offset

Figure 122: Number of connected satellites

Figure 123: Position Modes of the GNSS throughout the day
5.1.4.3 Outlook

As mentioned in the introduction of 5.1.4, the initial setup for the Centralized Lane Change tests contained a precise positioning system in only one out of the three test vehicles. When this manoeuvre was performed in close vehicle proximity and high speeds, as is a common situation on the highway, we could observe that the standard GNSS solution of the other two vehicles was not precise enough for the Manoeuvring Service to correctly identify their location. Therefore, the driving recommendations were not accurate enough. Under these conditions, a positioning accuracy of 10-20 cm is required. We also observed that if the distance between vehicles is large enough during the CLC manoeuvre, there is a higher error tolerance.

In the last phase, the three vehicles were equipped with precise positioning modules with Point Perfect correction system, as explained in Section 5.1.4.1, managing to have a smaller positioning error during the complete manoeuvre. Due to three identical positioning systems in the three cars, the previously faced issue of time synchronization between each individual positioning system could be avoided. Therefore, the artificially implemented delay of several hundreds of milliseconds could be removed because each installed GNSS device finally receives positioning data at a synchronized time stamp.

By looking at the figures which cover the entire ride (Figure 108 and Figure 115), there is no deviation visible. By zooming in (as shown in the detailed view in Figure 109 and Figure 116), at some point a deviation can be identified. Also, plots for latitude and longitude don’t overlap precisely, and one reason is the time delay.

As the figures with the Delta TOW plots hint, there is a timing offset of around 85 ms in the mean between the Motius Positioning system and the installed Ground Truth system. However, this delay was not noticeable for drivers during the tests and didn’t impact the Cooperative Driving applications or tested manoeuvres.

During the tests, a connection to almost always 12 satellites could be established while we allowed our device to connect only to GPS and GLONASS. To improve the overall positioning quality even further, the integration of an IMU system and wheel ticks can be considered in the future. Dead Reckoning would be one resulting benefit that could be leveraged during bad satellite coverage.

<table>
<thead>
<tr>
<th>Flag</th>
<th>Status</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>invalid</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>stand-alone</td>
<td>around 10 m</td>
</tr>
<tr>
<td>2</td>
<td>DGNSS</td>
<td>between 10 m and 1 m</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>RTK fix</td>
<td>&lt; 10 cm</td>
</tr>
<tr>
<td>5</td>
<td>RTK float</td>
<td>between 1 m to 0.1 m</td>
</tr>
</tbody>
</table>

5.1.5 Lab tests on experimental Cooperative Lane Change Components: Response Router, Local Manager & Main Manager

In this section we will present the test we have performed over the three components designed and implemented by FBK to support the CLC scenario: Response Router, Main Manager and Local Manager.

Response Router supports the other CLC service components in returning feedback (recommendation/support messages) to the car clients, via AMQP Broker. The Local Manager is subscribed to the AMQP Broker to the
same topics that car clients use to feed the S-LDM and checks car position to determine if a support message (i.e., the collection of service endpoints available at car’s position) shall be sent. Finally, the Main Manager supports car clients in registering to the service, providing a fixed endpoint for joining the service and the first support message. Main Manager also provides local configuration to each Local Manager instance and works on demand can provide an updated support message to those car clients that cannot connect to the previously suggested AMQP Broker endpoint.

Response Router has been tested on the field and used also in the CLC scenario, fully integrated with the other components; Main Manager and Local Manager have been instead tested in emulations running actual instances deployed on the DTAG and MTA MECs fed by lab emulated components, but not in a complete real scenario.

### 5.1.5.1 Response Router

The Response Router (RR) is the CLC component in charge of forwarding any message from the other CLC components to a given car (or set of cars). To fulfil such a task, the RR is capable of interfacing with one AMQP Broker (or more than one, if needed) and leverages on the Selector feature of AMQP messages, which allow to enable a filter over the potential destinations of a message, selecting only those matching a provided condition. In the RR case, RR specifies the Car Identifier (Car_ID) value associated univocally to each car and also provided by each car when registering as consumer to the AMQP Broker (thus associating each broker-to-car channel with that car identifier). This way, the Broker can identify the message designated receiver(s) and send it only to that destination (those destinations).

As said before, by default the RR connects to a single AMQP broker, but the tool has been designed to support a connection with more than one broker, if needed. If many broker endpoints are defined, the RR sends a copy of each message to each message broker. This is envisaged as a back-up solution to achieve the cross-border continuity in case of SLDM modules not supporting the registration to multiple brokers or the missing support for message interchange between two bordering AMQP brokers. In CLC scenario, we have envisaged only two types of messages sent from other CLC components to RR:

- **Recommendation Message:** sent by Manoeuvring Service (MS), it is the message containing the results of all the computations of the MS, i.e., a list of car-specific messages meant to provide system feedback to each car client running on each car involved in the detected situation that triggered the MS evaluation;

- **Support Message:** sent by Local Manager, it is the message carrying all the information for a car regarding the available AMQP endpoints available (per Network Operator) at car’s current position, providing also information about the system suggested AMQP Broker endpoint priority and some backup information (i.e., Main Manager endpoint) to be used in case of service anomalies/disruption. More details regarding the content of the support message is provided in the `<MainManagerSection>`

In both cases, the structure of the message received by RR is the following:

```json
{
  "messages": [
    <car-specific-message-1>,
    <car-specific-message-2>,
    ...
  ]
}
```

With the structure of each car-specific-message item being this one:

```json
{
  ...
}
```
This JSON message is actually a collection of recommendation/support messages (stored in the “messages” list), with each message being a dictionary structured in the following way:

- “Car_ID”: the identifier of the destination car;
- “pos”: the position of the car as a quadtree code;
- “message”: the message (CAM message if the sender is the MS or Support Message in case of the sender being the LM) to be sent to the “Car_ID” car client via the AMQP Broker

The Response Router processes the whole message list, extracting each single message, wrapping it into an AMQP message and assigning the Car_ID value to a dedicated Selector that will allow the broker to forward it to the right destination car client.

RR has been introduced to decouple the sending of messages from other CLC modules: if not present, each module meant to send messages to the car clients need to know AMQP Broker endpoint (even credentials) and also to know the format and rules to be applied when sending the message. With RR, the other modules can focus on their actual activities, leaving the RR to take care of the proper interaction with the AMQP Broker. Moreover, being the transmission of messages a stateless operation (not depending on previous sent messages), this also allow to deploy the RR as a set of single RR instances coordinated by a Load Balancer, distributing the messages to be sent in a balanced way among the several RR instances, thus making the transmission process more time efficient (in the perspective of high number of car clients scenarios).

In the test performed at the Austrian-German border on June 23, two RR instances has been deployed through the 5G-CARMEN Orchestration Platform on both the Deployment VMs at DTAG and MTA MEC. In this scenario, the RR receives only recommendation messages from the MS, since the Main Manager and the Local Manager component have not been involved in the test. As explained in section 5.1.3.2, 3 cars were involved in the test, thus the RR receives a message from the MS containing 3 recommendation message, one for each car: the RR extracts each of these messages and forwards it to the destination car specific for that message.

The average RR computational time measured for managing a response message from the MS containing 3 recommendation messages (one for each car involved) is the following:

\[
\begin{align*}
\text{DTAG} & \quad 0.189 \pm/\ 0.023 \text{ ms} \\
\text{MTA} & \quad 0.091 \pm/\ 0.016 \text{ ms}
\end{align*}
\]

As highlighted in D4.3 (Table 2), the different performance of DTAG and MTA instance is most likely associated with the different resources configured at the two deployment VMs (which makes instances running at MTA more performing in terms of computational time).

The measured numbers are in line with some emulations previously performed on instances running at both Austrian and German MEC. In these emulations, we fed both the instances with generated MS response messages referring to situations with different number of involved cars and we measured the average RR computational time over those situations sharing the same number of involved cars. Please note that we are talking of situations, not scenarios: the scenario is made by N cars, but a triggering situation may involve from 2 up to N cars (depending on car proximity and interaction). The results are listed in the table here below

<table>
<thead>
<tr>
<th>Average RR Computational time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 cars</td>
</tr>
</tbody>
</table>

Table 32: Average computational time of the Response Router
The chart in Figure 124 emphasizes the linear increment of the RR computational time with the increment of the involved cars. The impact of this increment over the performance of the system is clearly established by the frequency of the updates coming from MS: the more the time interval between two consecutive updates becomes comparable with the average RR computational time, the more the added delay may affect the performance. E.g., in case of 20Hz updates, a new update is released every 50 ms: in case of a 500 cars situation, almost 50% of the time between two updates would be consumed by the RR computational time, which summed with the overall delays can have also disruptive effects on the quality of the service provided. But we need also to consider how realistic is a situation like this, where 500 cars are directly affected by a car trying to change the lane: something unlikely to happen.

As a final note, it is worth highlighting that the RR operates as a stateless component (i.e., the results of the past operations are not affecting the current one): this makes the RR component suitable for being deployed in several instances managed by a load balancer. Moreover, to furtherly help a balanced processing of the incoming MS requests by leveraging on the load balancer feature, the MS may send its results split in a set of smaller messages (e.g., instead of 1 POST request with 100 recommendation messages in it, 10 POST requests with 10 recommendations), which the load balancer will redistribute among the available RR instances (thus increasing the chance for parallel processing).
5.1.5.2 Main Manager

The Main Manager (MM) module is meant to support the car client by providing the service supporting AMQP broker endpoints available at car position. Moreover, the MM provide the configuration to all the Local Managers under its covered area.

Each car client knows the endpoint of a reference MM and it may query that MM for the list of the available AMQP broker endpoints. After receiving a request referring the car position, the MM answers by returning a Support Message, a JSON message containing a description of the available endpoints (ranked according to the recommended priority for usage).

The Support Message is structured as follows

```
[  
   {  
       "priority": <priority index>,  
       "netop": <network operator id>,  
       "mmep": <main manager endpoint>,  
       "amqpep": <amqp broker endpoint>  
   },  
   ...  
]
```

Each element of the list is a AMQP Broker endpoint, where:

- Priority: the priority value of the AMQP Broker endpoint (the lower the value, the higher the priority: the higher the priority, the more the associated endpoint is recommended to be used)
- Netop: the identifier of the network associated with the endpoint
- Mmep: the main manager endpoint, useful reference in case of errors/malfunctioning (for refreshing the support message)
- Amqpep: the amqp broker endpoint, to connect with to join the service

An example of a support message is given here below:

```
[  
   {  
       "priority": "1",  
       "netop": "dtag",  
       "mmep": "80.159.227.46:31377",  
       "amqpep": "80.159.227.2:5672"  
   },  
   {  
       "priority": "2",  
       "netop": "mta",  
       "mmep": "188.125.17.78:31377",  
       "amqpep": "213.162.90.227:5672"  
   }
]
```
The MM is configured via a dedicated POST request, which also contains the list of Local Managers covered by the MM and their configuration. MM sends to each of these associated LMs their configuration. When the MM is configured, it is ready to answer car client requests.

The MM has been designed to index the Support Message information to allow an almost constant response computational time, independent from the number of quadtree codes associated with the message. To test the MM computational response time (i.e., the time needed by MM to retrieve the Support Message associated with the requested quadtree code and triggering the response – but excluding any transmission time), through the 5G-CARMEN Orchestration Platform we deployed at DTAG and MTA MEC two instances of MM and we performed some test by configuring them with a different number of covered quadtree codes, i.e., 1000, 10000, 50000, 100000 and 500000 distinct positions (i.e., quadtree codes) and then triggering 500 sequential requests over randomly generated positions (among those given in the configuration). Just to give a more understandable real-world meaning to the above numbers, given that each 18-char quadtree code identifies a squared portion of space having more or less an area of 0.01 square kilometres, the coverage associated with the previous list of positions is 10, 100, 500, 1000 and 5000 km².

Table 33: Average response computational time of the Main Manager

<table>
<thead>
<tr>
<th></th>
<th>Average MM Response Computational time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000 pos</td>
</tr>
<tr>
<td>DTAG</td>
<td>0.057</td>
</tr>
<tr>
<td>MTA</td>
<td>0.025</td>
</tr>
</tbody>
</table>

The test results are reported in the above table and chart: they show how the average MM computational response time is almost constant and very fast. Indeed, with a computational delay much lower than 1 millisecond, the most relevant component of the overall transmission time is the transmission-related delay.

We would like to remark that the Main Manager is a component that is designed to cover a wider area compared to the one monitored by a single S-LDM (and then MS): indeed, it is supposed to cover the union of many of (if not all) the S-LDMs operating for a given Network Operator. Because of this, it is not necessary to have it running at the MEC, but it could be deployed in the cloud. Clearly, the further from the user the service is, the higher most likely will be the transmission delay, but since the MM is involved only when a new car client
enters the service or when the car client detects anomalies in the information store in its last Support Message and the surrounding actual situation (i.e., no connectivity towards the advertised endpoint), some additional delay is tolerable, because the service is not yet in place or it is corrupted and required to be reinitialized. Moreover, in a “healthy” system, the number of queries toward the MM should be minimal, being restricted in the ideal case only to the first request of a new car client for joining the service. Thus, the “stress” over the MM is high only in case of large number of cars joining the service at the same time or when some issue occurs, but in ordinary situations is minimal.

5.1.5.3 Local Manager

The Local Manager (LM) is responsible for checking the position of each car and trigger the sending of a Support Message to its associate client when:

- the car position changed to a position with a different Support Message, compared to the one currently in use
- a configurable timeout is expired since the last Support Message has been sent to the car

LM receives its configuration with a push strategy, i.e., by receiving a POST request (usually, from MM) providing all the covered quadtree codes, the associated Support Messages, the AMQP endpoint to subscribe for incoming car messages and the RR endpoint where to send the support messages update/refresh.

LM is subscribed as consumer to a given AMQP broker for all the messages coming from car clients: basically, it is the same kind of subscription done by the S-LDM module. Differently from the S-LDM, the LM does not perform an analysis of the content of the DENM-CAM message sent by the car, but of the properties of the wrapping AMQP message. Indeed, it checks two parameters: the Car_ID value and the car position, which are two parameters that car clients, by design, are requested to include in the AMQP message. By knowing these two values, LM checks if the car changed to a position with a different Support Message or if the refresh time interval has expired for that car (LM keeps track of the message sent to each car in a dedicated cache, so it could evaluate when refresh is required)

According to the results of the check operation, a check is said positive if an update/refresh is sent, negative otherwise. Positive checks imply longer computational time for the LM compared to negative ones, since the former trigger the creation and sending of new/refreshed Support Message, while the latter don’t.

LM leverages on the same indexing solution adopted for MM, which has been tested to provide quasi-constant retrieval time, independent from the number of monitored positions (see 5.1.5.2).

A similar approach is used to cache the information associated to the last Support Message update sent to each car.

As for the MM in the previous section, we tested the stand alone performances of the LM by deploying two instances through the 5G-CARMEN Orchestration Platform at DTAG and MTA MEC, providing different configurations in terms of covered positions (1000, 10000, 50000, 100000 and 500000 distinct positions) and measuring the time required for performing a negative and a positive check.

Results are listed in the below tables and depicted in the following chart. As for MM, the computational time is mildly affected by the size of the set of covered quadtree codes. Thus, time required for performing the check is low: anyway, the overall performance of the LM is also defined by the frequency such a check is performed. The frequency depends on the number of cars and the frequency each car sends messages to the AMQP broker: basically, the number of checks per seconds are defined as the product of the car number times the number of messages emitted (on average) every second by each car. So, the more cars and/or higher the message frequency, the more checks will be performed. Then the number of positive checks is affected by the speed of the cars (which increases the chance for a car to move into position with different Support Message) and by the length of the refresh timeout (the shorter, the more frequent a positive check will occur)

Table 34: Average Check Computational time of the Local Manager
<table>
<thead>
<tr>
<th>Average LM Negative Check Computational time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 pos</td>
</tr>
<tr>
<td>DTAG</td>
</tr>
<tr>
<td>MTA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average LM Positive Check Computational time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 pos</td>
</tr>
<tr>
<td>DTAG</td>
</tr>
<tr>
<td>MTA</td>
</tr>
</tbody>
</table>

Figure 126: Average computational time of the Local Manager

Differently from RR and MM, the Local Manager is a stateful component, since it relies on previous results in order to perform its current evaluations (e.g., it needs to know the last time Support Message has been sent to a given car to decide either sending it again or not). It could be still converted in a stateless one, but in that case a support local database accessible (in reading and writing) by all locally running instances is required to grant all instances to be aligned. The reading and writing on the database may slow down a bit the check duration, but on the other side the chance for parallel processing shall widely compensate it.

Moreover, it is also possible to add some internal filtering in the LM to decimate the incoming messages from each car client, since the Support Message notification service is not as real time critical as for other services provided in CLC. E.g., if 1 second delay is tolerated by the system, then adding a filter that accepts just 1 message every second from each car client does not cripple the system and makes things easier to be handled at LM side.
5.2 Connected and Automated Driving: connected and automated lane-change (decentralized) and in-lane maneuvers

5.2.1 CRF prototype overview

CRF vehicle prototypes, two Maserati Ghibli, are capable of combining 5G information, thanks to QCGER CV2X units, with the vehicle’s own sensors (front, surrounding) in order to perform extended vehicle perception and enable L4 Automated Driving functionalities. In particular, in order for the subject vehicle (called “Host Vehicle” or HV), the hypotheses Table 35 have been made, they have been implemented and tested functionally on the pilot. In addition, the two prototype are connected with a direct link exploiting PC5. They are not exhaustive for L4 driving but represent a meaningful baseline for an R&D prototype implementation.

<table>
<thead>
<tr>
<th>Case</th>
<th>L4 ODD assumptions</th>
</tr>
</thead>
</table>
| 1. Isolated vehicle (out of test scope) | Highway, main road, far from junctions, with time horizon of 10s.  
L3 is available and engaged  
Absence of perceived objects within an estimated time horizon of 10s, i.e.  
  • No vehicles detected by surround sensors  
  • No vehicles detected by V2X (>400m range)  
  • No other V2X hazard warnings |
| 2. Vehicle in traffic (in test scope) | Highway, main road (including junctions)  
L3 is available and engaged  
Extended perception condition |
The “vehicle in traffic” is the actual 5G pilot focus. In particular, the case when the host vehicle is following a cooperative lead vehicle with extended perception mode (“see what I see”) as already described in D5.1 and D8.2, and is enabled only when 5G is available.

The “isolated vehicle” case has been implemented to fulfil all the possible states of the autopilot, but it is not representative of the addressed scenarios.

### 5.2.1.1 On-board system

The on board system, already presented in D5.2, integrates several components, as in the functional scheme of Figure 128.

**Figure 128: Functional components of CRF prototype**

The functionalities of each component shown are briefly outlined hereafter.

**PC5 Radio Access** (on PC5 Roadrunner modem by QCGER) enables direct V2V/V2I communications over the side-link (PC5 interface).

**PC5 Cooperative Message encoding/decoding** encodes and decodes C-ITS messages.

- Sends Over-The-Air messages, generated at the application layer, using PC5 access
- Forwards encoded messages coming from the application layer to the MEC 5G CARMEN services through the modem as User Datagram Protocol (UDP) packets on 5G access.
- Sends encoded messages to the AMQP client (producer); communication with AMQP client relies on UDP.
- Receives and decodes messages from the MEC 5G CARMEN services and from AMQP client (consumer).
• Manages received messages from MEC services and direct communication PC5 forwarding them to the application layer.

5G Radio Access (on 5G modem by QCGER) enables 5G V2N communications (if 5G is not available the modem scales to lower technology standard.

AMQP producer/consumer incorporates two functions:

• interaction with the AMQP server via Transmission Control Protocol - Internet Protocol (TCP-IP) to publish or receive events, as AMQP client
• Receives C-ITS messages from the PC5 Cooperative Message encoding/decoding and publish them on the AMQP server adding the properties based on the payload of the messages.

C-V2X application manages the C-ITS messages received through Uu and PC5 interfacing the C-V2X application to the AD proto app.

• V-LDM (by CRF, CNIT and third parties on QCGER unit and other units) performs application layer functionalities of the V2X on-board system:
  o pre-filtering of CAM messages received by vehicles according to areas of interest around the host vehicle based on a Local Dynamic Map approach, outlined by using SAE-J2945 as reference.
  o reception and interpretation of DENM/IVIM information based on C-ITS priority services (e.g. Weather Warning, Traffic Jam Warning), forwarding relevant information to the ADAS unit
  o generation of the CAM payload based on vehicle’s data and Global Navigation Satellite System (GNSS)
  o triggering of DENM (VSSS)

• C-V2X connectivity management application managing reconnection at borders, as described in 5.2.3.

• C-V2X data control is a novel module with respect to the state of art which has been introduced to monitor the quality of data received by the C-V2X unit in terms of latency, redundancy, accuracy, predictive availability and other KPIs that are being defined. It provides such V2X meta-information to the ADAS unit.

GNSS precise positioning (by DTAG; first solution by CRF) provides sub meter absolute position for lane level positioning.

Environmental Sensors are novel systems installed on-board which detect environment conditions especially related to low visibility.

Obstacle Sensors are the on-board sensors (radar, cameras) that are used to detect and classify objects in the surroundings. Classification enables the recognition of the remote object as vehicle, truck or pedestrian.

Vehicle Data Gateway provides the C-V2X unit with the vehicle data to be shared via the CAM.

ADAS/AD prototype application relates to positioning, situation awareness, decision, and state sharing functionalities; in particular it performs:

• relative positioning of the vehicle with respect to the road (lane occupancy)
• data fusion of C-V2X relevant information, obstacle detections, environmental conditions, GNSS and manoeuvre data
• decision whether to warn the driver, suggest manoeuvres, act on Advanced Driving (AD) control parameters or disengage the AD functionality
• sharing vehicle’s sensor and state information, when the event should be notified to other vehicles (hazard, bad weather conditions, etc.)

The physical view and the deployment of the in-vehicle components is shown in Figure 129.
5.2.1.2 HMI of the final prototype

With respect to the preliminary pilot report D5.2, the Human Machine Interaction has been improved, with better view of both the connectivity and the dynamic road view (scene in front of the vehicle).

The HMI, shown in the figures below, is divided in three main vertical areas:

- The left area visualizes AD/DA and V2X states and allows user interaction
- The central area is able to show the back situation and performance indicators
- The right area represents the Dynamic Road View, i.e., ego vehicle and surrounding scenario

For sake of explanation, the following two figures represent the HMI before and after the C-ACC engagement.
Figure 130: HMI before C-ACC engagement
In the left area, the following information is presented:

- **AD/DA Status:**
  - Levels of automation from L0 to L4. The engaged level is specified in green; the available levels are coloured in cyan. Levels from L0 to L2 may be engaged depending on the situation:
    - L0: manual driving, no automation; in this case L1 is available;
    - L1: automated longitudinal actuation, e.g., ACC, if ACC is engaged L2 becomes available;
    - L2: automated lateral and longitudinal actuation, e.g., lane centering; in this case L3 and L4 become available depending on the signal quality (4G/5G, latency, accuracy…)
  - ACC Settings:
    - On the left in green: target speed of the car production ACC in km/h;
    - On the right in orange: target speed of the ACC handled by V2X in km/h;
    - Information about C-ACC engagement;
    - Information about Extended Perception availability;
    - An arrow indicating the ego vehicle adaptation with respect to the remote vehicle, i.e., up arrow if accelerating, down arrow if decelerating (available for both C-ACC and cut-in functionalities).
- **V2X Status:**
  - The ego vehicle in green and the remote vehicle in orange;
  - Uu (green link to the network and back) and PC5 (blue direct link between vehicles) connections, with bi-directional data flow diagnostics (V2V, V2N);
  - Relative distance between them in meters (negative if remote behind ego, positive vice versa) derived from the own position and the one sent by the remote vehicle through its CAM;
  - Type of cellular technology available and used, e.g., 4G or 5G;

**Figure 131: HMI after C-ACC engagement**
- Related quality level of the signal, expressed with four bars (also the used technology is expressed through different colour: yellow for 4G and green for 5G);
- Related telecommunication operator, for example TIM or Magenta
- User input: ACC engagement, with the possibility to accept or discard the C-ACC enabling and cut-it enabler (if requested from the remote vehicle).

In the central area, the following information is displayed:
- Back situations, e.g., an emergency vehicle approaching;
- Uu Latency related to the nearest remote vehicle expressed in milliseconds. The latency is calculated considering the time that the message is coded on vehicle 1 and the time in which it is decoded on vehicle 2;
- Positioning accuracy related to the nearest remote vehicle expressed in meters. Position accuracy relies on the confidence ellipse related to the own position that the remote vehicle codes in its CAM.

The right area, lastly, represents the ego vehicle and the surrounding scenario.

On the top, a bird’s eye view of the ego car with the lanes occupancies is represented: the surrounding lines are red to represent occupied lanes, white otherwise. This is determined according to the blind spot sensors, rear radars and V2X.

On the bottom, a dynamic road view of scenario seen by the ego point of view is shown. The actors are coloured according to the following legenda:
- Green: ego vehicle
- Cyan: vehicle sensed by the ego camera
- Orange: remote vehicle, i.e., vehicle communicating with ego via V2V (standard CAM)
- Red: road user sensed by the camera of a communicating vehicle with a perception message. The perception message informs about the road users sensed by the camera of the other connected vehicles.

A cyan line connects the ego vehicle with the nearest remote vehicle; in particular, it is dashed when the vehicles are simply connected, then it becomes solid when the C-ACC between them is engaged.

The actors have three different shapes according to their type:
- Thin block: pedestrians
- Medium block: cars, cyclists, motorcyclists
- Large block: trucks, vans

Moreover, this area is able to show the extended perception, i.e., the combination of V2V communication with camera sensing to augment environmental awareness. It is represented by a red or orange glow below the vehicles perceived with both V2V communication and camera.

The identification of the vehicles perceived with V2V and camera simultaneously, for both the red and orange glows situations, is based on the definition of a cost function considering position and velocity for each couple of V2V message and camera. The resulting matching is based on the best cost function with settable parameters related to position and velocity thresholds. A similar additional matching algorithm was implemented to remove overlapping between ego vehicle and CAM information.

Furthermore, a longitudinal settable threshold was defined (optimal between 50m and 100m), derived by the log analysis, in order to disable the remote vehicles visualization beyond the threshold horizon.

### 5.2.2 Precise Positioning tests

Two CRF prototype vehicles were equipped with a Swift Navigation evaluation system supplied by DTAG within the 5G-CARMEN project. This system is able to operate even if the GNSS satellites are temporarily
unavailable (e.g. parking garages and tunnels) due to the integration of an IMU and wheel odometry to enable dead reckoning.

The positioning On Board Units (OBUs) were firmly installed in order to avoid vibrations that would degrade the IMU performances. They were also configured to receive wheel tick signals via CAN bus; this information is used to improve dead-reckoning estimation and to support advanced features such as Fusion Aided Outlier Detection.

Several measurements were taken in order to identify the lever arms (offsets) between:

- GNSS antenna and the positioning OBU,
- wheels reference position and the positioning OBU,
- vehicle reference position and the positioning OBU.

The solution is based on a dual frequency L1/L2 GNSS receiver which supports the following constellations: GPS, GALILEO, GLONASS and BEIDOU. The positioning unit generates a GNSS solution at a maximum frequency of 10 Hz but it is possible to increase the output rate up to 50 Hz by fusing the GNSS position with data coming from the IMU.

The positioning solution requires GNSS corrections that are received via cellular connectivity to achieve sub-meter accuracy. The correction service used was the Skylark Cloud Correction Service from Swift Navigation, which models GNSS errors rather than performing an average of the corrections among several base stations (as is traditionally performed by an RTK VRS solution). These corrections are transmitted in State Space Representation (SSR) format, meaning that the same correction data can be broadcast to an arbitrary number of vehicles within the region of validity (commonly referred to as a “tile”).

The validation of the 5G-Carmen positioning system was performed in different testing areas.

1. Section 5.2.2.2 details the preliminary analysis performed in controlled areas. These tests were conducted to verify the stability of the solution and assess the availability of GNSS signals, GNSS corrections and fix types in controlled testing conditions.

2. Section 5.2.2.3 details the results for the Italian section of the 5G-Carmen corridor from Trento to Brenner. This area was selected because it is particularly challenging since it runs in the middle of a narrow valley with several tunnels along the way. The results for this area were already reported in D5.2, but the current deliverable includes new results obtained with the latest firmware available for the GNSS receiver and the Swift Navigation positioning engine and a deeper integration with the CRF demonstrator vehicles (i.e. wheel ticks from four wheels were used for the dead-reckoning evaluation).

3. Section 5.2.2.6 outlines the concept of positioning integrity, how it can support next generation automated driving functions and the integrity performance measured along the Italian test-site. Positioning integrity is not necessary for the 5G-Carmen use-cases and therefore it was not incorporated into the V2X messages; nevertheless, protection levels will be necessary to achieve the ASIL B classification necessary for production programs.

4. Section 5.2.2.7 describes the results for a longer trip along the 5G-Carmen corridor. The selected path was from Trento in Italy to Kufstein in Austria. The test route includes 500 km of driving performed over a period of more than 5 hours. The motorways pass through the Alps: the vehicles had to drive in narrow valleys and cross several tunnels (which could reach up to 1 km length). The valley geometry and the tunnels also impact on the positioning performance. The continuity of the cellular connectivity is crucial to maintain performance within the 20 cm threshold and the operation of the protection levels. The selected path of the 5G-Carmen corridor crosses three countries (Italy, Austria and Germany), therefore two Inter PLMN transitions must be handled by the telecom operator at the Italian-Austrian border (Brenner pass) and Austrian-German side (Kufstein town). The first part of this section describes the average positioning performance obtained for the entire trip. The second part focuses on the connectivity performance with particular focus at the borders.

5.2.2.1 Experimental set-up
The C-V2X application subscribes to the positioning service to populate the positioning frames and generate the CAMs at 20 Hz.

The following signals are used to populate the V2X messages:

- Reference position: absolute geographical latitude, longitude and altitude in the WGS84 coordinate system.
- Position confidence ellipse: horizontal position accuracy in the shape of an ellipse with a 95% confidence level. The centre of the ellipse shape corresponds to the reference position.
- Heading value: orientation of the heading with regards to WGS84 north.

Several testing measurements were performed to validate the performance of the positioning solution. One of the two demonstrators was equipped with a survey grade positioning solution (which integrates a more sophisticated IMU and GNSS antenna) to evaluate the performance against the automotive version, see Figure 132.

![Antenna configuration of two CRF demonstrator vehicles](image)

**Figure 132: Antenna configuration of two CRF demonstrator vehicles**

The following parameters were monitored to evaluate the positioning performance:

- The estimated accuracy of the positioning solution based on the solution type,
- The positioning performance when driving through bridges and tunnels,
- The continuity of the connectivity necessary to obtain the GNSS corrections.

5.2.2.2 Preliminary validation

The cars drove in the following areas:

- Trento hill-area: from CRF offices to the motorway (Trento South gate entry). A limited number of satellites are visible along this route due to mountains and buildings occasionally hindering the GNSS signals.
• Trento motorway: from Trento South gate entry to San Michele gate exit. Driving in the centre of the valley with good sky-visibility in respect to the previous scenario. No buildings hindering the GNSS signals.
• Turin Stellantis Safety track, closed to traffic. Medium speed ring (testing speed up to 70 km/h) available with clear GNSS sky visibility.
• Balocco Stellantis Proving ground: FCA test track closed to traffic. High-speed ring (testing speed up to 130 km/h) available with clear GNSS sky visibility.

Table 36: Experimental results of precise positioning in the test areas

<table>
<thead>
<tr>
<th>Test Area</th>
<th>Duration (HH:mm)</th>
<th>Distance travelled (km)</th>
<th>Availability of RTK Float</th>
<th>Availability of RTK Integer</th>
<th>Dead Reckoning</th>
<th>Average of satellite used in the solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRF Trento (hill-area)</td>
<td>0:26</td>
<td>6.3</td>
<td>63.56%</td>
<td>12.82%</td>
<td>15.10%</td>
<td>9</td>
</tr>
<tr>
<td>CRF Trento (motorway)</td>
<td>0:19</td>
<td>20.25</td>
<td>40.33%</td>
<td>42.19%</td>
<td>6.09%</td>
<td>12</td>
</tr>
<tr>
<td>CRF Safety Track (Turin, Italy)</td>
<td>0:45</td>
<td>26.5</td>
<td>53.18%</td>
<td>38.64%</td>
<td>0.52%</td>
<td>12</td>
</tr>
<tr>
<td>FCA Proving Ground (Balocco, Italy)</td>
<td>3:10</td>
<td>200</td>
<td>10.11%</td>
<td>89.27%</td>
<td>0.15%</td>
<td>12</td>
</tr>
</tbody>
</table>

It was found that it is possible to achieve accuracies of up to 5 cm in open sky conditions with the described setup.

Nevertheless, during the testing campaign we have identified degraded performances, in terms of horizontal accuracy, ranging from 20 to 70 cm, when 6 (or less) satellites in the L2 frequency band are in view.

This condition frequently occurred in the surrounding area of CRF Trento facility due to the mountains blocking some of the GNSS satellite signals. It was noticed that the problem occurred with the Skylark service while a traditional RTK solution was able to operate continuously in such conditions as it requires a lower number of satellites to be visible at a given time.

DTAG and CRF investigated this issue. It turned out the problem was related to the structure of the L2 signal, which was not designed for such high accuracy applications. The problem was partly solved by a firmware upgrade of the GNSS receiver but in the near future, the automotive industry will move from L1+L2 frequency to L1+L5, or even to L1+L2+L5 and we expect that in this new configuration the GNSS problem should be resolved.

L5 support in the satellites is part of the ongoing deployment and modernization of the GNSS constellations, and therefore the availability of the signal is not at the level of a completely rolled out satellite system. For this reason, in 5G-CARMEN, we will continue to use the L1+L2 GNSS frequencies.

5.2.2.3 Positioning validation in the Italian corridor

2 RTK Float solution implies that the accuracy of the solution is typically lower than 50 cm.
3 RTK Integer solution implies that the accuracy of the solution is typically lower than 10 cm.
The positioning solution was validated in the 5G-Carmen Italian corridor. The majority of these tests were performed in the motorway section from Trento to Brenner (the Italian/Austrian border). The selected area is more challenging in respect to Open-Sky scenarios in terms of GNSS signal availability and cellular coverage: the valley becomes quite narrow in the last 100 kilometres and several tunnels are present along the way, creating signal interruptions, see Figure 133(a). Figure 133(b) shows all the tunnels present in the A22 motorway: the longest one is 887 meters long.

Figure 133: 5G-Carmen Italian test-site. (a) A22 motorway testing area: from Trento to Brenner in the Adige valley. (b) Tunnels in the A22 motorway: Virgolo is the longest tunnel along the motorway (887 m)

5.2.2.4 Test results – 2021 integration
The reports below summarise some of the statistics collected by the CRF demonstrators during a trip along the Italian corridor in July 2021 to assess the typical performance of the 5G-Carmen positioning solution in highway conditions. Demo Car 1 was also fitted with a high accuracy measurement system to serve as ground truth reference.

Table 37 Positioning statistics for CRF demonstrator in the Italy-Austria testing area.

<table>
<thead>
<tr>
<th>CRF Demo Car 1</th>
<th>CRF Demo Car 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution Frequency:</strong></td>
<td>20.0 Hz</td>
</tr>
<tr>
<td>Test duration: 1 hr 22'</td>
<td></td>
</tr>
<tr>
<td>Distance travelled: 140.54 km,</td>
<td></td>
</tr>
<tr>
<td>Correction availability: 95.43%</td>
<td></td>
</tr>
</tbody>
</table>

**Solution Availability**
- No fix (i.e. Faults): 0.00%
- SPS: 0.84%
- SBAS: 12.34%
- DGPS: 0.44%
- RTK Float: 48.89%
- RTK Fixed: 33.19%
- RTK(Float+Fixed): 82.08%
- DR: 4.29%

**Satellites Used**
- Maximum: 22
- Average: 11.8

**Estimated Horizontal Position Error**
- Minimum: 0.060 m
- Maximum: 11.240 m
- Average: 0.205 m

**Estimated Vertical Position Error**
- Minimum: 0.090 m
- Maximum: 2.000 m
- Average: 0.266 m

<table>
<thead>
<tr>
<th>CRF Demo Car 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution Frequency:</strong></td>
<td>20.0 Hz</td>
</tr>
<tr>
<td>Test duration: 1 hr 39'</td>
<td></td>
</tr>
<tr>
<td>Distance travelled: 142.65 km,</td>
<td></td>
</tr>
<tr>
<td>Correction availability: 96.31%</td>
<td></td>
</tr>
</tbody>
</table>

**Solution Availability**
- No fix (i.e. Faults): 0.00%
- SPS: 0.00%
- SBAS: 5.37%
- DGPS: 0.44%
- RTK Float: 40.40%
- RTK Fixed: 50.09%
- RTK(Float+Fixed): 90.49%
- DR: 3.70%

**Satellites Used**
- Maximum: 22
- Average: 12.3

**Estimated Horizontal Position Error**
- Minimum: 0.050 m
- Maximum: 2.980 m
- Average: 0.147 m

**Estimated Vertical Position Error**
- Minimum: 0.070 m
- Maximum: 1.720 m
- Average: 0.204 m

It can be seen that both of the demonstration vehicles reported an average estimated horizontal error (68th percentile) of approximately 20 cm. The system was able to compute an RTK solution (i.e. a position with expected horizontal accuracy below 50 cm) for at least 80% of the epochs.

Figure 134 shows the Cumulative Distribution Function, which represents the percentage of epochs affected by a given error in comparison to the ground truth system. These measurements indicate that the following horizontal accuracies were achieved by Demo Car 1:

- 68th percentile (1σ): 29 cm,
- 95th percentile (2σ): 46 cm,
- 99th percentile (3σ): 74 cm.

Overall, there are no significant deviations from the performances achieved by the ground truth system.
Figure 134: Cumulative Distribution Function for July 2021 test drive in Italian Corridor

Figure 135 shows the distribution of positioning fixes along the testing area. This plot (and those which follow in the remainder of this section) shows the positioning results from Demo Car 2, although similar performance was also observed with Demo Car 1. Green segments represent positions with RTK (Integer) Fixed position mode with expected horizontal accuracy lower than 10 centimetres; blue segments represent positions with expected horizontal accuracy lower than 50 centimetres and, finally, black segments are positions generated without the aid of GNSS signals.

Figure 135: Position type distribution of CRF demo car 2. Brenner to Trento test drive

Figure 136.(a) shows the estimated horizontal position error for the trip from Brenner to Trento. In the first 2 minutes, the system initialised all the components: the acquisition of GNSS signals, the subscription to the cellular network and performed the calibration of the internal IMU. Once the solution converged, the estimated position accuracy (at 1σ) was typically lower than 20 centimetres in good GNSS sky conditions.
The peaks highlighted with the red box are associated with dead-reckoning navigation. In such conditions there are not enough GNSS signals to compute a fix; the position is estimated based on the relative offset computed by the IMU and the wheel odometer measurements (i.e. dead reckoning). As expected, the positioning error increases with the travelled distance. The first peak corresponds to the Fortezza tunnel (tunnel number 3 according to Figure 133) which is 754 meters long (driving along the motorway in southward direction); the associated estimated error gradually increases up to 2.8 meters when the vehicle exits the tunnel and recovers the GNSS signals. The orange circles in Figure 136.(b) show the increasing estimated error plotted on a satellite image. Similar positioning degradation can be seen in the other tunnels, more in detail: for a tunnel with a length of 300m, the positioning error has been estimated approximately 2 meters. The last peak corresponds to the Virgolo tunnel, which has a similar length to the Fortezza one and almost the same horizontal error. The other peaks in the red box, characterized by 1 meter estimated error, occurred when the vehicle was running close to the mountains in an area where the valley is quite narrow. Figure 136.(c) shows the driving area that was responsible for the first 1 meter peak: an insufficient number of GNSS signals is available for the computation of the absolute position.

Focusing on a region without physical obstructions to the GNSS signals, orange box from Figure 136.(a), we can extrapolate some additional information on the typical behaviour of the Estimated Horizontal Position Error. In Figure 136.(e), the estimated error can be as low as 6 centimetres (1σ value) when the position type was RTK Integer (green points). The estimated horizontal error is typically bounded to 20 centimetres when a RTK Float solution is reported by the GNSS receiver. According to the testing campaign, on average 12 satellites (L1+L2 signals) were available to compute the RTK solution in the centre of the Adige valley; meaning there is, for most of the time, a good chance to compute a fix with at least 6 satellites in view with both L1 and L2 signals. Unavailability of the two frequency signals or the interruption of the line of sight component will degrade the overall performance. For instance, the bridges, frequently present on the Italian motorways, temporary block the GNSS signals. In Figure 136.(e) the position output switches from green (RTK Integer) to blue (RTK Float) due to the interruption of the signals causing a larger estimated error. In Figure 136.(d), the blue bars represent the sudden loss of the GNSS signals and the related degradation of the positioning output (in orange). Performance starts to degrade when GNSS tracking is lost: the green box in Figure 136.(d) represents the position degradation occurring due to a 25 meter long underpass, where the estimated error increases to 25 cm. The multiple subsequent GNSS signal blockages were caused by a toll gate which brought to a more severe signal degradation: up to 0.5 meters.

To achieve accuracies lower than 1 meter, a GNSS receiver requires GNSS corrections. These corrections must be periodically updated (at 1 Hz frequency) to allow the GNSS receiver to compensate for errors in the GNSS range measurements. In 5G-Carmen, the corrections were received via cellular connectivity. According to the log data collected from the test trials, the A22 motorway is well covered by cellular connectivity: in the 150 km monitored, the cellular connectivity was lost only in in the longer tunnels. In tunnel conditions, no GNSS signals are available and hence availability of correction data is irrelevant. The system properly recovers the correction flow when the internet connectivity is restored. Figure 137 shows the age of the corrections: the corrections are available for 96.54% of the entire trip.
Figure 136: Estimated Horizontal Position Error (EHPE) for CRF demo car 2 (Brenner to Trento test): (a) Overall error, (b) EHPE in the tunnel, (c) EHPE in case of low GNSS availability, (d) EHPE in case of GNSS short interruption, (e) Details on Position Mode for the (d) scenario.
5.2.2.5 Test results – 2022 integration

A second drive test along the Italian corridor was performed in April 2022 with an updated version of the Swift Navigation evaluation system. This test was performed using the same CRF Demo Car 1 test vehicle that was used for the July 2021 tests. The results for this area were already reported in D5.2, but the current deliverable includes new results obtained with the latest firmware available for the GNSS receiver and the Swift Navigation positioning engine and a deeper integration with the CRF demonstrator vehicles (i.e. wheel ticks from four wheels were used for the dead-reckoning evaluation). The high-level statistics collected during this drive are summarised below.
Table 38 Positioning statistics for CRF demonstrator in the Italy-Austria testing area.

<table>
<thead>
<tr>
<th>CRF Demo Car 1</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Frequency:</td>
<td>20.0 Hz</td>
</tr>
<tr>
<td>Test duration: 1 hr 29', Distance travelled: 147.53 km, Correction availability:</td>
<td>95.24%</td>
</tr>
</tbody>
</table>

**Solution Availability**
- No fix (i.e. Faults): 0.00%
- SPS: 0.28%
- SBAS: 8.44%
- DGPS: 0.39%
- RTK Float: 44.84%
- RTK Fixed: 41.63%
- RTK fixes (Float+Fixed): 86.2%
- DR: 4.42%

**Satellites Used**
- Maximum: 22
- Average: 11.8

**Estimated Horizontal Position Error**
- Minimum: 0.080 m
- Maximum: 10.000 m
- Average: 0.247 m

**Estimated Vertical Position Error**
- Minimum: 0.110 m
- Maximum: 10.000 m
- Average: 0.285 m

Similar to the previous trip, it can be seen that RTK solutions were available for more than 80% of the epochs and that approximately 4% of epochs were derived from dead reckoning due to the prevalence of tunnels along the route.

Figure 138 shows the Cumulative Distribution Function, which represents the percentage of epochs affected by a given error in comparison to the ground truth system. This plot indicates that the following horizontal accuracies were achieved during the April 2022 test drive:

- 68th percentile (1σ): 17 cm,
- 95th percentile (2σ): 44 cm,
- 99th percentile (3σ): 74 cm.

The 1σ value shows some improvement in comparison to the previous test (29 cm) whereas the 2σ and 3σ values show little to no variation (46 cm and 74 cm respectively).
In general, the horizontal position error is smaller than 20 centimetres when enough satellites are in visibility, satisfying the positioning needs of the 5G-Carmen project. Some deviations from these performance requirements were experienced due to the geometry of the valley, especially when the vehicle is driving close to the mountainside. Nevertheless, the positioning solution, thanks to the integration of the IMU and wheel odometry data is able, for the majority of the time, to limit the error to less than 50 centimetres. In the 5G-Carmen Italian test site there are several tunnels, the longest one is 800 meters long and the lack of GNSS signals creates an estimated error up to 3 meters. The testing activities never suffered from the lack of GNSS corrections since the Italian motorway provides continuous cellular connectivity in the area from Trento to the Brenner pass.

**Figure 138: Cumulative Distribution Function for April 2022 test drive in Italian Corridor**

**Figure 139: Position type distribution. Brenner to CRF test trip.**
5.2.2.6 Integrity algorithms and Protection Levels along the Italian corridor

Integrity Overview

Integrity refers to the measure of trust that can be placed in the correctness of information supplied by a navigation system. It is specified by the following parameters:

1. **Alert Limit**: The largest absolute error allowable for safe operation
2. **Integrity Risk**: The probability of providing a signal that is out of tolerance (i.e. an estimated position which error exceeds the alert limit) without warning the user within a given period of time. It is usually expressed per a particular duration of the critical operation, for example per hour.
3. **Time To Alert**: The maximum allowable elapsed time from the onset of a positioning failure until the equipment annunciates the alert
4. **Protection Level**: The distance from the reported position that describes a region assured to contain the true position within the given allocated integrity risk probability

In the case of horizontal error, the following definitions are used:

- **Horizontal Position Error (HPE)**: The difference between the reported position and true position as measured in the plane beneath the vehicle
- **Horizontal Alert Limit (HAL)**: The maximum allowable value of HPE which allows safe operation to be maintained
- **Horizontal Protection Level (HPL)**: The radius of a circle in the horizontal plane with its centre being at the reported position, that describes the region assured to contain the true position within the given allocated integrity risk probability

These parameters are represented graphically in Figure 141.
The \textit{Target Integrity Risk} (TIR) for a given application depends upon the specifics of the system safety case which incorporates factors such as potential hazardous events, controllability, and the \textit{Operational Design Domain} (ODD). For systems involving automated actuation of a vehicle, typical TIR values range from $10^{-4}$/hour to $10^{-7}$/hour. A TIR value of $10^{-7}$/hour means that a misleading event may occur once per 1.1 years of constant operation, whereas a TIR value of $10^{-4}$/hour means that this may only occur once every 1140.77 years. In some cases, multiple TIRs are specified to differentiate between Misleading Information (MI) and Hazardous Misleading Information (HMI).

The Swift Navigation positioning solution includes state-of-the-art integrity mechanisms. These integrity mechanisms are based upon a systematic analysis of the underlying positioning performance and all potential fault modes which may occur, with dedicated monitors to detect and reject inputs which are not in line with the system observation model. Potential error in the measurements is translated into the position solution by converting the observation error model into the state domain. It also includes a feature known as \textit{Continuous Protection Levels}, which allows integrity guarantees to be provided based upon sensor input even in the absence of GNSS satellite visibility or GNSS correction availability.

The Stanford Plot is the industry-standard method for representing integrity information. These plots show the relationship between the reported protection level values (Y axis) and the true error (X axis). They also include lines (one horizontal and one vertical) indicating the Alert Limit. The area above the horizontal Alert Limit line is not relevant to safety, rather, it indicates the availability of the system. Any point above the line X=Y can be considered safe since it indicates that the reported protection level value is less than the true error. Points below the X=Y line are misleading since they indicate that the reported protection level value is less than the true error. Should the error be larger than both the Protection Level and the vertical Alert Limit line, the system is unsafe.

The TIR defines the probability that a reported protection level value may be in the misleading/unsafe region instead of in the safe region.

Figure 142 shows an example Stanford Plot, where the following regions can be seen:

- Above X=Y line and PL < AL (white): Nominal operation
- Above X=Y line and PL > AL (yellow): System unavailable (but safe)
- Below X=Y line: Misleading
• Below X=Y line and PE > AL (red): Unsafe

![Diagram](image.png)

**Figure 142: Example Stanford Plot**

**Results from Italian Corridor**

The data from the April 2022 drive in the Italian Corridor (see Section 5.2.2.5) was used to evaluate the reliability of the Protection Level values reported by the Swift Navigation positioning solution. Evaluation of positioning integrity was not originally scoped for the 5G-Carmen project; however, it is expected that the deployment of automated lane changing functionality into automotive production programs will require high integrity positioning, and therefore the results of such an evaluation should be of interest to all project participants.

For the purposes of the 5G-Carmen evaluation, a TIR of $10^{-6}$/hour was selected since this value has been determined as a reasonable value for reaching the safety requirement for AD Level 3 systems. An Alert Limit of 5 m was used since this provides a road-level boundary to inhibit inappropriate activation of automated driving functionality in highway conditions. It should be noted that it is typically necessary to find the right balance between the TIR and the Alert Limit – stricter TIRs result in higher values being reported for the Protection Level (since the Protection Level must incorporate hazardous events with a lower likelihood of occurrence) and therefore overly strict TIRs or Alert Limits can limit system availability.
The key findings from this plot are as follows:

1. All of the reported HPL values are above the line X=Y, implying that the reported values were always less than the true HPE, 
2. 85.1% of the reported HPL values were lower than the unavailability, meaning that the system was in the nominal operating state (i.e. safe position available with Protection Level below Alert Limit) for the majority of the drive,
3. Higher levels of availability can potentially be achieved by using less strict values for the TIR and/or horizontal Alert Limit.

It should also be noted that the Swift Navigation high integrity positioning solution is still under active development and that additional improvements can be expected in future versions. Protection Levels were also continuously generated through changing environmental conditions as described in the test overview.

5.2.2.7 5G-Carmen corridor results

Overall Performance

A round-trip journey between Trento and Kufstein was undertaken in June 2022. This test was performed using the same CRF Demo Car 1 test vehicle that was used for the tests in the Italian Corridor. It was split into two drive segments:

1. Outbound segment (294 km): From Trento (Italy) to Degerndorf (Germany) to Kufstein (Austria),
2. Return segment (210 km): Kramsach (Austria) to Trento (Italy).
An overview of the driven route is shown in Figure 144. Table 39 reports the statistic for the return segment of the trip: travel from Kufstein to Trento. The overall performances are close to the ones observed on the Italian side of the corridor. For the outbound segment, the test vehicle was equipped with an LTE modem receiving data from regular commercial cellular networks. For the return segment the test vehicle was equipped with a 5G modem receiving data from the 5G test network developed within 5G-Carmen activities.

![Figure 144: Route driven along 5G-Carmen corridor](image)

Table 39 Positioning statistics for CRF demonstrator for the Kramsach (close to Kufstein) to Trento trip.

<table>
<thead>
<tr>
<th>CRF Demo Car 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution Frequency:</strong></td>
</tr>
<tr>
<td>20.0 Hz</td>
</tr>
<tr>
<td><strong>Test duration:</strong></td>
</tr>
<tr>
<td>2 hr 16',</td>
</tr>
<tr>
<td><strong>Distance travelled:</strong></td>
</tr>
<tr>
<td>210.53 km,</td>
</tr>
<tr>
<td><strong>Correction availability:</strong></td>
</tr>
<tr>
<td>95.80%</td>
</tr>
<tr>
<td><strong>Solution Availability</strong></td>
</tr>
<tr>
<td>No fix (i.e. Faults):</td>
</tr>
<tr>
<td>0.00%</td>
</tr>
<tr>
<td>SPS:</td>
</tr>
<tr>
<td>0.09%</td>
</tr>
<tr>
<td>SBAS:</td>
</tr>
<tr>
<td>15.55%</td>
</tr>
<tr>
<td>DGPS:</td>
</tr>
<tr>
<td>0.42%</td>
</tr>
<tr>
<td>RTK Float:</td>
</tr>
<tr>
<td>37.15%</td>
</tr>
<tr>
<td>RTK Fixed:</td>
</tr>
<tr>
<td>42.82%</td>
</tr>
<tr>
<td>RTK fixes (Float+Fixed):</td>
</tr>
<tr>
<td>79.97%</td>
</tr>
</tbody>
</table>
### DR:
3.97%

#### Satellites Used
- **Maximum:** 22
- **Average:** 12.6

#### Estimated Horizontal Position Error
- **Minimum:** 0.080 m
- **Maximum:** 10.000 m
- **Average:** 0.250 m

#### Estimated Vertical Position Error
- **Minimum:** 0.110 m
- **Maximum:** 10.000 m
- **Average:** 0.317 m

Figure 145 shows the Cumulative Distribution Function obtained from aggregating the data from both drive segments. This plot indicates that the following horizontal accuracies were achieved from more than 500 km of driving encompassing 3 different countries:

- 68th percentile (1σ): 20 cm,
- 95th percentile (2σ): 51 cm,
- 99th percentile (3σ): 88 cm.

---

![Cumulative Distribution Function for test drive along the Carmen-5G corridor](image)

**Figure 145: Cumulative Distribution Function for test drive along the Carmen-5G corridor**

Figure 149(a) shows the estimated horizontal position error for the return trip. Several peaks are present in the plot which correspond to the tunnel present on the route. The last group, on the right, corresponds to the ones present on the Italian part of the corridor, consistently with the results reported in Figure 136(a) and Figure 140. The estimated error inside the tunnel is strictly correlated to the tunnel length: an estimated horizontal error of roughly 3 meters is observed for an 800 m tunnel. The system is able to reach an estimated position accuracy lower than 50 cm when RTK Float fix is available, see Figure 149(b), and an estimated position accuracy lower than 10 cm when RTK fix is available. Several factors limit the capability of the system to perform a constant RTK fix solution: interruption of GNSS signals due to bridges or buildings, unavailability of a sufficiently high number of satellites on both L1 or L2 frequencies, delays in the corrections availability. In any case thanks to the coupling with the IMU data the system is able to temporary compensate the lack of GNSS data and provide a smooth position output.
Figure 146: Estimated Horizontal Position Error for the test drive along the 5G-Carmen corridor: (a) EHPE for the entire trip, (b) EHPE for epochs with RTK Float position mode (orange box above), (c) EHPE for epochs with RTK Fix position mode (red box above).
Looking into the collected data the positioning performance on the Austrian side of the 5G-Carmen corridor are slightly worse in respect to the ones experienced on the Italian side. Table 40 reports the statistics for the Austrian and the Italian test drive. It is evident the RTK Float and RTK Fixed position outputs are almost switched. In addition to that the number of SBAS position is also higher on the Austrian side in respect to the one on the Italian territory. This implies, on the Austrian side, that even if the system was occasionally in conditions to compute a positioning output with horizontal estimated accuracy lower than 10 cm, the average values was estimated error was 32 cm. On the contrary on the Italian side an average error of 19 cm was achieved.

Table 40: Positioning statistics for CRF demonstrator in the Italy-Austria 5G-Carmen corridor.

<table>
<thead>
<tr>
<th>CRF Demo Car 1– Austrian side (blue path below)</th>
<th>CRF Demo Car 1–Italian side (orange path below)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Frequency: 20.0 Hz</td>
<td>Solution Frequency: 20.0 Hz</td>
</tr>
<tr>
<td>Test duration: 0 hr 56'</td>
<td>Test duration: 1 hr 19'</td>
</tr>
<tr>
<td>Distance travelled: 78.25 km,</td>
<td>Distance travelled: 132.28 km,</td>
</tr>
<tr>
<td>Correction availability: 96.47%</td>
<td>Correction availability: 95.32%</td>
</tr>
<tr>
<td>Solution Availability</td>
<td>Solution Availability</td>
</tr>
<tr>
<td>No fix (i.e. Faults): 0.00%</td>
<td>No fix (i.e. Faults): 0.00%</td>
</tr>
<tr>
<td>SPS: 0.22%</td>
<td>SPS: 0.00%</td>
</tr>
<tr>
<td>SBAS: 22.58%</td>
<td>SBAS: 10.56%</td>
</tr>
<tr>
<td>DGPS: 0.35%</td>
<td>DGPS: 0.46%</td>
</tr>
<tr>
<td>RTK Float: 55.52%</td>
<td>RTK Float: 24.12%</td>
</tr>
<tr>
<td>RTK Fixed: 17.95%</td>
<td>RTK Fixed: 60.46%</td>
</tr>
<tr>
<td>RTK(Float+Fixed): 73.47%</td>
<td>RTK(Float+Fixed): 84.58%</td>
</tr>
<tr>
<td>DR: 3.38%</td>
<td>DR: 4.40%</td>
</tr>
<tr>
<td>Satellites Used</td>
<td>Satellites Used</td>
</tr>
<tr>
<td>Maximum: 22</td>
<td>Maximum: 22</td>
</tr>
<tr>
<td>Average: 12.9</td>
<td>Average: 12.5</td>
</tr>
<tr>
<td>Estimated Horizontal Position Error</td>
<td>Estimated Horizontal Position Error</td>
</tr>
<tr>
<td>Minimum: 0.080 m</td>
<td>Minimum: 0.080 m</td>
</tr>
<tr>
<td>Maximum: 10.00 m</td>
<td>Maximum: 2.910 m</td>
</tr>
<tr>
<td>Average: 0.329 m</td>
<td>Average: 0.195 m</td>
</tr>
<tr>
<td>Estimated Vertical Position Error</td>
<td>Estimated Vertical Position Error</td>
</tr>
<tr>
<td>Minimum: 0.120 m</td>
<td>Minimum: 0.110 m</td>
</tr>
<tr>
<td>Maximum: 10.00 m</td>
<td>Maximum: 1.640 m</td>
</tr>
<tr>
<td>Average: 0.428 m</td>
<td>Average: 0.238 m</td>
</tr>
</tbody>
</table>
Figure 147 shows the distribution of the position type on the Austrian and on the Italian side of the 5G-Carmen corridor. On the Austrian side the RTK Float position output (blue segments) was computed for the majority of the time while on the Italian side was possible to achieve RTK Fix (green segments) for the majority of the time. The log data suggests this behaviour is linked to the Dilution Of Precision (DOP) available in the Lower Inn valley (Austria). The Austrian valley is wider in comparison to the Italian one but very few satellites were in visibility along the North/South direction. On the contrary the Alto Adige valley (in Italy), even if it is narrower, enough satellites were in visibility across the entire sky to compute the RTK Fix solution. In Figure 148 is reported the Position Dilution Of Precision (PDOP) for the Austrian (Figure 148.a) and the Italian (Figure 148.b) data sets. The smaller the PDOP value the better is the satellite distribution to compute the positioning output. The average PDOP value for the Austrian samples is 1.801, the PDOP for the Italian one is 1.685. It might be noticed that PDOP values are subject to multiples spikes, caused by frequently interruptions of the GNSS signals caused by many obstructions to the satellite signals. Nevertheless, thanks to the data-fusion with the IMU and vehicle data, the system is capable to handle these interruptions and limit the error degradation.

Figure 147 Position type for the 5G-Carmen corridor: (a) Austrian side, (b) Italian side. Blue segments represent areas where RTK float were computed, green segments areas where RTK fix were computed.

Figure 148 Position Dilution Of Precision (PDOP) for (a) Austrian and (b) Italian data sets. The smaller the PDOP value the better is the satellite distribution to compute the positioning output.

4 Dilution of precision: https://en.wikipedia.org/wiki/Dilution_of_precision_(navigation), last access 15/06/2022
Figure 148 Position Dilution Of Precision for the 5G-Carmen corridor: (a) Austrian side, (b) Italian side.

**GNSS correction availability**

Figure 149 shows the age of the GNSS corrections which the positioning system received from the cellular modem during the drive segments described in the previous section. These values may be used as a proxy for assessing cellular network performance since the age of corrections indicates the amount of time for which data was not available from the cellular network. In nominal conditions the correction age should be 1-2 seconds since new correction data is sent every second. The peaks highlighted in orange correspond to lengthy (≥ 500 m) tunnels along the route. The peaks highlighted in red correspond to border crossings between different countries.

From the plots above, it can be observed that each border crossing made with the LTE modem during the outbound journey resulted in an absence of correction data for more than 90 seconds. However, when using the 5G-Carmen network during the return journey, the handover between the Austrian and Italian cellular networks resulted in no observable delay in the correction data stream. The different cellular modems/networks did not have any meaningful impact on the length of the outages during tunnel events. Figure 150 reports a details on the impact of the handover on the GNSS correction age and estimated error. In Figure 150(a) it is presented a
plot where the LTE commercial network was used to collect the GNSS corrections. The positioning system was not able to reach the correction provider for 140 seconds due to the cellular operator switch. The corrections have been used for 90 s: after this amount of time, they cannot help in the computation of new positions. Hence, the estimated positioning output degrades from 24 cm to 1.8 m. Figure 150(b) shows the case where the 5G-Carmen fast-reselection process is adopted to handle the handover. An overall delay in the correction availability of 3.4 s was experienced in this case, with negligible impact in terms of positioning error. Therefore the 5G-Carmen proved to be efficient in removing the positioning degradation caused by the cross-border handover.

![Figure 150: Handover impact on Correction Age at the Italy-Austria border: (a) LTE commercial network travelling from Italy to Austria, (b) 5G-Carmen fast reselection travelling from Austria to Italy. The 3.4 s outage is negligible on estimated position error.](image)

As final remark, the cellular connectivity present along the 5G-Carmen corridor proved to be sufficient to support the positioning provision of GNSS corrections: no problems in the continuity of the service have been identified at the end of the project; not even at the Italy-Austria and Austria-Germany border thanks to the fast-reselection mechanism developed among the 5G-Carmen telecom operators.

The remaining source of positioning error left, along the 5G-Carmen corridor, are coming from the tunnels present on both the sides of the Brenner pass. Inside the tunnels both GNSS signals and cellular connectivity are not available preventing the usage of GNSS positioning as input parameter for the localization and the trajectory planning tasks.
5.2.3 Service connectivity at borders

This chapter has the purpose of describing the functionalities of the application component designed and implemented by CRF for allowing the automatic switch of the MEC services usage.

The application developed runs on the C-V2X Unit and a part of it, which will be called “component”, is aimed at controlling the UDP/IP sockets used to transport the outgoing and incoming traffic of the two CRF demonstrator vehicles towards the MEC service of the respective country in which the vehicle is driving.

Figure 151 shows a scheme of the functional architecture of the component considered is shown. It represents the case in which one vehicle is sending and receiving CAM PDUs to/from the GeoService running on MEC in Italy, and it is almost to cross the border with Austria.

![Functional architecture of cross-border UDP socket switching application component](image)

Figure 151: Cross-border connectivity at the application layer

Figure 1xx: Functional architecture of cross-border UDP socket switching application component at IT-AT border
The modem represented on the left side of the figure exchanges data with the cellular network collecting, for instance, the Mobile Country Code (MCC), which in the case considered is assumed to have value 222, Mobile Network Code (MNC), APN, and so on and so forth.

Those data are requested from the application component via the Android Debug Bridge (ADB) and collected in the form of PDU, the packet data unit from here on out called “modem PDU”.

The modem PDU contains the information related to the country of the mobile network.

In the example in Figure 152, part of the information considered for the purpose is the MCC. The vehicle is driving in Italy and the modem reports the value of the MCC equal to 222 which is the code identifying Italy.

This value is stored in the modem PDU soon after the application component reads the value. The application component can open the UDP/IP socket which allows the communication between itself and the Geoservice web service. The Geoservice receives the CAMs from the vehicle and sends back to it, using a further UDP/IP socket, the CAMs related to the vehicles in the surrounding within a defined radius.

When the host vehicle is driving towards the border, at a certain point in time, the modem PDU will contain the value of MCC related to the neighbouring country. For instance, if the vehicle is crossing the border between Italy and Austria. When the application component reads from the modem PDU the value of the new MCC, immediately closes the socket created for the previous country and re-opens a UDP socket which in this example will allow the vehicle to communicate with the Geoservice running in Austria.

Another methodology used to switch from a socket to another for enabling the different service per country is the cellular network interface IP. This IP is available at the modem interface and encapsulated in the modem PDU at the application layer.

Depending on the country, the network address is known at the vehicle side. In this way, it is possible to understand at which country network the modem is connected from the IP address.

During the experiments executed both the approaches have been used in combination in order to increase the degree of reliability.

![Figure 152: Reconnection time: measured values, mean and median values](image)

One of the metrics considered during the experiments has been the reconnection time: it represents how many seconds the network remains not reachable when a cross-border service switch is handled. This metric is calculated by measuring the amount of time elapsed since the IP address at the network interface of the modem is not available up to the instant in which it becomes available again. It is measured in seconds.

A set of sample measures is reported in the graph above (Reconnection time measurement) at Brennero. The mean value is 2,372, the median is 1,749. The standard deviation is 2,292. Note that the derived values of reconnection time are a bit too small, since the los of IP address can only be found out after a certain time when the modem is already undergoing the related procedures need for the inter PLMN change.
In addition to the reconnection time, defined above, a further metric has been utilised to estimate the data loss and more precisely the amount of time in which a vehicle cannot communicate with another vehicle.

Since the PDU considered is still the CAM PDU, the metric used for the purpose is the packet (the PDU) inter-arrival time, which is defined as follows.

The Packet Inter-arrival Time (PIAT) is the amount of time elapsed between the reception of a packet and the reception of the following one.

At the border the PIAT is used to determine the amount of time in which the communication suffers outage conditions.

The measure of the in-country PIATs performs as expected. Figure 153 shows the packet inter-arrival measure in-country (no operator switch and/or IP switch has been performed) for the CAM PDUs received at Geoservice side and sent from the vehicle.

It is easy to observe that the PIAT is around 50-60 ms, which is coherent with the fact that the vehicle sends CAMs with a frequency of 20 Hz when in coverage.

![Packet inter-arrival time in-country](image)

**Figure 153: Packet inter-arrival time in-country: arrival of CAM PDUs every 50-60 ms**

When the vehicle reaches the border, it has been observed that this metric assumes values dramatically above 50 ms (PIAT > 6s) and this is expected since the communication is interrupted due to the operator switching. When the IP is reassigned, the magnitude of the outage is represented by the reconnection time. When, instead, the PDUs are lost for the same reason, the magnitude of the outage in time is expressed by the PIAT.

The graph of Figure 162 shows an example of the PIAT measured when traversing the border from Austria to Italy. Each bar represents a CAM PDU received at Geoservice side during the trip.
The data recorded during the experiments have been processed and analysed. One of the analyses executed is related to the frequency of the PIAT values during an entire session of experiments lasted about 7 hours.

The graph of Figure 163 shows a higher frequency of 1s values and a very low frequency for values around 5.

In the following tables some measurements of PIAT are reported. The samples on the left have been produced during a test executed passing through the tunnel close to Brenner following the direction from Austria to Italy. The samples on the right have been produced during a test executed passing through the tunnel close to Brenner following the direction from Austria to Germany.
The PIAT has been measured in the link from a vehicle to the Geoservice. The results indicate that at the border, passing from Austria to Italy, it is possible to perceive a delay of 6.3 s on average in the communication between the vehicle and the Geoservice. In the same manner it is possible to perceive a delay of 7.4 s on average when passing from Austria to Germany. In this case, in the outcome it is also noticeable a degree of dispersion. The standard deviation calculated is 3.6. Nevertheless, the global results satisfy the expectations.

Considering the graph in figure (Figure 1xx: Packet inter-arrival time frequency of an experiment with a total duration of about 7h.), the cross-border PIAT values reported in the table 1xx below can be considered as sporadic.

On the other hand, the outcome of the experiments held passing from Italy to Austria show different results since the fast network reselection is not present when the vehicle needs to switch from the Italian telecom operator to the Austrian one. In fact, the mean value of the packet inter-arrival time in this case is 32.5 s and the standard deviation is 19.6.

The case is furthermore different for the route from Germany to Austria: the results show a higher delay when switching operators with a mean value of 141.6 s and a standard deviation of 58.4.
5.2.4 On board extended perception module for L4 automation

5.2.4.1 Extended Perception improvements

Recalling D5.2, here we highlight those components used in the test, how the extended perception was done and the difference in behaviour of the lead vehicle (transmitter vehicle, sending its perception) with respect to the host vehicle (receiver vehicle, enhancing its perception). Notice that in reality the two vehicles identical in terms of equipment and components, but for ease of understanding of the information flow, the components
were highlighted in one way of communication only (from right to left).

EXTENDED VEHICLE PERCEPTION ARCHITECTURE

In particular the vehicle uses:

- a **precise positioning module**, providing very accurate estimates of coordinates and orientation
- a **5G modem**, providing a low latency communication interface
- a **V2X OBU** able to encode and decode CAM messages using both PC5 link and 5G link, interfacing the V2X stack with the AD unit, estimate the data quality level, and provide connection to the Geoservice interface and to the AMQP broker.
- an **AD unit**, dedicated to sensor data processing, V2X applications and autonomous driving tasks.

The functional components needed for the extended perception module system are: in transmission mode:

- **dynamic sensor filter**: it tracks vehicles perceived by the host vehicle sensors, decides which ones are relevant, identify its cruising lane, and provide a high frequency estimate of its position, relative speed and orientation expressed with respect to the vehicle reference frame;
- **objects absolute coordinates estimator**: it gets information from the precise positioning module and estimates the position of the perceived vehicles in absolute global coordinates. It then packs all this information and sends them to the V2X OBU;
- **virtual CAM message encoder**: it encodes a Virtual CAM message for the vehicles perceived by on board sensors, filling it with the data estimated by the AD unit;

**Geoservice Interface and AMQP application**: this applications send, acting like a publisher, to the respective services the encoded CAM and Virtual CAM through the 5GModem; while in reception mode:

- **Geoservice Interface and AMQP application**: they get from the services all the CAM and Virtual CAM sent by the connected vehicles travelling near the host vehicle;
- **CAM message decoder**: it decodes the CAM messages received from services and through PC5 direct communication, extracting the relevant information and providing them to the Quality of Service Module and to the AD application;
- **In-Vehicle QoS Module**: It analyses the quality of the received CAM, in telecommunication and physical measurement terms. These data are then used by the AD module to decide for which application such CAM can be used, and in which automation level the vehicle can apply;

---

Figure 157: functional representation showing the different roles of transmitting and receiving the V2X data
• **AD Applications:** The AD applications analyse the surrounding scenario and vehicles perceived both, by on board sensors, and by means of C-ITS communication (direct and cellular). It then uses such data to decide which automation level can be enabled, by the perception point of view, and also performs some automated manoeuvres (in terms of longitudinal control), such as the cooperative adaptive cruise control and cut-in enabling.

Remote objects are detected and classified from the Host Vehicle frontal sensors. The detected remote objects are triangulated and their absolute position.

Virtual CAMs are used to report to the other connected vehicle the presence of the detected object. The Virtual CAM is a standard compliant CAM whose content is used to report the presence of remote object.

The Extended perception relies on Virtual CAM and proper CAM from connected vehicles to give to the driver an overview of the others road users, connected and not. To enhance this application CRF improve the Extended Perception algorithm considering the type of the detected object. For this, in the Virtual CAM, it is included the type of the detected object expressed through the stationType Data Element.

CRF gives priority to truck and pedestrian detection that are reported in HMI through boxes of different size, as reported in section 5.2.1.2.

![Figure 158: HMI with dynamic road view (lower right part) whereby different size boxes marking truck and normal vehicles (car)](image)

Extended Perception CAM and VCAM dissemination between connected vehicles relies on GeoService. During the several tests performed in-country (on A22 near Trento), at Brenner and in Kufstein, it was reported to CRF and overload of the GeoService in terms of messages reception rate. This overload does not depend on the Uu network, but it is on GeoService side in terms of processing speed of single-source messages.

To improve the consistency, CRF and NOKIA agreed to introduce a systematic delay after each message transmission to the GeoService of 2ms. This delay was dimensioned considering the time elapsed by the GeoService to manage the received packets on the socket via UDP. CRF tested this solution noticing an improvement in term of demo consistency without affecting the general performance of the Extended Perception application.
5.2.4.2 Measurements

This Section evaluates the perception enhancement given by the extended perception module both in terms of total number of vehicles ‘seen’ by the equipped car and distance of such perceived remote vehicles.

The validation and performance evaluation of the extended perception module has been performed in the A22 Highway area and at the Italian-Austrian border, in medium-high traffic conditions. During the tests, the two connected vehicles travelled on the same lane at a distance ranging from around 20m to 160m. It is counted the number of valid road objects perceived by the sensors at each time instant and the number of valid virtual CAMs received by the communicating vehicle. The results in the box plots in Figure 159 show on the left the number of vehicles seen by the sensors only and on the right the sum of the sensed objects plus the valid virtual objects received via the extended perception module. With respect to the solution relying only on the host vehicle sensors, the number of vehicles perceived with the extended perception module is more than doubled. The results of the statistical analysis are listed in Table 43:

Table 43: Number of perceived vehicles: comparison between the extended perception solution and the own sensor perception

<table>
<thead>
<tr>
<th></th>
<th>Sensors only</th>
<th>Extended perception module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (number of vehicles)</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Median (number of vehicles)</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Maximum (number of vehicles)</td>
<td>7</td>
<td>13</td>
</tr>
</tbody>
</table>

Figure 159: Number of vehicles perceived in front of the host vehicle, comparing the extended perception (HV sensors + sensor sharing by one vehicle in front) with the own sensor perception
The analysis regarding the distance of the perceived remote vehicles is performed by considering at each time instant the relative position of the valid sensed objects and the absolute distance from the ego vehicle of the virtual CAMs. Since the distances between the host vehicle and the connected vehicle lay in a wide range among the considered datasets (20m-160m), the data is divided into three subsets according to the relative absolute distance of the two vehicles. In this way the distance gains in the vehicle’s field of perception can be assessed in different driving scenarios. Table 44 shows the results of the analysis for the following driving conditions:

1. The distance between the host and the connected vehicles lays in the range between 20m and 60m.
2. The distance between the host and the connected vehicles lays in the range between 60m and 100m.
3. The distance between the host and the connected vehicles lays in the range between 100m and 160m.

It is noticeable how the gain in performance of the module in terms of extension of the visibility range increases as the two connected vehicles get further apart. Note that for inter-vehicle distances of 100m-160m the ego vehicle’s sensors extended by the connected vehicle’s sensors cover the whole distance range from the position to the ego vehicle up to 350m. The statistical values of interest are reported in the table below (Table 48):

<table>
<thead>
<tr>
<th></th>
<th>20m – 60m</th>
<th>60m-100m</th>
<th>100m-160m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (m)</td>
<td>67.9m</td>
<td>87.8m</td>
<td>68.7m</td>
</tr>
<tr>
<td>Median (m)</td>
<td>57.4m</td>
<td>82.5m</td>
<td>65.8m</td>
</tr>
<tr>
<td>Max (m)</td>
<td>208.1m</td>
<td>251.3m</td>
<td>206.1m</td>
</tr>
</tbody>
</table>
5.2.5 S-LDM – enhanced collective perception

This Section describes the main laboratory and road tests and preliminary results on the S-LDM component, developed by CNIT as part of the centralized Cooperative Lane Change use case.

Although it has been mainly developed for the Cooperative and Automated Lane-Change Maneuvers, this 5G-enabled MEC component proves to be very useful for a profusion of different use cases. It is indeed able to provide a “map” of the road, with detailed information on all the vehicles travelling on a certain stretch of road, to any MEC service, thanks to its modular and easily extensible architecture.

5.2.5.1 Service description

The Server Local Dynamic Map (in short, S-LDM) is a 5G-enabled MEC service storing a centralized local dynamic map of the road, containing the most up-to-date and historical data of all the vehicles (and other non-connected objects detected thanks to sensors) travelling in a given area. It can then provide a filtered and processed version of this data to other MEC services, which require up-to-date information on the situation of the road.

Figure 160: Vehicle distance to perceived objects, comparing the extended perception (HV sensors + sensor sharing by one cooperative vehicle in front) with the own sensor perception
As described in [1], [4], [2], the S-LDM can build a map of the road thanks to the reception of ETSI messages (mainly CAMs, but also DENMs, CPMs and other types of messages), through one or more AMQP brokers it subscribes to.

It is thus including an open-source library for AMQP message reception (i.e., Apache Qpid Proton) and a custom ETSI ITS decoding stack, developed to be as much efficient as possible with the aim of enabling very high update rates of the internal dynamic map.

This service is also able to detect when a certain triggering condition occurs, i.e., a situation on roads requires the intervention of a MEC service or a vehicle perform some action to signal that a maneuver with a high level of automation has been requested. When this is happening, the S-LDM will compute a context around the reference vehicle or object, containing all the information on vehicles and other non-connected objects within a certain configurable radius around the reference node. This context is then made available via a dedicated REST interface to other MEC services for highly automated maneuvers, including the Maneuvering Service for Cooperative Lane Change, thanks to the capabilities of the underlying 5G network architecture.

The internal architecture of the S-LDM is briefly schematized in Figure 161.

![Figure 161: S-LDM internal architecture](image_url)

As can be seen, several modules compose the whole service, which all contribute to the overall performance of the S-LDM, which have been tested as part of the 5G-CARMEN project.

In order to support cross-border use cases and tackle scalability, each S-LDM instance has been specifically thought to cover a limited portion of the road, and filter out all the messages of vehicles coming from outside this area (thanks to the “Area Filter” module). In order to extensively cover the road, several S-LDM instances should be created, each one covering an area starting from where the previous S-LDMs areas end, as in the simplified scheme depicted in Figure 162.
The overall areas covered by neighboring S-LDMs should also superimpose, in order to let each instance store a complete view of the road, even when the context generation involves a vehicle travelling near the border of the coverage area (like the green vehicle in Figure 162).

As receiving all messages from all vehicles on the road and then filtering them out inside the Area Filter module (which requires decoding each single message) would be a computationally expensive operation, each AMQP client of each S-LDM instance is set to receive only the messages of vehicles travelling in an area slightly larger than the actual coverage area. This limits the amount of “out of range” messages discarded at the Area Filter module and improve the performance of this latency critical MEC service.

The pre-filtering messages happens at an AMQP broker level thanks to the Quadkey mechanism described in [4].

As mentioned, the S-LDM not only contains information about connected vehicles, but it is able to gather information about non-connected objects coming from the connected vehicles’ sensors. Leveraging the fact that vehicles in 5G-CARMEN are able to distinguish between different types of detected objects from their sensors, the S-LDM has the ability to classify these different objects relying on custom StationTypeId values inside CAMs. These custom values, defined by the 5G-CARMEN project, point to different types of detected objects, and are compliant to the ETSI TS 102 894-2 standard [12]. Indeed, ETSI allows the StationTypeId field to assume custom values up to 255, outside a set of predefined ones which should be used only under specific circumstances. Thus the custom values chosen to be used for the 5G-CARMEN projects are the following:

- Detected vehicles -> stationType = 0
- Detected pedestrians -> stationType = 110
- Detected trucks -> stationType = 117

Finally, the ability of distinguishing between different types of detected objects increase the details of the context stored in the database for an enhanced perception of the road, and it is reflected in the last version of the web-based Graphical User Interface (GUI) shown in Figure 163. This GUI can provide useful information to the road operators leveraging the S-LDM, such as A22, as it can display in real-time and with highly accurate data the situation on a certain stretch of motorway, including both connected and detected objects.

Figure 163: Screenshot of the S-LDM web-based GUI showing different StationTypeIds saved in the database
5.2.5.2 Experimental set-up

The S-LDM has been tested so far under different conditions, as reported in [3]:

1. Preliminary performance evaluation of the S-LDM enablers (database and REST API towards the Manoeuvring Service), with different CPUs to understand the impact of the resource assignment to the S-LDM database performance.

2. Laboratory pre-deployment performance tests of the S-LDM sub-modules, while running a local copy of the S-LDM and of the AMQP broker on well-known hardware.

3. Cross-border road tests with the S-LDM deployed on both MTA and TIM’s MEC, involving CRF vehicles; the S-LDM instances were containerized and deployed on the NEC orchestrated edge platform and connected to MTA and TIM’s AMQP brokers. The two S-LDM instances deployed covering the whole stretch of road, for each test, have been evaluated. Furthermore, the effect of network reselection on the S-LDM has been assessed through the cross-border road tests.

The tests (1) have been performed by:

- Filling in different databases with a certain amount of sample data, followed by the insertion of realistic vehicle data (always performed as last operation, in order to consider a worst-case scenario for non-relational databases which scan the list of entries depending on the order in which the data has been inserted), in order to evaluate their performance with respect to the amount of data stored and select the best option for the S-LDM. The results of these tests include the performance evaluation of the database which has been eventually selected for S-LDM.

- Relying on a sample REST client and REST server (which has then been sent to BMW for the development of the Manoeuvring Service) to test the performance of the REST interface towards the other services and towards the Manoeuvring Service.

The tests (2) have been performed, instead, on the full S-LDM and thanks to a realistic vehicle emulation and simulation framework, entirely developed by Politecnico di Torino, one of the universities participating as CNIT in 5G-CARMEN.

This framework is called ms-van3t\(^5\) and it is able to emulate an arbitrary number of vehicles, after setting up a realistic scenario on a stretch of road of interest. The messages coming from the vehicles can then be either directly broadcasted, as if real vehicles were transmitting them on a physical interface of the device running ms-van3t, or sent via UDP to an external server.

We relied on this last possibility, together with a UDP-AMQP relayer/server module, to emulate the presence of vehicles sending their messages to an AMQP broker. It is worth mentioning that this relayer facility is also able to compute the per-vehicle Quadkeys to be inserted inside each AMQP message.

As the S-LDM receives the messages directly from the AMQP broker, its behaviour will be exactly the same, no matter whether these messages are originated from a simulated scenario or from real Stellantis or BMW vehicles travelling on parts of the A22 motorway.

The testbed setup for the tests (2) is reported in Figure 164.

\(^5\) Available here: https://github.com/ms-van3t-devs/ms-van3t
The tests (3) are instead better described in following Section.

### 5.2.5.3 Capability measurements and cross-border road tests

#### Performance evaluation of the S-LDM enablers (resume)

This Section resumes the results of the performance evaluation of the main S-LDM enablers (i.e., interface to the Manoeuvring Service and database), reported in [3].

The evaluation of the database integrated inside the S-LDM and of other possible good alternatives has been performed on two different devices, in order to analyse the impact of the available resources on the performance of the database solutions.

After testing four different types of promising databases, including a custom thread-safe C++ database in main memory, the latter appeared to be best choice in terms of performance.

Indeed, from the analysis of the main results reported in D5.2 [3], the custom C++ database is able to perform an INSERT operation in under a 1 microsecond when the database is not performing other concurrent activities, far below the maximum end-to-end latency required for latency critical MEC services. Furthermore, the custom C++ database has been developed to support efficient locking mechanism when a thread attempts to read from the database (for instance, when a triggering condition is detected) and another tries to write to the same database to perform, for instance, an INSTANCE operation.

The second set of measurements was instead targeted at determining the delay introduced by the REST interface, which was chosen as an interface between the S-LDM and the Manoeuvring Service (or any other MEC service for automated manoeuvre management).

This interface involves a REST server deployed inside the Manoeuvring Service, to which a client, embedded inside the S-LDM, can connect.

Several tests have been performed, as reported in D5.2 [3]. The results show how the average one-way delay introduced by the REST interface is slightly less than 1 ms (with maximum values up to around 2 ms). This additional delay is relatively small, and it can be considered as a positive outcome. Indeed, it enables the S-LDM to comply with, at the same time, the target of having a full-chain latency of maximum 10 ms and the provision of a standardized interface between the different 5G-CARMEN MEC components.
Laboratory pre-deployment tests of the S-LDM sub-modules (resume)

This Section resumes the results of the performance evaluation of the S-LDM’s sub-modules, reported in D5.2 [3], in terms of computational time, while performing laboratory pre-deployment tests. For these tests, a map of the A22 section between Trento Nord and San Michele all’Adige has been imported into the ms-van3t emulation and simulation framework with the aim of emulating a number of vehicles travelling on that stretch of road. The test campaign described in this section was performed on a local instance of the S-LDM with ms-van3t running as a separate process and emulating an increasing number of vehicles. During the laboratory tests, the emulation parameters were changed directly on the framework’s configuration files.

All the tests have been performed by setting the local instance of the S-LDM to cover an area around the chosen stretch of road. The focus of these tests was to analyse the first three sub-modules of the S-LDM right after the AMQP client, i.e. Message Decoder, Area Filter and Database Update.

The performance of each of these modules, in terms of time required by them to perform all the needed operations, is shown together with the total time for message handling (i.e, comprising the whole chain in Figure 164 up to “Update DB”).

The main results are reported in Figure 165.

![Figure 165: S-LDM pre-deployment sub-modules performance tests](image)

As can be seen, the S-LDM performance, for an increasing number of vehicles from 1 to 30, remains stable, with some very small oscillations up to 3 microseconds. This is a good indication on how the S-LDM can scale well, at least when considering a limited number of subscribers. Furthermore, the most demanding sub-module appears to be the Message Decoder, further justifying the pre-filtering approach with the Quadkeys.

It is worth noting that all the measured times for these tests are much lower than 10 ms (few tens of microseconds are required to process each message), and probably noticeably lower that the latency contribution introduced by other components in the 5G-CARMEN architecture, proving the S-LDM component as an efficient low-latency 5G enabler for high levels of automation.

Cross-border road tests with CRF vehicles
This Section describes the results of road tests targeted at evaluating the S-LDM with CRF vehicles travelling on cross-border along the A22 motorway, including the Brennerpass border. Results reported on D5.2 [3], for the first near-border test campaigns of the S-LDM, proved the effectiveness of our component in enabling low-latency 5G edge services.

Starting from the first laboratory pre-deployment tests and performing the first road tests in collaboration with CRF and NEC, it was possible to prove how the S-LDM can efficiently handle 20 Hz update rates, involving both connected vehicles and sensed objects (through virtual CAMs).

As outlined in D5.2 [3] further tests, which results are reported in this section, include the evaluation of cross-border features to enable the generation of cross-border local dynamic maps thanks to the subscription to multiple AMQP brokers (in turn enabled by the 5G-CARMEN inter-MEC communication infrastructure). Furthermore, an analysis is made of the S-LDM behaviour when relatively long communication disruptions occur in the AMQP client - AMQP broker communication.

These tests have been performed on the E45-A22 stretch of road between Nößlach and Brennerpass. The path followed by one of the vehicles during the tests is depicted in Figure 166. This plot shows how the S-LDM can be leveraged, as an additional feature, to understand under which network a vehicle is connected to, given its geographical position. Indeed, the depicted path is based on the accumulated geographical information of messages received from the MTA AMQP broker, denoted in red, and the messages received from the TIM AMQP broker, denoted in blue. For the set of outcomes presented here, a deviation from the E45 motorway was performed at Brennersee to take the B182 road in Austria and perform the border crossing through the SS12 road at Brennero.

Figure 166: Path followed by the Stellantis vehicles during the cross-border road tests. The messages received by the S-LDM from the TIM network and AMQP broker are depicted in blue, while the messages from the MTA network and broker are represented by red points. This picture focused on the Austria to Italy direction.
The S-LDM version used for the tests is the 1.1.10-beta. This new version of the S-LDM compared to the one tested on the initial road tests reported in [3], in addition to the enhanced web-GUI described in Section 5.2.5.1 introduces the ability to subscribe to multiple AMQP brokers for cross border scenarios and the addition of the ageCheck feature. This feature, relying on the GeoNetworking timestamp extracted from the messages, checks the age of the data stored inside the database before updating it with the new receive data and thus discarding potential outdated messages received after crossing the border. This situation may occur in presence of out-of-order packets.

The outcome of the tests was positive, as the S-LDM was able to track the connected vehicles as well as the detected ones on both sides of the border by processing the messages from the respective AMQP brokers, depicted, in all figures, in red for MTA and blue for TIM.

It is worth noting that all messages depicted in Figure 166 correspond to the ones depicted in Figure 167, where for both figures, only one of the runs performed during the tests is reported in order to make a more descriptive outline of the results. In particular, taking as reference the S-LDM running on the TIM MEC platform, the normalized message delay (i.e., a measurement of the delay between message transmission from vehicles and reception by the S-LDM, normalized to the minimum observed during the whole test) along the duration of the aforementioned selected test, is reported in Figure 167. Leveraging a normalized delay value was necessary as the time synchronization between the different operator MEC platforms was not guaranteed, thus not ensuring consistent measurements in case of absolute delay values. The normalized delay remains stable with very few spikes which duration is always relatively short and under a second for all cases. These spikes are probably due to the jitter and delay caused by the underlying network architecture. Furthermore, it can be observed that the disconnection interval at the border, focusing on the Austria to Italy direction, corresponds to only 13 seconds, which remained the stable for all the tests performed as shown in Table 45.

![Figure 167: Normalized message delay (i.e., a measurement of the delay between message transmission from vehicles and reception by the S-LDM, normalized to the minimum observed during the whole test) along the duration of a single test run, for a single vehicle.](image-url)
Table 45: Disconnection intervals for all cross-border runs during driving tests

<table>
<thead>
<tr>
<th>Disconnection intervals for all cross-border tests [seconds]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>13.3729</td>
</tr>
</tbody>
</table>

Furthermore, from the cumulative distribution function of time between consecutive database updates, depicted in Figure 168 and Figure 169, it can be observed that 80% of the messages along the entire test, for a given vehicle, are received with a periodicity of 50ms in accordance with the CAM frequency of 20 Hz by CRF vehicles. It can be seen that the same behaviour is observed on both instances of the S-LDM component, deployed at TIM’s MEC (depicted in Figure 169) and MTA’s MEC (depicted in Figure 168) respectively. This assessment is further justified by the results shown on Table 46 and Table 47, for both TIM’s MEC and MTA’s MEC respectively, that report an average value below 50ms for the entire duration of the test.

Table 46: Time between consecutive database updates for each vehicle, at TIM’s MEC S-LDM instance.

<table>
<thead>
<tr>
<th>S-LDM database update periodicity TIM’s MEC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Mean [milliseconds]</td>
</tr>
<tr>
<td>Vehicle 1</td>
<td>43.1643 ms</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>46.4376 ms</td>
</tr>
</tbody>
</table>

Table 47: Time between consecutive database updates for each vehicle, at MTA’s MEC S-LDM instance.

<table>
<thead>
<tr>
<th>S-LDM database update periodicity MTA’s MEC</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Mean [milliseconds]</td>
</tr>
<tr>
<td>Vehicle 1</td>
<td>43.1144 ms</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>48.9504 ms</td>
</tr>
</tbody>
</table>
Figure 168: cumulative distribution function of time between consecutive database updates for each vehicle, at MTA’s MEC S-LDM instance

Figure 169: cumulative distribution function of time between consecutive database updates for each vehicle, at TIM’s MEC S-LDM instance

Lastly, concerning the message processing time along the cross-border tests, the cumulative distribution function of the entire duration of the tests is reported in Figure 170 for the S-LDM instance at MTA MEC, and in Figure 171 for the instance at TIM MEC. The obtained outcome, reported in Table 48 and

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Mean [microseconds]</th>
<th>Standard Deviation [microseconds]</th>
<th>90% Percentile [microseconds]</th>
<th>95% Percentile [microseconds]</th>
<th>95% Confidence Interval [nanoseconds]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle 1</td>
<td>34.9 us</td>
<td>26.7 us</td>
<td>67.9 us</td>
<td>83.3 us</td>
<td>± 0.1671 ns</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>35.3 us</td>
<td>28.1 us</td>
<td>71.7 us</td>
<td>85.7 us</td>
<td>± 0.1835 ns</td>
</tr>
</tbody>
</table>
Table 49, is good as it shows that 90% of messages are processed in under 72 microseconds, for the instance at TIM MEC, and 50 microseconds for the instance at MTA MEC. The delay introduced by the S-LDM itself appears thus to be, in all cases, well below the target “full chain” delay of 10 ms.

Table 48: Message processing times for each vehicle, at TIM’s MEC S-LDM instance

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Mean [microseconds]</th>
<th>Standard Deviation [microseconds]</th>
<th>90% Percentile [microseconds]</th>
<th>95% Percentile [microseconds]</th>
<th>95% Confidence Interval [nanoseconds]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle 1</td>
<td>34.9 us</td>
<td>26.7 us</td>
<td>67.9 us</td>
<td>83.3 us</td>
<td>± 0.1671 ns</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>35.3 us</td>
<td>28.1 us</td>
<td>71.7 us</td>
<td>85.7 us</td>
<td>± 0.1835 ns</td>
</tr>
</tbody>
</table>

Table 49: Message processing times for each vehicle, at MTA’s MEC S-LDM instance

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Mean [microseconds]</th>
<th>Standard Deviation [microseconds]</th>
<th>90% Percentile [microseconds]</th>
<th>95% Percentile [microseconds]</th>
<th>95% Confidence Interval [nanoseconds]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle 1</td>
<td>28.2 us</td>
<td>20.2 us</td>
<td>48.4 us</td>
<td>58.4 us</td>
<td>±0.1261 ns</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>27.5 us</td>
<td>21.3 us</td>
<td>48.4 us</td>
<td>58.3 us</td>
<td>±0.1509 ns</td>
</tr>
</tbody>
</table>

Figure 170: Cumulative distribution function of message processing times during the test, for each connected vehicle, at MTA’s MEC S-LDM instance
5.2.6 5G-CARMEN CCAM services: assessing performance at borders

The usage of C-V2X/5G-based communication medium for supporting autonomous vehicle manoeuvres relies on the capability of guaranteeing the expected Quality of Service (QoS) in the connectivity, e.g., the performance of the communication medium required to effectively use communication data for supporting the vehicle’s manoeuvres. Possible performance degradations could lead to unexpected effects and potentially compromising the capability of the vehicle to adequately reacting and effectively taking decisions. To avoid this, the 5G-Carmen vehicle architecture is enriched with a software module, named “in-vehicle QoS module” (invQoS), that continuously checks if the expected QoS requirements are met during the vehicle movement. invQoS continuously collect and analyses metrics about: (i) the V2X/5G message quality, (ii) both ego and remote vehicle position accuracy, and (iii) the mobile network quality and performance. This monitoring activity of invQoS aims at making the vehicle ready for proactively adapting its behaviours and decisions on the autonomous manoeuvres, thus avoiding interruptions or unexpected, and potentially dangerous, situations.

This report describes the first pilot tests and preliminary results on the behaviour of the invQoS module while monitoring the data input, thus the quality control on board system.

5.2.6.1 AMQP functionality and performance cross-border

The 5G-CARMEN MEC-based platform adopted an AMQP broker as an option for message dispatching in both Vehicle-to-Vehicle and Vehicle-to-Infrastructure scenarios.

AMQP 1.0 is an open Internet protocol for business messaging. With AMQP, client applications – publishers and subscribers – can send and receive information through the message broker, a middleware component that handles message routing and delivery (Figure 172).

---

6 [https://docs.oasis-open.org/amqp/core/v1.0/amqp-core-messaging-v1.0.html](https://docs.oasis-open.org/amqp/core/v1.0/amqp-core-messaging-v1.0.html)
In 5G-CARMEN, the AMQP broker can take care of cross-border interoperability. Brokers of different countries can connect to each other and exchange C-ITS messages (the so-called AMQP Sync feature). In cross-border areas, messages coming from another country could be shared and aired on both short-range (Direct Communication) and long-range (5G Uu) channels.

To connect the AMQP brokers hosted in the Italian and Austrian MEC, an AMQP client was added to the architecture. The client works as a bridge between the two brokers (Figure 173):

- it connects to the Italian broker and subscribes to all messages
- it sends to the Austrian broker every message delivered by the Italian broker

The bridging component is based on Apache Camel, an open-source integration framework. With Camel it is possible to sync the brokers in both directions, defining two different clients. In the actual implementation, the Italian MEC manages the AMQP Sync for the Italian-Austrian border, and the Austrian MEC does the same for the Austrian-German border (it may not be the best design choice, but it provides a more manageable and testable environment).

The following is an excerpt from Camel’s configuration on the Italian MEC:

```xml
<route id="AmqpBridge-IT2AT" trace="false">
  <description>AMQP Bridge from IT to AT</description>
  <from uri="CarmenIT:topic:5gcarmen?selector=importedMsg IS NULL"/>
  <setHeader headerName="importedMsg"> <constant>true</constant> </setHeader>
  <log message="AmqpBridge-IT2AT: ${id}, prod=${headers[prod]}, messageType=${headers[messageType]}, originatingCountry=${headers[originatingCountry]}"/>
  <to uri="CarmenAT:topic:5gcarmen"/>
</route>

<route id="AmqpBridge-AT2IT" trace="false">
  <description>AMQP Bridge from AT to IT</description>
  <from uri="CarmenAT:topic:5gcarmen?selector=importedMsg IS NULL"/>
  <setHeader headerName="importedMsg"> <constant>true</constant> </setHeader>
  <log message="AmqpBridge-AT2IT: ${id}, prod=${headers[prod]}, messageType=${headers[messageType]}"/>
  <to uri="CarmenIT:topic:5gcarmen"/>
</route>
```

7 [https://camel.apache.org/](https://camel.apache.org/)
The AMQP Sync, if not carefully handled, may cause an infinite loop, with the messages bouncing back and forth between two brokers. In 5G-CARMEN – leveraging open-source technologies like Apache ActiveMQ and Apache Camel – the message looping was definitely an issue, and it was solved using a selector (see below). It should be pointed out that the message looping heavily depends on the implementations on both sides (i.e., the technologies), and it may not happen at all.

The selector is an SQL-like statement, declared by the subscriber, which allows content-based routing. The AMQP broker will deliver only the messages that are matching the selector. The chosen selector exploited the “originatingCountry” property (“AT” for Austria, “DE” for Germany and “IT” for Italy) to get only the messages coming from the second country (i.e., Italian messages in Austria and Austrian messages in Italy).

This selector works only in one direction:

- when the Italian vehicles are moving from Italy to Austria, CAM messages published in Italy are sent to the Austrian broker, as expected
- in Austria, Italian vehicles will still label their messages as “IT”, because the “originatingCountry” is a built-in feature and does not depend on the actual location. Therefore, (Italian) CAM messages published in Austria are filtered out, even if they should be sent to the Italian broker. Removing the filter will cause a loop

A different approach to loop avoidance solved the issue, but it was not used during on-field tests.

The AMQP Sync feature was measured using Camel’s logging capabilities:

- in Italy, a Camel client subscribes to the Italian broker and logs incoming messages
- in Italy, the Camel client bridging the two brokers logs outgoing messages
- in Austria, a Camel client subscribes to the Austrian broker and logs incoming messages

The comparison between the three logs revealed a significant loss in dispatched messages during the on-field tests held on 22 June 2022. CAM messages were published by 2 CRF vehicles with a frequency of 20 Hz. This evidence triggered another test session (held on 7 July 2022, with only one CRF vehicle involved) where two different frequencies were used (50 Hz and 10 Hz). This time the loss of messages was contained, with no loss when the publishing frequency was 10 Hz. Table 44 shows all results.

### Table 50: AMQP Sync results

<table>
<thead>
<tr>
<th>On-field Test Session</th>
<th>Message Rate</th>
<th>Published Messages (IT)</th>
<th>Published Messages (AT)</th>
<th>Message Loss</th>
<th>Message Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022-06-22 20 (2+N) Hz</td>
<td>208342</td>
<td>91081</td>
<td>117261</td>
<td>56.3</td>
<td></td>
</tr>
<tr>
<td>2022-07-07 50 Hz</td>
<td>27957</td>
<td>20727</td>
<td>7230</td>
<td>25.9</td>
<td></td>
</tr>
<tr>
<td>2022-07-07 50 Hz</td>
<td>31874</td>
<td>25752</td>
<td>6122</td>
<td>19.2</td>
<td></td>
</tr>
<tr>
<td>2022-07-07 50 Hz</td>
<td>54846</td>
<td>42.68</td>
<td>12478</td>
<td>22.7</td>
<td></td>
</tr>
<tr>
<td>2022-07-07 50 Hz</td>
<td>87689</td>
<td>72200</td>
<td>15489</td>
<td>17.6</td>
<td></td>
</tr>
</tbody>
</table>

---

8 Both the Italian (TIM) and Austrian (Swarco) broker are based on Apache ActiveMQ, an open-source, multi-protocol message broker ([https://activemq.apache.org/](https://activemq.apache.org/)).

9 The actual sources were more than just 2, because vehicles were also sending “virtual CAM” for N external objects detected by on-board sensors (up to 7 objects).
The ActiveMQ documentation suggests that the loss of messages may be related to a “prefetch limit”\(^\text{10}\).

“(…) message consumption typically being much slower than message delivery. To avoid this situation ActiveMQ therefore employs a prefetch limit to limit the maximum number of messages that can be dispatched to an individual consumer at once. The consumer in turn uses the prefetch limit to size its prefetch message buffer.

Once the broker has dispatched a prefetch limit number of messages to a consumer it will not dispatch any more messages to that consumer until the consumer has acknowledged at least 50% of the prefetched messages, e.g., prefetch/2, that it received. When the broker has received said acknowledgements it will dispatch a further prefetch/2 number of messages to the consumer to ‘top-up’, as it were, its prefetch buffer. Note that it’s possible to specify a prefetch limit on a per consumer basis.

Large prefetch values are recommended for high performance with high message volumes. However, for lower message volumes, where each message takes a long time to process, the prefetch should be set to 1. This ensures that a consumer is only processing one message at a time.”.

The AMQP protocol provides different ways to control the message flow\(^\text{11}\). It is worth noting that the Italian log file shows a much wider range for the interval between two incoming messages (3-40 msec) than its Austrian counterpart (27-31 msec). This may indicate that the Camel client bridging the two brokers has a prefetch (credit) value set to 1, and it is processing one message at a time (Table 51). Each message is dispatched by the Italian broker only after receiving the acknowledgement of the previous one.

With a 20/40/50 Hz (and higher) publishing rate, a prefetch value set to 1 may well cause Camel to end up having too many messages pending.

The default configuration of ActiveMQ and Camel should be investigated further to confirm this explanation.

Table 51: Intervals between incoming messages

<table>
<thead>
<tr>
<th>Incoming Message (Italian Broker)</th>
<th>Interval (msec)</th>
<th>Incoming Message (Austrian Broker)</th>
<th>Interval (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022-07-07 07:58:55,522</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^\text{10}\) [https://activemq.apache.org/what-is-the-prefetch-limit-for](https://activemq.apache.org/what-is-the-prefetch-limit-for)

\(^\text{11}\) “(…) during the opening connection process, the two peers negotiate a maximum frame size that defines the maximum size of each single frame that can be exchanged. The first level of flow control is provided by session; each session endpoint has an incoming and outgoing window with a size defined as frame count. On both sides (sender and receiver), the frame’s exchange can be stopped when the window is full (the sender doesn’t have more window space to send, the receiver doesn’t have more window space to receive); each transfer decrements the window size. The last flow control level is at the messaging level, where each link has a “link credit”, which is the number of messages the receiver is able to receive. The receiver can set this value using the “flow” performative; for each incoming message the counter is decremented until a value of zero suspends transfer.” ([https://dzone.com/refcardz/amqp-essentials#section-5](https://dzone.com/refcardz/amqp-essentials#section-5))
The almost constant time interval between two incoming messages on the Austrian broker (27-31 msec) is useful to estimate the latency at play for the AMQP Sync. The 27-31 msec cover:

- the message publication time, including the time spent over the public Internet to reach the Austrian broker
- the message processing time on the Austrian broker
- the message reception and logging on the Austrian client

The tcpdump command gives a Round Trip Time of 29 msec ca. between the two brokers (Figure 185), a pretty consistent result. The total processing time could really be just few msec.

Figure 174: Round Trip Time between the two brokers

As an aside, the line-by-line comparison of the Italian and Austrian log files is not useful to estimate the total latency, because the VMS are not synchronized (there is a rough difference of 21 sec). Camel log files do not provide “absolute” timestamps, because the message logging is much slower than the actual processing. For example, the following is an excerpt from the log file showing the messages published by CRF vehicles:

The following is an excerpt from the log file (still in the Italian MEC) showing the publication of the same message on the Austrian broker:
The logging of the incoming message happens 1 msec after the same message has been published on the Austrian broker! This is because the two log files are written by different, concurrent logging processes, and the former takes more time to be written. Once again, we sense that the actual processing time may be just one/few msec.

If we assume that CAM messages are processed one at a time by the Austrian broker, in 28 msec ca., this means that Camel (the real bottleneck) and the Austrian broker can process roughly 1000/28 = 35.7 msg/sec. It becomes possible to estimate the expected message loss for different rates (Table 52).

**Table 52: Expected message loss**

<table>
<thead>
<tr>
<th>Message Rate</th>
<th>Published Messages</th>
<th>Processing Capacity</th>
<th>Message Loss</th>
<th>Message Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Hz</td>
<td>10 msg/sec</td>
<td>36 msg/sec</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20 Hz</td>
<td>20 msg/sec</td>
<td>36 msg/sec</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40 Hz</td>
<td>40 msg/sec</td>
<td>36 msg/sec</td>
<td>4 msg/sec</td>
<td>10</td>
</tr>
<tr>
<td>50 Hz</td>
<td>50 msg/sec</td>
<td>36 msg/sec</td>
<td>14 msg/sec</td>
<td>28</td>
</tr>
<tr>
<td>100 Hz</td>
<td>100 msg/sec</td>
<td>36 msg/sec</td>
<td>64 msg/sec</td>
<td>64</td>
</tr>
</tbody>
</table>

Expected message losses for 10 and 50 Hz (Table 52) are similar enough to the actual results (Table 50) to validate the explanation.

In conclusion, the testing sessions provided major insights into the AMQP Sync feature:

- AMQP brokers are a suitable technology for V2V and V2I low-latency message dispatching
- brokers can be connected to each other and synced. With proper filtering, message loops are avoided
- it is possible to manage the AMQP Sync in both directions from the same side, but every broker should really take care of syncing with its own peers
- 5G-CARMEN should define a reference architecture and detailed requirements on message handling (flow control, “link credit”, QoS), message rates and expected KPIs
- AMQP brokers hosted on MECs cannot rely on public Internet (28 msec ca. between Italy and Austria) and need a faster network. A lower network latency will directly affect the processing capacity of the AMQP Sync feature as a whole, enhancing the performance
5.2.6.2 Geoservice functionality and performance

**Latency**

Geoservice functionality and performance tests are based on the analysis of the packets (CAM and Virtual CAM) exchanged between the vehicle and the network and back.

To perform this analysis on the latency, CRF processed data from different test sessions acquired between the tests between Italy, Austria and Germany. CRF processed both the logs acquired by NOKIA regarding the network traffic registered from the national Geoservice and the logs acquired by CRF in vehicle.

The objective is to report an overview of the latency that affect the communication between the vehicles, the Geoservice and back.

Different latencies were taken into account:

- The up-link latency from the vehicle (timestamp in which the C-ITS message is packed) to the Geoservice (the inbound timestamp which logs when the message is received by the Geoservice);
- The process latency of the Geoservice (from the inbound timestamp of the Geoservice to the outbound timestamp of the Geoservice that logs when the message is sent out by the Geoservice;
- The down-link latency from the Geoservice (from the outband timestamp of the Geoservice) to the vehicle (timestamp in which the C-ITS relative output is given, after the decoding and the processing of the information on the vehicle OBU).

![Diagram showing latency measurement of Geoservice component during decentralized manoeuvres](image-url)

**Figure 175: Latency measurement of Geoservice component during decentralized manoeuvres**
The downlink latency is not directly available, but CRF has to compute it considering the total latency (end to end, from vehicle 1 to vehicle 2) logged on vehicle and the sum of the uplink and processing latency had to be computed by the logs of the Geoservice network traffic.

To delete spikes and erroneous data, the latency computed from all the logs were bounded between 0 and 100 [ms]. Negative or higher data were omitted from the computation in order to have a more precise analysis on the average values.

It is important to highlight that the data used were extracted from real test session where CRF was driving in the different test side, also for this reason, the data were prefiltered as described in the previous paragraph.

In the tables below are reported the different latency and throughput between vehicles and the national Geoservice:

- Italian Geoservice through TIM network;
- Austrian Geoservice through Magenta network;
- German Geoservice through Deutsche Telekom network,

In the pilots, TIM SIM cards were used at the Italian-Austrian border, and Deutsche Telekom SIM cards at the German-Austrian border. In both the scenarios, Austrian network was a visited network meaning that roaming SIM card were used; Magenta SIM cards in fact were not used during the tests (as they cannot use LBO with the respective MEC connected in Germany and Italy).

Uplink and processing latencies are computed from the .pcap logged by the Geoservice while the global latency is acquired directly on CRF vehicles. Given this difference source, it is important to highlight that the logs between the vehicles and the Geoservice have different time base considering that they are acquired by 2 different sources. In any case, since average values are compared, it is possible to use the 2 asynchronous sources to compute the average downlink latency (that is not directly logged but it has to be derived).

In fact, the downlink latency is computed from the difference between total latency (from CRF in-vehicle logs) and the sum of uplink and processing (from Geoservice logs).

In the following tables, the minimum values of latency are reported too. The minimum values are only referred to the data that coming from direct measurements: minimum uplink plus processing latency (Geoservice) and minimum total latency (vehicle). The minimum downlink latency has not a statistical and meaningful value since it has no sense to perform a difference between to unsynchronized data.

It is important to highlight how the measured latency is not dependent from the couple SIM nationality and host-network nationality; in fact, CRF and NOKIA measure comparable latency on Magenta network using both Italian and German SIM cards. The latency measured on Magenta network are more over comparable to the latency on German network, in which the SIM card is from the same telecom operator of the network (Deutsche Telekom). In Italy instead, the latency, primarily the Up-Link ones, are slightly higher while the global latency is comparable.
Table 53: Latency measurements of V2N2V communication over the different networks (TIM, MTA, DTAG)

<table>
<thead>
<tr>
<th>Meas. Set</th>
<th>SIM cards</th>
<th># of samples (pcap)</th>
<th>TIM (Average)</th>
<th>TIM (Minimum)</th>
<th>MAGENTA (Average)</th>
<th>MAGENTA (Minimum)</th>
<th>DEUTSCHE TELEKOM (Average)</th>
<th>DEUTSCHE TELEKOM (Minimum)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>UPLINK [ms]</td>
<td>PROCESSING [ms]</td>
<td>DOWNLINK [ms]</td>
<td>GLOBAL [ms]</td>
<td>UPLINK [ms]</td>
<td>PROCESSING [ms]</td>
</tr>
<tr>
<td>1</td>
<td>TIM</td>
<td>472386</td>
<td>27</td>
<td>0.3</td>
<td>27</td>
<td>54</td>
<td>11</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>TIM</td>
<td>346454</td>
<td>25</td>
<td>0.5</td>
<td>28</td>
<td>54</td>
<td>11</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>TIM</td>
<td>207669</td>
<td>28</td>
<td>0.7</td>
<td>35</td>
<td>63</td>
<td>14</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>TIM</td>
<td>346807</td>
<td>27</td>
<td>0.3</td>
<td>54</td>
<td></td>
<td>12</td>
<td>0.3</td>
</tr>
<tr>
<td>5</td>
<td>TIM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*From PCAP *From Stellantis log
Throughput

Table 54 reports the throughput measurements in both up-link and downlink. This is measured at the Geoservice with two vehicles exchanging their trajectories (CAM) as well as the sensed objects (virtual CAM’s), each message having a message payload size of 118 Bytes in average plus 42 Bytes of Ethernet, IPv4 and UDP Headers. Results yield a throughput up a maximum of 0.361 Mbps in uplink and 0.605 Mbps in downlink kbps depending on traffic conditions, on connectivity conditions and number of perceived objects. The average throughput of 0.101 Mbps in uplink and 0.106 Mbps. This means and average of 0.052 Mbps per vehicle.

Table 54: Throughput measurements at Geoservice in uplink and downlink

<table>
<thead>
<tr>
<th>Measurements set</th>
<th>IP and UDP Headers Dimension [bytes]</th>
<th>Payload Dimension [bytes]</th>
<th>Up-Link Throughput</th>
<th>Down-Link Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max [Mbps]</td>
<td>Average [Mbps]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max [Mbps]</td>
<td>Average [Mbps]</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>116</td>
<td>0.240</td>
<td>0.081</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>119</td>
<td>0.261</td>
<td>0.100</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>118</td>
<td>0.361</td>
<td>0.112</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>119</td>
<td>0.221</td>
<td>0.111</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>0.361</td>
<td>0.101</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max [Mbps]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max [Mbps]</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>120</td>
<td>0.605</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>118</td>
<td>0.247</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>117</td>
<td>0.476</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>119</td>
<td>0.221</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>0.605</td>
</tr>
</tbody>
</table>
5.2.6.3 Back Situation Awareness functionality and performance

5.2.6.3.1. BSA Functionality

As Multi Access Edge Computing (MEC) and Network Function Virtualization (NFV) are considered as one of the key technology enablers for 5G and beyond systems [13] the Back-Situation Awareness (BSA) application service is designed as a dedicated MEC service to support the use case Cooperative and Automated Lane Change Manoeuvres, thereby providing an extended context about emergency vehicles when the decisions on the lane change manoeuvres are being made.

In particular, the on-demand BSA application service has been designed and developed for multi-domain MEC systems, to in-advance inform vehicles on the roads about an approaching Emergency Vehicle (EmV) with the ultimate goal of decreasing the overall response time of emergency responders. As this MEC service is placed in the context of public safety, its high-level overview is provided in Figure 176, where MEC system is leveraged to notify the vehicles about the Estimated Time of Arrival (ETA) of an approaching EmV, whose presence is beyond the audio and visual range of those vehicles. To extend the range and support service continuity across country borders, the BSA service is dynamically made available in multiple MEC systems that might be in the same or different edge domains in order to cover the entire route-path of the EmV (Figure 176). The edge domains might be a part of a single administrative domain or, when the emergency case happens close to the border, two administrative domains, i.e., mobile operators in different countries. In the context of 5G-CARMEN, the Orchestrated Edges platform is in charge of a dynamic instantiation of BSA application on various MEC platforms (e.g., TIM MEC, MTA MEC, or DTAG MEC), making the service proactively available in the edge domains that are affected by the emergency situations.

![Figure 176: Back Situation Awareness (BSA) on the highways spanning over multiple countries.](image)

The application service is triggered upon the MEC systems receiving a notification message from an Emergency Management Authority (EMA), such as 112 (in EU) or 911 (in USA), providing the EmV ID, event location information, and the route path of the selected EmV. In response, the Orchestrated Edges system selects the relevant MEC hosts along the route-path and deploys the BSA service instances. In particular, such multi-
domain deployment extends the range of notifications for civilian vehicles along the route-path, informing them timely on the expected arrival of an EmV.

The deployed application instances are then used by the dispatched EmV to periodically send Cooperative Awareness Messages (CAMs) towards the newly instantiated BSA application on the MEC systems (see red arrow line in Figure 176), for each of the GPS points on the road taken by EmV. Taking into account the EmV's ID, speed, location, and direction information, extracted from the CAM notifications, the BSA application computes the ETA values of the EmV for different dissemination areas, which the BSA application derives along the route-path. The computed ETA values are then encoded in the Decentralized Environmental Notification Messages (DENMs), which are broadcasted in the geographic regions bound to dissemination areas relevant to the encoded ETA value (see yellow arrow line in Figure 176). In the following we denote the distribution of DENMs in the dissemination areas as geocast.

All the vehicles in the dissemination area shall decode the received DENM notifications to have the ETA values displayed to the driver. This process is repeated each time a CAM is received by the BSA service. For the range extension, the BSA service that is directly receiving the CAM notifications from the EmV will forward the EmV's state/metadata information to the peering BSA service instances that are instantiated on the corresponding MEC hosts along the route path, in order to compute ETA values for the dissemination areas within their domain coverage. In other words, a federated multi-domain BSA service is created spanning over multiple MEC hosts.

This multi-domain deployment is supported by BSA applications as they are edge-aware. This feature makes MEC applications aware of i) the edge location and the geographic area that they serve, as they can proactively inform orchestration entities about the need for an application instance in the other edge domains, as well as of ii) the other peering applications from the other edge domains to which they need to connect. The edge awareness also applies to the deployment of such MEC applications, as orchestration entities consider the availability of the network and computing resources in edge domains, as well as the location of MEC hosts, while making decisions on the application service deployment.

It is intuitive that decreasing the response time of emergency responders leads to a larger probability of successful interventions, and there are studies that assess the average response time of emergency responders [14] [15] [16], and how such response time affects the success of emergency interventions and patients' mortality. Looking from a more technical perspective, there are also various approaches that leverage digital technologies and services to broadcast the information about the presence of an EmV on the roads, but they utilize the short-range Vehicle-to-Vehicle (V2V) communication that sends the required information about an EmV only in a close vicinity from this EmV [17][18], thereby only addressing those vehicles that are approximately 300m away from them [19]. Thus, the V2V coverage of 300m is not enough for addressing emergency situations in an efficient manner by sending in-advance notifications, as emergency journeys are usually kilometers long and EmVs are moving at a high speed, reducing reaction time of the drivers. For example, the observational cohort study with 10,315 cases transported by four English ambulance services [20] reported that ambulance journey distances ranged from 0 to 58km (with a median of 5km). One effort to extend the awareness is given by Moroi and Takami [21], who propose a Vehicle-to-Infrastructure (V2I) approach, but this is still not enough given that transmission range of roadside units is between 400 and 500m, with the average delay in message transmission of 487ms and 574ms [22].

To address the aforementioned gaps in existing approaches, the BSA system relies on the Vehicle-to-Network (V2N) communication, i.e., 5G-based MEC deployment where BSA application is running on the optimally selected edge cloud. Given that information such as current location/speed of a vehicle needs to be timely delivered to the BSA application via CAM message updates, the longer uplink latency can significantly affect the efficiency of the V2X application service, i.e., the accuracy of estimating ETA values in case of the BSA application service. Further delays in such communication will produce more errors in the estimation of EmV's time of arrival. Thus, it is important that for our BSA deployment, an optimal MEC is selected taking into account both the computing and network resource availability, so that low-latency and high-reliability can be achieved.

5.2.6.3.2. Functional components of the BSA application service
This advance notification of the EmV’s ETA shall afford the drivers enough time to calmly manoeuvre in a safe manner, i.e., without panicking, to create a clear corridor for the EmV to pass through unhindered, thereby enabling the EmV to reach the event location in time, enhancing mission success and road safety. In Figure 177, we provide a more detailed overview of the functional components of the edge-aware BSA application service whose operations stretches multiple MEC domains. In particular, once the CAM message encapsulated into a UDP packet is received by the BSA application service, whose UDP listener is activated and listening for upstream CAM traffic sent by the EmV, the decoding function of the BSA service is triggered to decode the CAM message and retrieve the EmV ID, speed, and location of the EmV.

As indicated in Figure 177, the output from the decoding function is further sent to both i) the BSA algorithm, i.e., the ETA algorithm that calculates ETA values for different dissemination areas on the road, and ii) the Smart app algorithm, which is deriving proactive decisions on when the peering application instance needs to be deployed in the neighbouring MEC systems, thereby informing the orchestrator elements within the Orchestrated edges platform (via Internal message broker) to proceed with cross-border service instantiation. Further, when the ETA values are derived by the ETA algorithm, the encoding function is called to encode the ETA values into the corresponding DENM messages. The encoded DENM messages are further sent to the Message producer for the translation into the Kafka REST proxy-friendly format so that such DENM messages can be further disseminated via Geoservice to various geographic locations where the civilian vehicles are located. More details about the software design of the components presented in Figure 177 can be found in D4.2 [4].

![Figure 177: Functional components of the edge-aware BSA application service.](image)

5.2.6.3.3. Smartness and edge awareness of MEC application services
The smartness and edge-awareness of cloud-native MEC application services is a particular design feature that we define in 5G-CARMEN project, and leverage as an orchestration booster, as it enhances the decisions made by orchestration layers by allowing them to use the notifications generated by orchestrated MEC application services themselves, and thus, enabling them to retrieve some application-specific insights (e.g., change in route of vehicles connected to the service application, current positions of relevant vehicles, proximity from the country borders, detection of obstacles on the road, and network re-selection) that are usually not known by orchestrators [23]. In particular, the application can be considered as smart and edge-aware in the 5G CCAM context if its design is allowing it to be aware of:

- the edge environment, such as the elements of an orchestrated MEC system, e.g., MEC Application Orchestrator (MEAO) and NFV Local Orchestrator (NFV-LO), which are defined and described in D4.2,
- the other edge applications that are relevant for their operation, such as other peering CCAM applications, or MEC Value-Added Services (VASs) as well as
- the clients running in vehicles that are connected to them and use their service, thus, providing them with real-time information about the movement of vehicles.

As mentioned above, such smart MEC applications are capable of generating various important notifications that could improve and boost their own life-cycle management by enhancing the decision-making process performed by orchestration layers. The notifications derived from application-specific operations can be generated using either data analytics and/or different Machine Learning (ML) models that are executed by applications, and they refer to the processes that are specific for the application operation such as mobility of the vehicle, proximity from the border between two edge domains, or the border between two countries.

If we take a look at the features that make a MEC application smart (listed above), being aware of the edge environment allows MEC applications:

- to retrieve the topological and service coverage of the orchestrators (e.g., coverage of one edge domain), which is a relevant input for determining the boundaries of the service regions covered by MEAO and NFV-LO, thereby used by smart edge applications to timely trigger their relocation e.g., if the vehicle is approaching to border between two edge domains, and
- to pass the notifications to the orchestration entities, which these entities can further use to optimize their orchestration decisions that trigger operations such as application service instantiation, scaling, migration, or termination, and thus maintain QoS at a required level.

Further, awareness of the other edge applications, such as peering MEC application services, enables extending the application service operation beyond one edge domain, as peering application service can use service-based interfaces to exchange application metadata, such as location/speed/heading of vehicles connected to them (mobility of the vehicles). The application service can get more insights into the radio network related information from a VAS such as RNIS, where the granularity can be adjusted per radio cell, or even UE, which in particular helps MEC application service to retrieve network connectivity information about a particular vehicle that is about to cross to border and re-select the network. Given such information, a smart application can apply a suitable ML model to predict network re-selection that usually breaks the service connectivity, and then based on such prediction, it can proactively trigger MEC application service instantiation/migration in the target domain. To retrieve a real-time update on the location/speed/heading of the vehicles connected to it, a smart MEC application service leverages either a VAS such as MEC location service, or it is aware of the clients in the vehicles that are connected and share their location data within CAM and DENM messages.

The principle of applying edge awareness and smartness to MEC application services described above is applied to BSA case. Given the real-time information about the EmV’s movement that BSA application service retrieves from upstream CAM messages, as well as the topological coverage of edge orchestrators (i.e., coverage area of one MEC platform in the project trials), BSA application service performs analysis and calculates the proximity from the border between the adjacent edge/administrative domains (source and target domain). When the proximity is determined, the rule-based algorithm compares it with the predefined thresholds and decides whether a peering application instance is needed in the target domain even before the vehicle reconnects to the other network. In such way, a proactive deployment of the target instance to which vehicle can connect as soon as it re-attaches from one MNO’s User Plane Function (UPF) to the other is achieved. Applying this concept to
a more generic use, applications can notify orchestration entities about the need for i) an on-demand instantiation of peering application instances in other edge and administrative domains, ii) a proactive application-context relocation to support service continuity, iii) an on-demand application termination when its services are not needed anymore by the users, so that resources can be released. The smartness of BSA application service can be further improved by leveraging e.g., RNIS, as the decision to trigger instantiation of peering application services in the other MEC domains can be further optimized knowing the usage of radio resources and attachment to a particular network and radio cell. Finally, leveraging different publish/subscribe mechanisms in the design of both applications and orchestration entities, orchestrators are capable to subscribe to the notifications published by applications and improve their internal decision-making process based on such application-specific insights.

5.2.6.3.4. BSA performance

In MEC systems, the multiple MEC applications are sharing a very limited pool of resources, and therefore it is important to understand the resource metering of MEC applications before they are hosted on the MEC platforms, in order to avoid degraded QoS of the respective MEC application and/or its adverse impact on other services due to extensive resource consumption during high load circumstances. Thus, in D4.2 and D4.3, we have provided a detailed overview of BSA application performance.

Functional and operational feasibility: In D4.2, we presented functional and operational feasibility of the BSA service in a real environment, its management and service performance, and we analyzed i) the overall response time to emergency events, studying all the contributing factors, as well as ii) the impact of the BSA service on the MEC computing resources that will aid the service designer in deriving MEC system specifications for reliable hosting of this critical service. The experimental setup is created in a realistic environment, where we deployed the BSA application instances on top of the MEC hosts within an orchestrated vehicular system. Due to the significant importance of decreasing the overall response time to the emergency events, we performed a thorough performance analysis of the BSA application service, and we presented it in D4.2, measuring the impact of emergency on the MEC system resources, and service response time. Moreover, we introduced a metric called panic indicator that provides a notion on how the proposed BSA service can potentially help in enabling drivers to calmly manoeuvre out of the path of an EmV, thereby increasing the road safety with a more efficient reaction to EmV's arrival. From the results presented in D4.2, we could conclude that it is important for BSA application to dynamically adjust the frequency of sending ETA updates to civilian vehicles, as panic is more likely to happen if the frequency is low. We show that the frequency of sending CAM messages from an EmV to the BSA application significantly affects the overall computing delay, hindering the time given to the application to perform computation before an updated CAM is received. As discussed, this issue can be mitigated by adjusting the reception of upstream CAMs at the application side, but taking into account the accuracy of calculating ETA for different areas. A similar effect on the computing delay is also noticed in the case of an increased number of simultaneously served EmVs, which can be solved by performing application scaling. Concerning the scaling of BSA application, reserving more resources needs to be properly managed due to the resource constraints in MEC systems, especially in the case of the higher CAM frequencies that showed an increased CPU and memory load.

ETA accuracy: Regarding the performance of the ETA algorithm, which calculates the ETA values for the defined areas for dissemination along the road, we conducted a detailed analytical, assessing the ETA accuracy and error estimation. In D4.3 [5], we presented the results of studying the accuracy of the ETA estimation achieved by different methods, where we made a comparison between i) Kalman filter, ii) one-step speed values from CAM referred to as Filter-less method, iii) the average speed values using Moving Average filter, and iv) the Exponential Moving Average filter. In line with the to the results presented in D4.3, the Kalman filter proved to produce the optimal result by providing the highest estimation accuracy, compared to the other prediction methods. This Kalman accuracy gain becomes even more relevant when the algorithm needs to predict ETA values for longer distances. Although the computational complexity of the Kalman Filter is higher compared to other methods because of its recursive nature, our experimentation has shown that the computational time of Kalman filter has the same order of magnitude as in case of the other methods, resulting in an increase in time that not significant. In addition, we can reduce the CAM input frequency (increase CAM period from 1s to 2s, or 3s), and still, Kalman filter sustains better stability in the accuracy compared to other methods. With such BSA system, when the ETA notification is beyond the audio and visual range of the EmV, drivers have enough
time to take the required actions and clear the lane. At the same time, the EmV can always select the shortest path toward the destination and drive at the maximum allowed speed for emergency systems. As a result, the proposed solution is expected to not only improve the road safety, but also to enhance the mission success and response time of emergency responders.

**Smart and edge-aware BSA application service:** The experimental setup that we leveraged on to evaluate the service continuity mechanism such as transparent edge bringing, i.e., the procedure that enables a smooth reattachment of vehicle from a smart edge application from one MNO domain to another, in case of BSA consists of i) two MEC platforms, one per each country, i.e., respective MNOs DTAG and MTA, ii) orchestrated edge platform installed in a Kubernetes cluster on each of these MEC platforms, iii) smart edge application for BSA application service, and iv) python-based client application running at lab premises emulating a virtual vehicle that sends CAM messages. The CAM messages that compose the traffic sent from a vehicle to an edge application (upstream CAM traffic) are encoding relevant information (e.g., speed, and location) over UDP, thereby emulating the movement of the vehicle on the corridor between Germany and Austria, and providing continuous location updates to the smart edge application. In the context of BSA application service, these location updates are used for calculating the estimated time of arrival of an EmV, which is further disseminated as notifications to the other vehicles on the corridor. In this evaluation, we showcase i) the proactive service instantiation based on the triggers/notifications generated by smart edge applications (Phase 1 in Figure 178) and ii) maintaining service continuity when vehicle is crossing the border via creating programmable data plane (Phase 2 in Figure 178). Here we briefly present the two phases illustrated in Figure 178.

To perform Phase 1 illustrated in Figure 178, we use a BSA type of smart edge application, which is containerized and deployed as Kubernetes POD on the edge system in Germany. This edge application notifies MEAO and NFV-LO (i.e., Orchestrated edge platform in Figure 178) to instantiate peering edge application in Austria (step 1, Figure 178), using the data-analytics algorithm that determines the corresponding moment for proactive instantiation, so that all required resources are allocated on the target edge before EmV crosses the border. Afterwards, NFV-LO in Germany is sending the instantiation request to NFV-LO in Austria (step 2, Figure 178), which then further uses Edge controller to instantiate peering edge application (step 3). Once edge application is up and running on the edge system in Austria (step 4), it connects to its peering instance from the source domain (step 5), and receives metadata based on which it can create notifications for dissemination areas in Austria. Upon instantiation, vehicle can re-attach from German to Austrian edge application at any moment, which is in our case determined again by the smart edge application.

![Figure 178: Overview of operations included in the Proactive service instantiation and cross-border service continuity, whereas the components are deployed on the MTA and DTAG MEC platforms; Note: MEC application service such as BSA is denoted as EdgeApp.](image)

In Phase 2, the transparent edge bridging procedure is applied, i.e., the procedure that enables a smooth reattachment of vehicle from a smart edge application in Germany to its peering instance in Austria. This is possible because of the programmable data plane of our orchestrated edge platform, which relays the packets...
sent from a vehicle to an edge application while vehicle is connected to Austrian network (MNO 2) but still on the German side of the border. Once smart edge application decides that relocation should happen (e.g., EmV close to the border between two countries), it sends notification to MEAO (step 5, Figure 178) after which the tunnel is dynamically created, and traffic steering rules applied (steps 6 and 7). This way, edge application that receives packets from EmV is a German one, and once EmV crosses the border, source edge application (Germany) triggers edge application termination (step 8), which breaks the tunnel, and terminates the source edge application. Finally, the CAM traffic coming from the EmV is being sent directly to Austrian instance (steps 9 and 10). More details about the transparent edge bridging procedure can be found in D4.3.

In Phase 2 shown in Figure 178, we measure the latency at the client side, which in our case is a python-based UDP client application running in the lab. This application can be easily on-boarded to the vehicles and used for sending CAMs from vehicle to edge application, thereby measuring the real-time latency as a round-trip time.

To evaluate the performance of proactive edge application service instantiation, we have tested i) the average processing delay of a smart edge application algorithm, which is the time needed for the algorithm running in the BSA edge application to make decisions about the peering edge application instantiation, and edge application relocation/termination, ii) the average instantiation delay calculated at the MEAO side as a time needed for MEAO to process the notifications coming from a smart edge application and instruct NFV-LO and Edge controller to deploy the application service, iii) the average delay of updating the tunnel, which is the time that MEAO takes to process the relocation notification received from the edge application and to trigger the updates on the tunnel that result in traffic steering from one domain to another, and iv) the average termination delay, which is calculated at the MEAO side as a time needed for MEAO to process the notifications coming from a smart edge application and instruct NFV-LO and Edge controller to terminate the source application service, i.e., edge application, break the tunnel, and allow vehicle to directly connect to the target edge application.

The result shown in Figure 179 provides an insight into the latency budget of processing notifications and deriving decisions at both edge application and orchestration layers, showing how essential it is to perform these operations proactively, i.e., before they start affecting the user experience by increasing perceived latency or decreasing service reliability. For instance, taking into account the current location and speed of an EmV, algorithm running in the edge application takes 190ms on average to derive a decision (e.g., whether a peering instance in the other domain needs to be instantiated, or a service needs to be relocated/terminated), and MEAO takes 10ms on average to process the notification received from the smart edge application and to proceed with the peering edge application instantiation. These 200ms do not affect the overall operation as both the decision-making and the edge application instantiation are performed proactively, i.e., while the vehicle is still connected to the source edge application. However, not applying such a proactive mechanism, will have an adverse impact on the service operation, as the vehicle will lose connectivity to the service right after re-attaching from the MNO 1 network to the MNO 2, thus, significantly disrupting the reliability of the edge application service. On the other side, if edge application relocation is triggered too early (e.g., vehicle far away from the border), the service will suffer from an increased latency due to the relaying procedure (further explained in Figure 180). Such a result helps to understand how proactive procedures should be triggered to prevent service downtime and disruptions for the highly susceptible services such as those designed for vehicular use cases.

While the result in Figure 179 shows the efficiency of proactive orchestration operations, Figure 180 illustrates the latency perceived by the end user, i.e., latency measured at the client side. In Figure 180, we present the result that shows the service continuity enhancements due to proactive steering of CAM traffic (i.e., traffic generated by the vehicle, and received by edge applications) from the edge system in Germany to the edge system in Austria. In this particular scenario, the result shows that the first 40 packets (i.e., CAM messages encoded into UDP packets) are sent directly to smart edge application in Germany. The relay procedure illustrates the scenario in which vehicle connects to Austrian network while being on the German side of the border, which requires programmable data plane to relay packets from Austria to Germany. Although there is

12 Python-based UDP client configured to produce a response to every received packet, enabling measurements of a round trip time.
an increase in latency during the relay, as soon as EmV crosses the border, i.e., starts sending packets directly to Austrian instance, the latency decreases and becomes more stable. The difference between the average latency in Germany (22.438ms), and Austria (27.728ms), is expected as the location of the client is in Germany (lab). Thus, the service continuity enhancements achieved by proactive edge application instantiation and traffic steering is evident, as vehicle does not lose the connectivity to the service, thereby being always connected to the optimal edge application.

Figure 179: Performance of i) the smart algorithm within the BSA application service, and ii) MEAO.

Figure 180: Cross-border service continuity enhancements due to proactive traffic steering initiated by the transparent edge bridging
Figure 181: BSA dashboard of MEC application instance deployed on the TIM MEC, while the EmV is being connected to the Austrian instance of the BSA application service.

Figure 182: One of the BSA testing scenarios on the border between Austria and Italy, where the full video can be accessed via the link.
Functional tests were performed on the pilot, experiencing the reception of DENM message from the Geoservice. As the dataset is limited, the statistical value of downlink latency KPI can be inferred from section 5.2.6.2 (CAM measurements) which gives from 30 to 40 ms delay estimation.

![Figure 183: BSA on-board the vehicle](image)

### 5.2.7 Tests on Decentralized Manoeuvres

#### 5.2.7.1 Experiments on in-lane and decentralized lane change manoeuvres

The in-lane scenario starts with a connected vehicle travelling in L1 automation level (Vehicle A). As soon as the car detects the presence of another connected vehicle (Vehicle B) moving in the same lane through its CAM, the driver of Vehicle A gets informed about the possibility to engage Cooperative Adaptive Cruise Control (C-ACC), having as target Vehicle B. With C-ACC engagement, Vehicle A sets dynamically the target speed of its cruise control to the speed of Vehicle B. In such configuration, whenever Vehicle B senses a not connected car (Vehicle C) through its radar and slows down rapidly to avoid collision, Vehicle A gets constantly informed about the upcoming danger in advance. Thanks to sensor sharing, Vehicle A can slow down before Vehicle B enters the field of view of its radar, keeping a larger headway from the car in front acting a smoother manoeuvre.
Figure 184: In-lane manoeuvres

The graphs in Figure 195 are an example from the test trials in the Austrian part of the corridor. The time intervals where C-ACC is engaged are shown by the thicker line plots.

Figure 185: longitudinal offset (above) and speed profile (below) during in lane manoeuvres
Referring to the longitudinal offset distance (upper part), the line represents the distance between leading and following vehicle, shown in thick blue when the C-ACC is engaged. The distance keeping by C-ACC (V2X) is larger than the one kept by the onboard sensor, especially in the time interval of 110 to 160s.

The speed profile plot (lower part) shows how the speed of the vehicle in the back follows the behaviour of the front vehicle speed, after some delay. To give an overall view, the following graph shows a plot of the speed difference between leading and following vehicle, over all the log files considered for C-ACC.

Figure 186: Speed difference during cooperative and automated in-lane manoeuvres

The delay is explained by considering that the instantaneous speed of the leading vehicle determines the target cruise speed of the following vehicle. Thus, changes of the leading vehicle speed yield changes in the target speed of the following one. If the distance is sufficiently high (like in this case) the following vehicle control system will just follow the new target speed, with a smooth acceleration/deceleration which is characteristic of the ACC comfortable driving. At lower distances, the vehicle is perceived as an obstacle and the ACC headway keeping can override the target speed, yielding a fast reaction of the following vehicle, for example when the front vehicle brakes.

This explains also the variability in speed difference between leading and following vehicle: speed following depends on the kind of in-lane manoeuvre and on the abruptness of the manoeuvre itself. Smooth speed changes of the front vehicle are followed steadily, whereas faster speed changes yield a delayed, and also damped, speed profile behaviour. The result is that the C-ACC acts as a low pass filter on speed profile, which falls entirely in the scope of ensuring a comfortable driving of the vehicle following, damping the abrupt changes (this was also shown in the public demonstration).

The previous Figure 185 exemplified the damping effect: the speed profile of the leading vehicle which resembles a sinusoid (it was generated on purpose) is damped at the following vehicle. Figure 187 shows a slow down manoeuvre whereby the following and leading vehicle have a distance >70 m and speed 80km/h: the following vehicle behaviour is smoother (the peak of the red speed curve just before t=120s is filtered out) and a bit delayed, but more than sufficient to keep the safety conditions, given the high distance (which is initially 80m and reaches 20m when the two vehicles run below 30km/h).
Figure 187: Longitudinal offset (above) and speed profile (below) during cooperative and automated in-lane manoeuvres

**Lane change Manoeuvre (cut-in)**

The non-centralized lane change manoeuvre starts when a 5G-connected vehicle (Vehicle B) approaches in the left lane another connected vehicle (Vehicle A) travelling on the right lane in L1 automation mode following a non-equipped vehicle in the front. As soon as Vehicle A senses Vehicle B through its CAM and Vehicle B communicates its intention to change its travelling lane (using the physical turn indicator light that is considered in the CAM), the driver of Vehicle A receives a cut-in request through the 5G-CARMEN HMI. After the request acceptance, the cruise control’s target speed of Vehicle A starts decreasing according to the position and speed of Vehicle B, increasing the headway from Vehicle C. As soon as the headway between Vehicle A and Vehicle B is large enough, the driver of Vehicle B can complete the lane change. Vehicle B evaluates the possibility to complete the lane change using both sensor data and V2V information about Vehicle’s A position. After the completion of the manoeuvre, the connected cars travel on the same lane, with Vehicle A following
Vehicle B.

Figure 188: Lane change manoeuvres decentralized

The graphs in Figure 189 show how the lane change manoeuvre is performed. The scenario example has been taken from trials in the Austrian part of the Corridor.

Figure 189: Inter-vehicle distance and speed profile during a cooperative decentralized lane change manoeuvre
The lane-change manoeuvre starts at approximately $t=50s$ and ends at $t=60s$, i.e., from the time the driver of Vehicle A accepts the cut-in request until Vehicle A detects that vehicle B is entering its frontal area (ahead in lane). In this case the total manoeuvre time was around 10s. During that time, as can be seen in the lower part, the speed profile of Vehicle A decreased automatically to ease the cut-in. The cut-in was performed in absence of the non-connected front vehicle (Vehicle C) in public roads and started very smoothly towards $t=57$.

### 5.2.7.2 Quality of Service

While driving, the onboard quality of service software constantly monitors connectivity and positioning having 5G-CARMEN KPI as metrics. In particular, it considers:

- Ego vehicle position accuracy
- Remote vehicle position accuracy
- Packet Delivery Ratio (PDR)
- Data Rate
- Latency
- Jitter

Especially position accuracy and latency are critical for the quality of connectivity and to enable higher AD levels. Therefore, these have been considered as main factors for the cooperative automated manoeuvres and are hereafter treated in the cross-border environment.

### 5.2.7.3 Cross-border effects on connected and automated driving

This section reports measurements on quality of service impacting on ODD (Operational Design Domain) evolution during the Austrian-Italian cross-border transition, and in particular of the SAE automation level adaptation.

**Austria-Italy**

The scenario is described in Figure 190. Vehicle A is the host vehicle (HV), which is connected and following through Cooperative-ACC the leading Vehicle B during the cross-border transition. The two main players in the automation level handing involve the position accuracy of both vehicles (which influence also the position accuracy of the virtual road users sensed by Vehicle B and communicated to Vehicle A), and the communication outage due to the change in telecom operator at the border. The objective of this analysis is to give an overview of the change in the availability of SAE automation level 4 (L4) during the cross-border transition as perceived by Vehicle A.
Figure 190: Expected L4 availability in the Austrian-Italian border: positioning and connectivity discontinuities

The L4 continuity relies on the quality of service in terms of position accuracy of the leader connected vehicle. In the Austrian-Italian border the presence of the Brenner tunnel leads to a drop of the position accuracy performance of the leading vehicle. The deterioration of the absolute position measurements is detected by Vehicle B, since the dimensions of the confidence ellipse related to such measurements is constantly evaluated by the vehicle’s OBU. Consequently, Vehicle A decreases the suggested automation level given the worsening in terms of accuracy of the data received through the CAM by Vehicle B, causing the non-availability of L4 in the HV.

As reported in 5.2.2, the average horizontal position accuracy in the corridor is 44cm (2σ). This value is taken as reference for the ODD analysis in order to establish a threshold in the dimensions of the positioning confidence ellipse above which SAE L4 is to be considered unavailable. Such threshold is set at 60cm, being above the mean value in order to avoid chattering in the L4 availability along the corridor but small enough to guarantee lane-level accuracy. Figure 191 shows the loss in accuracy at the Austrian-Italian border for 15 trials, in particular considering the stretch of road from Nösslach to the Plessi Museum.
Figure 191: Horizontal position accuracy at the border.

As can be noticed, close to the Brenner tunnel precise positioning accuracy was sensibly above threshold (considering the in-country behaviour generally within threshold). The ca. 15 meters peak is due to the tunnel, while the subsequent smaller peaks are close to the cross-border area where the operator switch between Magenta (Austria) and TIM (Italy) occurs.

Hereafter (Figure 192), a sample trial is presented, where positioning data and service connectivity data (exchange of CAM) are plotted together over time. As can be seen, QoS degrades close to the border as follows: IP change takes between 3 and 4 s, but the absence of messages over Uu is between 4 and 5 seconds, as reported in Chapter 5.2.3; CAM service outage happens very close in time to IP disconnection and then lasts longer; positioning accuracy grows before the IP transition, and it reaches a peak after the reconnection.
Figure 192: Positioning and connectivity effects at the Austria-Italy border, southbound. IP change (up), positioning error (middle), Geoservice reception over time (abscissa shows values every 10s).

Figure 193: Austria-Italy cross border path and relevant points; cartesian representation on a plain.
As can be seen by mapping the logged path onto the local geography, the disconnection and reconnection happened inside the tunnel, towards the end of it, which is what the tester actually experienced in the trials.

![Map showing disconnection and reconnection points](image)

**Figure 194: Cross border zoom in on a map: disconnection and reconnection happen within the tunnel. Positioning accuracy peak is just outside**

Therefore, we can state that positioning effect due to the tunnel is predominant. Furthermore, the road stretch, where positioning QoS is well above the threshold (of more than one order of magnitude, > 6m) is by far longer than the section where Uu CAM’s are unavailable.

**Austria-Germany**

For comparison, we measured the data quality cross-border for the Austria-Germany transition where we also found smooth network reselection of less than 5 seconds. The graph in Figure 195 shows the corresponding break in received messages, which meets the expectations, and also a worsening of GPS position after the transition. The latter aspect was seen in other recordings and is always happening at the same point (U-turn). Whereas the cross-border transition happened at different positions (unlike Brenner pass, at Kufstein the border runs parallel to the road). The positioning effect and has been further analysed using dedicated toolset of the positioning component, to check for a possible correlation with the cross-border, with negative outcome. Results are discussed more in detail in D5.4, yield the conclusion is that again, the geography and satellite availability is again predominant over cross-border effect.
Figure 195: Positioning and connectivity effects at the Austria-Germany border, northbound. IP change (up), positioning error (middle), Geoservice reception over time (abscissa shows values every 10s).

Figure 196: Austria-Germany cross border path and relevant points; cartesian representation on a plain

For comparison, Figure 197 reports the case where both Cooperative Extended Perception (CAM and V-CAM) and positioning have a good quality. This example was taken from test trials in Austria.
Network reselection effect on connectivity reliability

As seen, network reselection caused an outage of 5s at the cross-border transition. To verify that this was actually a systematic effect which happens only at the border, the cross-border trials (around 10 minutes each) were compared with the in-country trials (several hours) in Italy and Austria. Germany was excluded as the log files were limited to some minutes after the border. Figure X shows the reliability measured as the percentage of time travelled receiving the Geoservice CAM and Virtual CAM, over the total time travelled in this condition, i.e. the true positive given the expected positive cases.

As we can see from the graph, reliability in country is more than 99.5%, while cross-border trials were between 96% and 98.8%. We also checked the number of times the service had such an outage during the trip and found out that these events happen really seldom in-country, whereas they are systematic in cross-border, as expected from the fast network reselection. For comparison, without fast network reselection, the outage is of the order of some minutes, therefore reliability in those 10 minutes trip would be less than 90%.

Figure 197: Austria-Germany cross border path and relevant points; cartesian representation on a plain
Figure 198: Availability of the CAMs from the Geoservice.
6 Conclusions

This D5.3 is a final pilot report and has given a snapshot of the 5G-CARMEN system deployed and tests conducted on the pilot at Q2 2022. With respect to the former D5.2 (a preliminary pilot report of Q3 2021 [3]) in the last project period, the installation of components was completed, and the tests were focussed on cross-border sites.

Fast Network Reselection is now available in terms of ePLMN in the 5G NSA, at Brennero when coming from Austria headed to Italy using both TIM and MTA SIM (previously it was only available with MTA SIM) while it has not been available in the other direction during the pilot activity (i.e. end of June 2022). ePLMN is available also between Austria-Germany in both directions.

Local Breakout to the closest MEC is available using DTAG SIM from Germany to Austria, and also using TIM SIM from Italy to Austria.

Both Fast Network Reselection and Local Breakout could be successfully tested both in terms of Modem Connectivity (February 2022) and Vehicle Use Cases (May-June 2022).

In Italy TIM performed network tests at Brenner, finding that 5G nodes offer good coverage of the whole region, in particular in the highway which is the main target for the pilots. 5G connectivity is possible also in part of the highway tunnel, and 5G signal indicators (RSRP and SINR) yield higher values on the highway than on the nearby statal road. Round Trip Time latency was measured. Compared to 4G, 5G showed lower latency more stability (which might be due to 4G networks being more loaded than 5G).

In Germany, DTAG performed network tests in Munich (4G and 5G) and in the border region Germany/Austria (4G and 5G) at Kiefersfelden/Kufstein on the 5G-CARMEN corridor. Results confirmed that 5G NSA gives relatively minor improvements regarding latency. Average throughput rates are significantly improved with NR compared to LTE, however, as in the Italian case, LTE is still more widely used than 5G NR.

In Austria, Magenta performed network tests close and cross the borders with Italy (Brenner) as well as with Germany (Kufstein). At the Italian border (Brenner Area), despite of the existence of 5G and although a big portion of the measurements have been done over the 5G network, parts of the network performances remain mediocre especially in UL (incl. RTT) and would require extensive further investigations.

QCGER performed tests with its 5G On Board Unit at both Italy-Austria and Austria-Germany borders, to test the cross-border service interruption times, comparing the new available features with the legacy situation: from 20 s the interruption could be reduced to 2.3 s with the implementation of ePLMN and fast NW reselection by RRC connection Release. CCAM related applications require continuous service without significant outages (tenths of ms). Such a reduction might be possible in case the different MNOs would implement inter PLMN handover, which is judged as not feasible due to the needed deep integration and connection between the networks. QCGER measured also RTT latency measurement using 64 bytes payload size in static conditions were 17-23 ms in Austria (19 ms on average), 23-37 ms in Germany (28 ms on average) and 31-51 ms in Italy (39.8 ms on average). In Germany 5G latency is sensibly less than 4G, whereas in Italy 4G and 5G performances were comparable. In this context C-V2X direct communication using the PC5 interface plays a relevant complementary role in keeping at least 1-10Hz awareness of the cooperative neighboring vehicles across borders in the short Uu outage interval. It is also well suited for latency-critical applications like basic safety, considering the end-to-end latencies experienced in some cases for Non-Stand Alone 5G.

Orchestrated 5G Edges platform has been deployed on the Multi-Access Edge Computing (MEC) platforms in all three countries (i.e., Italy, Austria, and Germany) by NEC, IMEC, WINGS and WP4 team. The set-up in all three countries consists of two orchestration layers, i.e., the top-level service orchestrator NFV Service Orchestrator (NFV-SO), and edge-level orchestrators NFV Local Orchestrator (NFV-LO) and MEC Application Orchestrator (MEAO) was treated extensively in WP4. All components were successfully deployed and
deployment tests completed in the previous period (Q3 2021). This last part of the project has been dedicated to completing the functional tests on components. It should be noted that this platform goes beyond the piloted use cases, and enables future CCAM services by means of low-latency cross-border service continuity. This includes features of smart edge applications to boost orchestration decisions and of a programmable edge data plane for transparent edge bridging (TEB) between different MNO edge networks. Detailed evaluation results based on the deployed Orchestrated Edges can be found in D4.3 [5].

**BMW and CRF, with support of Qualcomm, CNIT, FBK, DTAG, TIM and other partners, set-up 5 vehicle prototypes to demonstrate Connected and Highly Automated Driving functions** and performed functional testing of the Cooperative and Automated Use Cases in country, as planned, with first measurements up to the border.

The OEMs were especially interested in evaluating the enablers of SAE L4 connected and automated driving, namely: precise positioning, 5G-enabled extended perception, Uu and PC5 redundant connectivity, low-latency message brokers, local dynamic maps, manoeuvre recommendation service and Back Situation Awareness Function Service on MEC. Especially in the last part of the project (Q4 2021 and Q1-Q2 2022), tests have focussed on actual manoeuvres on the motorway stretch (at or close to borders), addressing Lane change centralized approach (BMW), in-lane manoeuvres based on forward detection (CRF) and lane-change manoeuvres (CRF). Perception, sensor fusion and decision making were based on Automated Vehicle prototypes, whereas actuation on public roads was limited to longitudinal control and lane-centring (Highway Assist), with HMI recommendations for lane changes.

**Precise positioning system of 5G-CARMEN (getting GNSS corrections by Swift Navigation-DTAG system) has been improved in terms of integration into the vehicle thoroughly validated by OEMs, also in cross border.** The results of 2021 were consolidated in 2022 by runs throughout the corridor (Trento-Kufstein and back) and the benefit of fast network reselection could be compared to the ordinary cross-border transition using the LTE network. As important result, 5G-CARMEN FNR solution proved to be sufficient to support the positioning provision of GNSS corrections: no problems in the continuity of the service have been identified at the end of the project. The horizontal position error is smaller than 20 centimetres when enough satellites are in visibility. Some deviations from these performances are due to the geometry of the valley especially when the vehicle is driving close to the mountainside. The integration of the IMU and vehicle generally limits the error to less than 50 centimetres, though in specific cases the positioning quality was higher, as was experienced also cross-border. A further analysis of these effects was performed and is treated in the D5.4 results assessment [1].

**The BMW Manoeuvring Service was able to send instructions to 3 BMW prototype vehicles and lane change manoeuvre was successfully executed.** This was tested in simulation, test track and on the highway close to the German-Austrian border. Successful execution depends on the initial distance and speed of each vehicle at the time when the manoeuvre is initiated. The average time goes from 20 seconds (close proximity) to 150 seconds (vehicles further apart). In order to be adapted to the real-life scenario, the manoeuvring service algorithm implemented faster update rates. The maneuvering service managed to calculate a sensible manoeuvre and also gave the merge confirmation at the right moment, i.e. when humans would merge too. Experiments showed a deviation and delay from the recommendations is due to the speeds being controlled by drivers, highlighting the difference between reaction times of a human driver compared to an automated system. For the Maneuvering Service to provide more accurate instructions in challenging scenarios, besides a faster update rate, a complete view of the traffic situation would be required.

**2 CRF Maserati test prototypes have been tested in L4 SAE level (up to decision making) enabled by 5G and PC5 redundant communication in the operational design domain.** The prototypes, with PC5 connectivity, Uu 5G connectivity to S-LDM (via AMQP broker) and to the Geoservice have been tested in cross-border demonstration scenarios and Operational Design Domain conditions at Brennero and, in the last project period, also at Kufstein. The tests were performed addressing both in-lane and lane-change manoeuvres in medium-high traffic conditions. The full integration of Back Situation awareness functionality was achieved and at Brennero, it was verified how a vehicle in Italy can be notified of an approaching emergency vehicle even when the latter is still in Austria. Performance tests on BSAF have been addressed mostly in the laboratory in WP4. Rather, the pilot evaluation focussed on the car following scenario and on the cooperative lane-change decentralized, based on the Geoservice data exchange (vehicle-to-network-to-vehicle). Both use cases were supported by the extended perception, which allowed sending Cooperative Awareness and
Perception data at 20Hz, by means of which the perception horizon in front of the vehicle has been extended up to 350m (Geoservice configuration parameters) and the number of objects detected frontally on average double with respect to standard on-board frontal sensors. Cooperative Adaptive Cruise Control has the capability of longitudinal control, following the car in front farther than 100 m, and yields smooth and damped slow-down effect in the following car, in case of sudden hard braking of the car in front. As smooth behaviour was experienced also in the slowdown of a vehicle to enable a lane-change manoeuvre.

The vehicles have an “in-vehicle QoS module” continuously checking if the expected QoS requirements are met during the vehicle movement. invQoS continuously collected and analyses metrics about V2X/5G message quality (latency above all), ego and remote vehicle position accuracy, and mobile network (including predictive QoS). The module is interfaced with the Automated Driving system to state which level of automation can be enabled. Despite the rather high latency values measured, the quality does not alter when passing, using a certain SIM card (e.g. Italian TIM SIM) from the home country to the visited network, thanks to Local Break Out. Communication outage at border was, as expected, of the order of 5 seconds in case of Fast Network reselection. It did have effects on the SAE automation level availability, but these effects seemed to be negligible in comparison to positioning QoS effects (this aspect has been addressed in D5.4 Results Assessment [1]).

Hereafter, the results are summarized. They are discussed in detail in D5.4 [1].

Table 55: Results in terms of the Use Case KPI

<table>
<thead>
<tr>
<th>KPI name</th>
<th>KPI value</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>UC.01 Position Accuracy</td>
<td>10 cm (2 sigma) in open sky with at least 7 satellites, elevation mask set 5° (&lt;20 cm tolerated)</td>
<td>&lt; 20 cm with good satellites view</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;50 cm in all scenarios</td>
</tr>
<tr>
<td>UC.02 Position Refresh Time</td>
<td>20 Hz</td>
<td>Achieved with few vehicles. Needs simulation stress tests (ongoing)</td>
</tr>
<tr>
<td>UC.03 Throughput</td>
<td>9.2 Mbps</td>
<td>Achieved 219 Mbps (network measurements)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uu stands 20Hz V2N2V, up to 10 CAM/V-CAM (use case measurements)</td>
</tr>
<tr>
<td>UC.04 Predictive QoS for take over time</td>
<td>&gt;10 seconds (AD take over time)</td>
<td>Static data</td>
</tr>
<tr>
<td>UC.05 Service Level Reliability</td>
<td>99.9%</td>
<td>For precise positioning: Good reliability in country</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reliability at borders of 5-6s break</td>
</tr>
<tr>
<td>UC.06 Communication range/Geocast area</td>
<td>&gt; 350 m (V2V)</td>
<td>Achieved as configuration and functional test and confirmed by measurements throughout the pilot.</td>
</tr>
<tr>
<td>UC.07 - Data refresh rate</td>
<td>20 Hz</td>
<td>Achieved (20Hz)</td>
</tr>
<tr>
<td>UC.08 - Service Level Latency</td>
<td>10 ms (AD L4)</td>
<td>50-60 ms on 4G</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20-50 ms on 5G</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geoservice &amp; LDM latency budget is &lt;1ms</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMQP adds around 10ms.</td>
</tr>
</tbody>
</table>
7 References

[12]. ETSI TS 102 894-2, “Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary”, V1.3.1, 2018-08.


