5G HEalth AquacultuRe and Transport validation trials

D4.4: Final Solutions for Transport Verticals Use of 5G

Revision: v.1.0

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<thead>
<tr>
<th>Work Package</th>
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<td>Task</td>
<td>Task T4.3</td>
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Abstract

This deliverable describes the Phase 3 (final) trials of the various use case scenarios of the transport vertical.

Keywords

5G, transport, trials
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¹ R: Document, report (excluding the periodic and final reports)
DEM: Demonstrator, pilot, prototype, plan designs
DEC: Websites, patents filing, press & media actions, videos
OTHER: Software, technical diagram
EXECUTIVE SUMMARY

A set of four representative use case categories (*Platooning, Autonomous/assisted driving, Support for remote driving, Vehicle data services*) have been considered for the transport vertical sector. In order to better focus the work for Phases 2 and 3, the main four use cases in the transport vertical have been divided to core and supplementary use case scenarios. By focusing the large-scale implementation and in-depth trialling activities to the core scenarios, the key 5G functionalities and KPIs of the transport vertical use cases have been investigated and validated more deeply. The supplementary scenarios have provided additional insight into the 5G performance by providing validation results for specific technology enablers.

The core use case scenarios in the transport vertical are: “T2S1: Smart junctions and network assisted & cooperative collision avoidance (CoCa); Trial track”, “T2S4: Human tachograph”, “T3S1: Tele-operated support (TeSo)”, “T4S5: End-to-end (E2E) slicing” and “T4S6: Vehicle sourced high-definition (HD) mapping”.

The supplementary use case scenarios in the transport vertical are: “T2S2: Smart junctions and network assisted & cooperative collision avoidance (CoCa); Simulation track”, “T2S3: Quality of service (QoS) for advanced driving”, “T4S1: Vehicle prognostics”, “T4S2: Over-the-air (OTA) updates”, “T4S3: Smart traffic corridors”, “T4S4: Location based advertising” and “T4S7: Environmental services”.

The 5G-HEART project has adopted a three-phased approach for trials and validations of the developed solutions: Phase 1 trials aimed to validate the baseline performance using fourth generation (4G)/long-term evolution (LTE) technologies. Phase 2 focused on early 5G-based solutions trialled over 5G non-standalone (NSA) culminating in Phase 3 trials and demonstrations over 5G standalone (SA) supported by various trial platforms.

This deliverable describes the final (Phase 3) trials setup, key metrics (application-level) and final solution designs developed in support of various use case scenarios of the transport vertical.
# TABLE OF CONTENTS

**EXECUTIVE SUMMARY** .............................................................................................................. 3  
**TABLE OF CONTENTS** ................................................................................................................. 4  
**LIST OF FIGURES** ......................................................................................................................... 9  
**LIST OF TABLES** ..........................................................................................................................11  
**ABBREVIATIONS** ........................................................................................................................ 12  
1 **INTRODUCTION** ..................................................................................................................16  
1.1 Use cases and Phase 3 trials overview ................................................................................16  
1.2 Definitions ............................................................................................................................17  
1.3 Organization of this deliverable .........................................................................................18  
2 **T2S1: SMART JUNCTIONS AND NETWORK ASSISTED & COOPERATIVE COLLISION AVOIDANCE (COCA); TRIAL TRACK** ...............................................................19  
2.1 Description and motivation...............................................................................................19  
2.2 Final setup .......................................................................................................................19  
2.2.1 Network architecture .........................................................................................................19  
2.2.2 User application architecture ..........................................................................................21  
2.2.3 Hardware components .....................................................................................................22  
2.2.4 Software components .......................................................................................................23  
2.3 Testing and verification ......................................................................................................23  
2.3.1 Methodology ..................................................................................................................23  
2.3.2 List of key performance indicators ................................................................................24  
2.3.3 Measurement and testing tools ....................................................................................25  
2.3.4 Final results ...................................................................................................................25  
2.4 Recommendations ............................................................................................................27  
3 **T2S4: HUMAN TACHOGRAPH** .........................................................................................28  
3.1 Description and motivation.............................................................................................28  
3.2 Final setup .......................................................................................................................28  
3.2.1 Network architecture .........................................................................................................28  
3.2.2 User application architecture ..........................................................................................29  
3.2.3 Hardware components .....................................................................................................30  
3.2.4 Software components .......................................................................................................30  
3.3 Testing and verification ......................................................................................................31  
3.3.1 Methodology ..................................................................................................................31  
3.3.2 List of key performance indicators ................................................................................33  
3.3.3 Measurement and testing tools ....................................................................................34  
3.3.4 Final results ...................................................................................................................34
# T4S1: TELE-OPERATED SUPPORT (TESO)

## 4.1 Description and motivation

## 4.2 Final setup

### 4.2.1 Network architecture

### 4.2.2 User application architecture

### 4.2.3 Hardware components

### 4.2.4 Software components

## 4.3 Testing and verification

### 4.3.1 Methodology

### 4.3.2 List of key performance indicators

### 4.3.3 Measurement and testing tools

### 4.3.4 Final results

## 4.4 Recommendations

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# T4S5: END-TO-END (E2E) SLICING

## 5.1 Description and motivation

## 5.2 Final setup

### 5.2.1 Network architecture

### 5.2.2 User application architecture

### 5.2.3 Hardware components

### 5.2.4 Software components

## 5.3 Testing and verification

### 5.3.1 Methodology

### 5.3.2 List of key performance indicators

### 5.3.3 Measurement and testing tools

### 5.3.4 Final results

## 5.4 Recommendations

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# T4S6: VEHICLE SOURCED HIGH-DEFINITION (HD) MAPPING

## 6.1 Description and motivation

## 6.2 Final setup

### 6.2.1 Network architecture

### 6.2.2 User application architecture

### 6.2.3 Hardware components

### 6.2.4 Software components

## 6.3 Testing and verification

### 6.3.1 Methodology
6.3.2 List of key performance indicators ................................................................. 50
6.3.3 Measurement and testing tools .................................................................... 50
6.3.4 Final results .................................................................................................. 50
6.4 Recommendations .......................................................................................... 50

7 T2S2: SMART JUNCTIONS AND NETWORK ASSISTED & COOPERATIVE COLLISION AVOIDANCE (COCA); SIMULATION TRACK .......................... 51
7.1 Description and motivation ............................................................................. 51
7.2 Final setup ...................................................................................................... 51
7.2.1 Network architecture ................................................................................. 51
7.2.2 User application architecture ...................................................................... 52
7.2.3 Hardware components ................................................................................. 52
7.2.4 Software components .................................................................................. 52
7.3 Testing and verification ................................................................................... 54
7.3.1 Methodology ............................................................................................... 54
7.3.2 List of key performance indicators ............................................................. 55
7.3.3 Measurement and testing tools ................................................................. 56
7.3.4 Final results ................................................................................................ 56
7.4 Recommendations .......................................................................................... 64

8 T2S3: QUALITY OF SERVICE (QOS) FOR ADVANCED DRIVING ................. 65
8.1 Description and motivation ............................................................................. 65
8.2 Final setup ...................................................................................................... 65
8.2.1 Network architecture ................................................................................. 65
8.2.2 User application architecture ..................................................................... 66
8.2.3 Hardware components ............................................................................... 68
8.2.4 Software components ............................................................................... 68
8.3 Testing and verification ................................................................................... 69
8.3.1 Methodology ............................................................................................... 69
8.3.2 List of key performance indicators ............................................................. 71
8.3.3 Measurement and testing tools ................................................................. 71
8.3.4 Final results ................................................................................................ 71
8.4 Recommendations .......................................................................................... 71

9 T4S1: VEHICLE PROGNOSTICS ........................................................................ 73
9.1 Description and motivation ............................................................................. 73
9.2 Final setup ...................................................................................................... 73
9.2.1 Network architecture ................................................................................. 73
9.2.2 User application architecture ..................................................................... 74
9.2.3 Hardware components ............................................................................... 74
LIST OF FIGURES

Figure 1. Network architecture of the final trials of the Smart Junctions use case ........................................20
Figure 2. Three configured Radio slices ........................................................................................................21
Figure 3. Phase 3 Data flow of Traffic Light Controller data through the 5GRONINGEN network................22
Figure 4. Test scenario of the combined phase-3 transport and healthcare trials ...........................................24
Figure 5. Observed uplink throughput of “All vehicle traffic” (H1C + T2S1) and general-purpose internet traffic ...................................................................................................................................26
Figure 6. Observed uplink throughput of “Video traffic” (H1C), CCAM traffic (T2S1) and general-purpose traffic ...................................................................................................................................27
Figure 7. Network architecture for the final trials of the human tachograph use case scenario .....................28
Figure 8. User application architecture for the final trials of the human tachograph use case scenario .......29
Figure 9. Human tachograph final trials performance measurement setup ..................................................32
Figure 10. Sensor data and KPI monitoring dashboard for the human tachograph service .........................32
Figure 11. Human tachograph final trials scalability measurement setup .....................................................33
Figure 12. High-level overview of the TeSo service's architecture ...............................................................36
Figure 13. ROC-GW design ..........................................................................................................................38
Figure 14. ROC GUI application ....................................................................................................................39
Figure 15. 5G RSRP values across the trial pathway .....................................................................................40
Figure 16. Complete operational cycle and measurement methodology ....................................................41
Figure 17. Network architecture of T4S6 ......................................................................................................49
Figure 18. User application architecture with 5G connectivity, T4S6 ............................................................49
Figure 19. Overall architecture of the CoCA system based on V2N 5G NR connectivity ............................52
Figure 20. Simulation modules and the interaction among them ..................................................................53
Figure 21: CPM structure ............................................................................................................................54
Figure 22. Traffic of CoCA application with on the left the average number of CPM messages per second and on the right the empirical CDF of CPM packet size (in Bytes) ..........................................................57
Figure 23. Evolution of the UL RAN latency with on the left the median UL RAN latency (with the quantile at 5% and 95%) and on the right the empirical CDF of the UL RAN latency for 10 and 100 vehicles in the intersection ..........................................................58
Figure 24. Evolution of the DL RAN latency with on the left the median DL RAN latency (with the quantile at 5% and 95%) and on the right the empirical CDF of the DL RAN latency for 10 and 100 vehicles in the intersection ..........................................................58
Figure 25. Evolution of the RAN latency with a bandwidth of 50 MHz. On the left, we have the median UL RAN latency (with the quantile at 5% and 95%) and on the right the median DL RAN latency (with the quantile at 5% and 95%) from 10 to 100 vehicles in the intersection ..........................................................58
Figure 26. Evolution of the RAN latency with MCS=5. On the left, we have the median UL RAN latency (with the quantile at 5% and 95%) and on the right the median DL RAN latency (with the quantile at 5% and 95%) from 10 to 100 vehicles in the intersection ..........................................................58
Figure 27. Evolution of the latency (median) for the decentralized and centralized MEC deployment as the function of the number of vehicles ..........................................................60
Figure 28. Evolution of the unconstrained PDR (left) and of the constrained PDR (right) ............61
Figure 29. Evolution of the constrained PDR for a bandwidth of 50 MHz (left) and MCS=5 (right)...62
Figure 30. (a) OMR with Th=1m, (b) OMR with Th=2m, (c) OMR with Th=4m .........................63
Figure 31. T2S3 scenario. An automated vehicle approaches the end of its ODD (green). To continue
with a high LoA, vehicle requests manoeuvre support from the cloud and can continue with high LoA
through the non-ODD area (orange) .............................................................................................65
Figure 32. T2S3 network architecture used in the final trials. User and service plane are provided by
TUC (green), access and core network by Vodafone (blue) ...........................................................66
Figure 33. T2S3 application architecture. Green: software components developed by TUC; Orange:
external hardware devices .................................................................................................................66
Figure 34. T2S3 message flow for an accepted scenario. .................................................................66
Figure 35. T2S3 network coverage map for assisted maneuver. Green denotes area where the reception
is expected to be good while red areas are known to have bad reception ........................................67
Figure 36. T2S3 front camera feed and detected objects, excerpt from the final trials ....................68
Figure 37. T2S3 Research vehicle Carai 3 used for development and validation trials ....................69
Figure 38. T2S3 validation trial location at TUC premises (left), output of the trajectory planner for the
validation scenario (right) ................................................................................................................70
Figure 39. T2S3 cloud PC location at TUC (left, blue), trial site (left, orange), base station at trial site
Schlettau (middle) and local map of Schlettau trial roads (right) ....................................................70
Figure 40. Network architecture for the final trials of the vehicle prognostics use case scenario ......73
Figure 41. Vehicle prognostics final trials scalability measurement setup ........................................75
Figure 42. Network architecture for the final trials of the OTA updates use case scenario ...............77
Figure 43. OTA updates final trials scalability measurement setup ..................................................79
Figure 44. Network architecture .....................................................................................................81
Figure 45. Web dashboard to visualize the proposed route to the end-user ......................................83
Figure 46. Network architecture of T4S4 .........................................................................................85
Figure 47. User application architecture with 5G connectivity, T4S4 ..............................................86
Figure 48. Screenshot of the multimedia playback application .......................................................87
Figure 49. Network architecture of T4S7 .........................................................................................90
Figure 50. OTA updates User application architecture with 5G connectivity, T4S7 .......................90
Figure 51. Screenshot of sensor data capture application ...............................................................91
LIST OF TABLES

Table 1. Trial locations and involved partners of the transport use case scenarios ........................................16
Table 2. Key performance indicators associated with the T2S1 use case ..........................................................24
Table 3. Summary metrics of selected experimental scenarios ...........................................................................42
Table 4. Target KPIs for T4S6 use case ........................................................................................................50
Table 5. Main radio parameters considered for the evaluation of 5G-NR technology in focused CoCA simulations .......................................................................................................................56
Table 6. Main messages parameters in focused CoCA simulations ........................................................................56
Table 7. T2S3 access network configuration ....................................................................................................70
Table 8. Key performance indicators associated with the T4S3 use case ...........................................................83
Table 9. Key user requirements .........................................................................................................................87
Table 10. Target KPIs for T4S7 use case ...........................................................................................................91
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>Two-Dimensional</td>
</tr>
<tr>
<td>3GPP</td>
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</tr>
<tr>
<td>4G</td>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>5G NR</td>
<td>5G New Radio</td>
</tr>
<tr>
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<td>5G Infrastructure Public Private Partnership</td>
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<td>AQI</td>
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</tr>
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<td>AR</td>
<td>Augmented Reality</td>
</tr>
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<tr>
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</tr>
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</tr>
<tr>
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<td>Cooperative Awareness Message</td>
</tr>
<tr>
<td>CCAM</td>
<td>Cooperative, Connected and Automated Mobility</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
</tr>
<tr>
<td>CLI</td>
<td>Command Line Interface</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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<td>Customer Premises Equipment</td>
</tr>
<tr>
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<td>Collective Perception Message</td>
</tr>
<tr>
<td>CR</td>
<td>Compression Ratio, Channel Occupancy Ratio</td>
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<td>Decentralised Congestion Control</td>
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<td>Decentralised Environmental Notification Message</td>
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<tr>
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<td>Evolved NodeB</td>
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<td>Evolved Packet Core</td>
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<td>European Telecommunications Standards Institute</td>
</tr>
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<td>Frequency Division Duplex</td>
</tr>
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<td>Green Light Optimal Speed Advice</td>
</tr>
<tr>
<td>gNB</td>
<td>Next Generation NodeB</td>
</tr>
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<td>Global Positioning System</td>
</tr>
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<td>Global System for Mobile Communications</td>
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<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
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<td>Gateway</td>
</tr>
<tr>
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<td>High-Definition</td>
</tr>
<tr>
<td>HLS</td>
<td>Hypertext Transfer Protocol Live Streaming</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
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<td>Heart Rate</td>
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<td>Hypertext Transfer Protocol</td>
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<td>Identifier</td>
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<td>Internet of Things</td>
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<td>Independent Opinion Poll</td>
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<td>Internet Protocol</td>
</tr>
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<td>Intelligent Transport System</td>
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<td>ITS-S</td>
<td>Intelligent Transport System - Station</td>
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<td>Key Performance Indicator</td>
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<td>Local Dynamic Map</td>
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<td>Light Detection and Ranging</td>
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<tr>
<td>LoA</td>
<td>Level of Automation</td>
</tr>
<tr>
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<td>Line of Sight</td>
</tr>
<tr>
<td>LTE</td>
<td>Long-Term Evolution</td>
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<tr>
<td>LWA</td>
<td>Long-Term Evolution – Wireless Local Area Network Aggregation</td>
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<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MAP</td>
<td>MapData Messages</td>
</tr>
<tr>
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<td>Multimedia Broadcast Multicast Service</td>
</tr>
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<td>MCE</td>
<td>Multicast Coordination Entity</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>MEC</td>
<td>Multi-access Edge Computing</td>
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<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<td>Machine Learning</td>
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<td>MQTT</td>
<td>Message Queuing Telemetry Transport</td>
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<td>Mean Square Error</td>
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<td>Maximum Transmission Unit</td>
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<td>Narrowband Internet of Things</td>
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<td>Non-Line of Sight</td>
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<td>National Marine Electronics Association</td>
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<td>Final Solutions for Transport Verticals Use of 5G</td>
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<tr>
<td>PPP</td>
<td>Point-to-Point Protocol</td>
</tr>
<tr>
<td>PPS</td>
<td>Pulse Per Second</td>
</tr>
<tr>
<td>PSNR</td>
<td>Peak Signal to Noise Ratio</td>
</tr>
<tr>
<td>PTP</td>
<td>Precision Time Protocol</td>
</tr>
<tr>
<td>QoE</td>
<td>Quality of Experience</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>RADAR</td>
<td>Radio Detection and Ranging</td>
</tr>
<tr>
<td>RAN</td>
<td>Radio Access Network</td>
</tr>
<tr>
<td>RAT</td>
<td>Radio Access Technology</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RDBMS</td>
<td>Relational Database Management System</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>ROC</td>
<td>Remote Operations Centre</td>
</tr>
<tr>
<td>RSRP</td>
<td>Reference Signal Received Power</td>
</tr>
<tr>
<td>RSU</td>
<td>Road Side Unit</td>
</tr>
<tr>
<td>RTT</td>
<td>Round-Trip Time</td>
</tr>
<tr>
<td>SA</td>
<td>Standalone</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SDK</td>
<td>Software Development Kit</td>
</tr>
<tr>
<td>SDR</td>
<td>Software-Defined Radio</td>
</tr>
<tr>
<td>SIC</td>
<td>Sensor Information Container</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>SLA</td>
<td>Service Level Agreement</td>
</tr>
<tr>
<td>SO2</td>
<td>Sulphur Dioxide</td>
</tr>
<tr>
<td>SoC</td>
<td>System on a Chip</td>
</tr>
<tr>
<td>SotA</td>
<td>State-of-the-Art</td>
</tr>
<tr>
<td>SPAT</td>
<td>Signal Phase and Timing</td>
</tr>
<tr>
<td>SRM</td>
<td>Signal Request Message</td>
</tr>
<tr>
<td>SSM</td>
<td>Signal State Message</td>
</tr>
<tr>
<td>SUMO</td>
<td>Simulation of Urban Mobility</td>
</tr>
<tr>
<td>SW</td>
<td>Software</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TeSo</td>
<td>Tele-operated Support</td>
</tr>
<tr>
<td>TLC</td>
<td>Traffic Light Controller</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>URLLC</td>
<td>Ultra-Reliable Low-Latency Communication</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Traverse Mercator</td>
</tr>
<tr>
<td>V2I</td>
<td>Vehicle-to-Infrastructure</td>
</tr>
<tr>
<td>V2N</td>
<td>Vehicle-to-Network</td>
</tr>
<tr>
<td>V2P</td>
<td>Vehicle-to-Pedestrian</td>
</tr>
<tr>
<td>V2V</td>
<td>Vehicle-to-Vehicle</td>
</tr>
<tr>
<td>V2X</td>
<td>Vehicle-to-Everything</td>
</tr>
<tr>
<td>VM</td>
<td>Virtual Machine</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>VRU</td>
<td>Vulnerable Road User</td>
</tr>
<tr>
<td>ZMTP</td>
<td>ZeroMQ Message Transport Protocol</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

This deliverable describes the Phase 3 trials setup of the transport vertical use cases of the 5G-HEART project. These trials contribute to the milestone MS6 (“Phase 3 trials of multiple verticals and final event”) from the perspective of WP4 (“Solutions for Delivery of Transport Vertical”). The described trials are based on the transport vertical use case scenarios defined in the 5G-HEART project deliverable D4.1 [1]. The contents of this deliverable are an update to the Phase 1 and Phase 2 trials described already in deliverables D4.2 [2] and D4.3 [3] respectively.

The deliverable contains the final Phase 3 solutions adopted for the transport vertical use cases as well as the final trial setups and application-level results. Detailed description of the network Key Performance Indicator (KPI) results and results analysis is provided in D6.4 [9].

1.1 Use cases and Phase 3 trials overview

Based on the initial transport vertical trial results reported in [2], the implementation work towards the final trials has been prioritised as shown in Table 1. In order to achieve in-depth validation of the identified key Fifth Generation (5G) functionalities for the use cases, five core scenarios have been selected as the main focus of the transport vertical. In parallel with the five core scenarios, a number of supplementary scenarios are also trialled with a focus on technology enablers, helping extend the knowledge gained from the large-scale trials of the core scenarios. Table 1 presents the overview of the transport vertical use case scenarios which have been investigated and trialled during the final phase of the 5G-HEART project.

Table 1. Trial locations and involved partners of the transport use case scenarios

<table>
<thead>
<tr>
<th>Use case scenario</th>
<th>Trial facility</th>
<th>Trial location</th>
<th>Scenario owner (other participating partners)</th>
<th>Other collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Core use case scenarios</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2S1: Smart junctions and network assisted &amp; cooperative collision avoidance (CoCa); Trial track</td>
<td>5Groningen</td>
<td>Groningen/Helmond, Netherlands</td>
<td>TNO (DYNNIQ)</td>
<td>collaboration with healthcare trials</td>
</tr>
<tr>
<td>T2S4: Human tachograph</td>
<td>5GTN</td>
<td>Oulu, Finland</td>
<td>VTT (POLAR)</td>
<td>-</td>
</tr>
<tr>
<td>T3S1: Tele-operated support (TeSo)</td>
<td>TUC test site</td>
<td>Chemnitz, Germany</td>
<td>NTUA (TUC, UOS)</td>
<td>-</td>
</tr>
<tr>
<td>T4S5: End-to-end (E2E) slicing</td>
<td>5GENESIS</td>
<td>Surrey, UK</td>
<td>UOS</td>
<td>-</td>
</tr>
<tr>
<td>T4S6: Vehicle sourced high-definition (HD) mapping</td>
<td>5GENESIS</td>
<td>Surrey, UK</td>
<td>EPI (UOS)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Supplementary use case scenarios</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2S2: Smart junctions and</td>
<td>N/A</td>
<td>N/A</td>
<td>CEA</td>
<td>-</td>
</tr>
</tbody>
</table>
network assisted & cooperative collision avoidance (CoCa); Simulation track

| T2S3: Quality of service (QoS) for advanced driving | TUC test site | Chemnitz, Germany | TUC (NTUA, UOS) | - |
| T4S1: Vehicle prognostics | 5GTN | Oulu, Finland | VTT | - |
| T4S2: Over-the-air (OTA) updates | 5GTN | Oulu, Finland | VTT | - |
| T4S3: Smart traffic corridors | 5GENESIS | Surrey, UK | WINGS (OCC, UOS) | - |
| T4S4: Location based advertising | 5GENESIS | Surrey, UK | EPI (UOS) | - |
| T4S7: Environmental services | 5GENESIS | Surrey, UK | EPI (UOS) | - |

1.2 Definitions

The following terminology and definitions are consistently being used across this document:

- **Roadside Unit (RSU):** A stationary infrastructure entity equipped with V2X capabilities. It can exchange messages with other entities supporting V2X applications. The RSU could be implemented in a Fourth Generation (4G) Evolved NodeB (eNB), 5G Next Generation NodeB (gNB) or in a stationary User Equipment (UE) [32].

- **Vehicle-to-Infrastructure (V2I):** The UEs, when equipped with V2I capabilities, can exchange messages containing V2I application information with an RSU or locally relevant application server.

- **Vehicle-to-Network (V2N):** The UEs supporting V2N applications can communicate with an application server via a Third Generation Partnership Project (3GPP) packet network.

- **Vehicle-to-Pedestrian (V2P):** The UEs supporting the V2P functionality can transmit messages containing V2P application information. Such information can be transmitted either by a UE in a vehicle (e.g., warning to pedestrian), or by a UE associated with a Vulnerable Road User (VRU) (e.g., warning to vehicle). The 3GPP transport of this information could be direct between UEs and/or via an infrastructure supporting V2X communication (e.g., On-Board Unit (OBU), RSU and application server).

- **Vehicle-to-Vehicle (V2V):** The UEs supporting the V2V functionality can transmit messages containing V2V application information (e.g. location, dynamics, and attributes). The 3GPP transport of these messages is predominantly broadcast-based. It may be direct between UEs and/or via an infrastructure supporting V2X communication (e.g., OBU, RSU and application server).

- **Vehicle-to-Everything (V2X):** V2X is an umbrella term that covers all 4 types mentioned above, i.e., V2I, V2N, V2P and V2V.

- **SAE levels:** The Society of Automotive Engineers (SAE) defines the following six levels of driving automation [33].

  0 – No Driving Automation,
  1 – Driver Assistance,
  2 – Partial Driving Automation,
  3 – Conditional Driving Automation,
4 – High Driving Automation,
5 – Full Driving Automation.

The classification is based on the degree of human involvement. For the lower automation levels (i.e., 0-2), the human operator is the main responsible for monitoring the driving environment and taking actions accordingly. For higher automation levels (i.e., 3-5), the automated system takes over the control of these tasks as the human operator becomes less involved.

1.3 Organization of this deliverable

Sections 2-13 provide descriptions of the Phase 3 trials for each of the considered scenarios, including the trial setup description (with testing and verification results reported in [9]):

- Section 2: T2S1: Smart junctions and network assisted & Cooperative Collision Avoidance (CoCA); Trial track
- Section 3: T2S4: Human tachograph
- Section 4: T3S1: Tele-operated Support (TeSo)
- Section 5: T4S5: End-to-End (E2E) slicing
- Section 6: T4S6: Vehicle sourced High-Definition (HD) mapping
- Section 7: T2S2: Smart junctions and network assisted & Cooperative Collision Avoidance (CoCA); Simulation track
- Section 8: T2S3: Quality of Service (QoS) for advanced driving
- Section 9: T4S1: Vehicle prognostics
- Section 10: T4S2: Over-The-Air (OTA) updates
- Section 11: T4S3: Smart traffic corridors
- Section 12: T4S4: Location based advertising
- Section 13: T4S7: Environmental services

Concluding remarks are provided in Section 14.
2 T2S1: SMART JUNCTIONS AND NETWORK ASSISTED & COOPERATIVE COLLISION AVOIDANCE (COCA); TRIAL TRACK

2.1 Description and motivation

As introduced in deliverables D4.1 [1], D4.2 [2] and D4.3 [3], the focus of the Smart Junctions use case is on providing time critical safety information at intersections to improve the overall traffic safety and efficiency at intersections and amongst corridors. The safety information at the intersection involves the exchange of precise traffic signal status information, vehicle information (e.g. location, speed, and trajectory), as well as location information of VRUs.

In this context, at the Helmond location of 5GRONINGEN test facility within the Netherlands, trials have been performed, combining this use case with a use case from the Healthcare vertical, “Remote Paramedic support”. The Healthcare trial on, ‘Remote Paramedic Support’, focuses on remote real-time video delivery from ambulance paramedics towards Chief Medical Officers (CMO’s) in hospitals for improved situational assessment and decision making.

By combining these trials, it becomes possible to reflect on real-life scenarios when performing the evaluation of multiple 5G technologies, considering that when 5G networks become widely available, multiple applications and services with different Quality of Service (QoS) requirements are expected to co-exist on the same 5G network.

One 5G technology which promises to support multiple applications and services is 5G network slicing. This technology allows for the creation of multiple virtual networks within a given physical network. In the context of 5G-HEART trials, we look at the tailoring and guaranteeing of QoS requirements and network capacity for specific services and applications. These network slices can extend across both the Radio Access Network (RAN) as well as the core network to provide a virtual end-to-end network. In this paper, we focus on the former.

2.2 Final setup

This use case scenario has been trialled on the 5GRONINGEN trial facility located in Groningen and Helmond, the Netherlands. The following section describes the architectures of the setup for the Phase 3 (final) trials of the 5G-HEART project, the combined trial of the Transport vertical with the Healthcare vertical.

2.2.1 Network architecture

As described in deliverable D4.3 [3], the 5GRONINGEN network architecture was upgraded and reconfigured to support 5G Standalone during the Phase 2 trials. With regard to this architecture, no changes have been made in the layout of the network for the final trials of the project, so the Figure 1 below is the same for the Phase 2 trials.
Even though the network layout has been unchanged, the configuration of the components within the network have been adjusted for 5G Standalone slicing. To that extent the configuration of the gNodeB has been upgraded as well as the configuration of the core network.

The gNodeB was upgraded to an operator-grade outdoor 5G Standalone base station with carrier frequency of 3.65 GHz (TDD), a maximum carrier bandwidth of 100 MHz, TDD downlink/uplink frame structure of DDDSU (10:2:2) and sub-carrier spacing of 30 kHz. As shown in Figure 1, the base station is deployed nearby an intersection of the highway A270 in Helmond, the Netherlands, with two directional antennas which aim to optimize network coverage along the highway.

For the Phase 3 trials we also implemented (RAN) Network slicing. Network slicing is a technology used to create multiple virtual networks within a given physical network, which can extend across both the Radio Access Network (RAN) as well as the core network for end-to-end QoS provisioning. In these evaluations we focus on RAN network slicing implemented in the used 5G Standalone base station. By introducing RAN slicing to the network, the network operator has direct control over the radio resource distribution between configured slices. This allows for guarantees to be made on certain QoS and capacity requirements posted by certain applications, even in an overloaded network.

Figure 1. Network architecture of the final trials of the Smart Junctions use case.
For the combined trials we configured three (RAN) network slices as shown in Figure 2. Starting with a default slice of lowest priority for general Internet traffic, followed by a medium priority slice for the video traffic of the H1C use case and a third, the highest priority slice, for the time critical Cooperative, Connected and Automated Mobility (CCAM) traffic of the T2S1 use case.

In our setup, a higher priority slice always has absolute priority over the lower priority slice(s). This means that the scheduling of traffic from a slice with highest priority will always be preferred by the RAN.

In what follows, the components will be described in more details together with the associated results.

### 2.2.2 User application architecture

For the Phase 3 trials at the Dutch 5GRONINGEN test facility the implementation with the connected intersection as used for the previous trials, has been combined with the application of the Healthcare vertical use case H1C Remote Paramedic support.

**The connected intersection architecture with ETSI MAP, SPAT, SRM and SSM messages**

For the Phase 3 trials an intelligent TLC from PEEK has been connected via a mobile edge to the 5GRONINGEN network. This facilitates the delivery of intersection topology and traffic light signal status information to the vehicles connected to the 5G network.

This traffic light signal status and intersection topology information is provided to the vehicles via ETSI SPAT and MAP messages [25]. Next to that, we also implemented priority requests via ETSI SRM [26] and SSM messages [27] for special vehicles like ambulances and fire engines.

This facilitates special cases when an individual vehicle, for example an ambulance or fire engine, is on its way to an accident, requests priority, if the schedule of the TLC allows, to instantly trigger a green phase on passing intersections. The vehicle can send an SRM to request priority, which will be answered by the RSU with an SSM. The SSM is generated by the TLC. Moreover, several authorisation steps must be taken to verify the authenticity of the priority request. Due to the disruptive nature of such requests, it is very important to restrict access to vehicles that really need it.
Figure 3 shows the information flow of Traffic Light Controller data going through the 5GRONINGEN network. The MQTT back-office server running in the edge of the 5G network acts as a message broker for the sending and receiving applications.

The vehicle position information and priority requests are published as ETSI CAM [28] and ETSI SRM messages respectively to the message broker. Via the message broker this information is forwarded to the corresponding Traffic Light Controller to be processed.

The intersection topology and traffic light signal status information are published to the message broker via ETSI MAP messages and ETSI SPAT messages. The Traffic Light Controller response and status of the vehicle’s priority request is published to the message broker via ETSI SSM messages. The vehicles can subscribe to the message broker at the edge of the network to receive the corresponding information.

The remote paramedic support architecture

For these tests, the remote paramedic on-site wears a so called BlueEye camera headset connected to a smartphone which streams the point-of-view video of the on-site paramedic to a Chief Medical Officer (CMO) within a hospital. The smartphone is connected (through a 5G SA capable OBU connected to a 5G network) to two servers in the control and user planes respectively: a server in charge of application management and control, while another server is dedicated to user-plane data (video-audio etc.) delivery.

The remote CMO, who can be located anywhere (home, office, hospital or on the move) can access the live video-audio feed (and vital data if any) using different types of devices (e.g., laptop, iPad, smartphone). Typically, a single dashboard is desired on the device to display the received video-audio and vital data, with which the CMO can easily switch between different types of patient information.

2.2.3 Hardware components

The Phase 3 trial network contains the following components, starting with the network components

- 5G Standalone gNB:
  - Running 5G Standalone at 3650 MHz with a Bandwidth (BW) of 100 MHz.
- 5G Core (5GC) network.
- IP based security cameras with object detection, e.g. vehicle and VRU tracking.
- Intelligent Traffic Light Controller with support for Emergency Vehicle priority request.
- Back-office edge server running an MQTT broker, hosting the object detections and traffic light status information.
User equipment at the vehicle side

- One OBU configured for both 5G SA and C-V2X.
  - 5G Standalone via Fibocom FM150-AE [29] + APU platform (Debian Linux device)
  - C-V2X via Quectel AG15 [30]

User equipment at the remote paramedic side

- Camera headset of RedZinc, coupled to an Android smartphone (Samsung Galaxy S20), which connects to the OBU inside the vehicle.

Roadside Unit for network KPI measurements

- Fibocom FM150-AE + APU platform.

### 2.2.4 Software components

The Phase 3 trial application architecture consists of components both on the vehicle side, residing within the OBU and the smartphone, and at the infrastructure side, running the intelligent Traffic Light Controller and a back-office server platform.

On the vehicle side, the OBU is functioning as a UE connecting to the network via 5G Standalone. The OBU’s application has two functions; one generating and publishing ETSI CAM and ETSI SRM messages to the network and another consuming the ETSI MAP, SPAT and SSM messages from the network.

On the infrastructure side, the back-office server is running an MQTT platform at which the intelligent Traffic Light Controller publishes its geographical layout, phase-timing, and priority request status information in the form of ETSI MAP, ETSI SPAT and ETSI SSM messages respectively and the vehicles publish their position information in the form of ETSI CAM messages.

Next to the above-described components for the Transport use case, the following components are added to support the healthcare use case: an Android application, installed on the smartphone, via which the remote paramedic can connect with the video server back-end and the BlueEye hot desk, which can be used by the CMO to receive the video streaming.

### 2.3 Testing and verification

The focus of the Phase 3 testing and verification has been on how the time critical CCAM traffic can be guaranteed while sharing the same network resources with the video traffic (for the H1C use case) and the general purpose (regular, consumer-type data) traffic via network slicing, in a more realistic ambulance scenario where the ambulance, for a large portion of the time, is on the move (in comparison to Phase 2 where there was no other traffic on the same network, see D4.3 [3])

#### 2.3.1 Methodology

The focus of the trials were on the initial 5G Standalone measurements for both the general network latency when introducing Edge Computing and Slicing and the throughput of the 5G Standalone network, as well as the TLC application layer E2E latency and the throughput and user experience quality of the remote support application. For the general delay and throughput measurements, the OBU used Ping and iPerf tools to measure the performance to different components within the network. To conduct these evaluations in a reproductive manner, we created a test scenario.

This scenario is depicted in Figure 4 that shows how the ambulance drives to the scene of the emergency (Steps 1-3), the paramedic examines the patient when arriving at the scene and in case necessary consults the remote CMO (Step 4), after which the ambulance drives towards the hospital with the patient on board (Steps 5-7). The used 5G Standalone base station is also depicted in this figure, noted as “GnB”, nearby the intersection. Pragmatically a TNO vehicle is used to emulate a real ambulance.
Each of the steps is described as follows:

- **Step 1**: at a parking lot on the highway, the OBU of the vehicle is connected to the 5G Standalone network.
- **Step 2**: after being successfully connected to the 5G Standalone network, the vehicle starts driving toward the intersection and the driver is being informed of the current phase-timing information of the upcoming traffic lights.
- **Step 3**: when approaching the intersection, the OBU automatically asks for a green-light priority; when a green-light priority is granted, the request is confirmed to the driver as well as the optimal speed to drive; at the intersection the vehicle turns right accordingly and drives to the scene of the emergency.
- **Step 4**: after examining the patient at the scene, the paramedic decides to consult the remote CMO by starting a video-audio streaming (H1C).
- **Step 5**: in consultation with the remote CMO, it’s decided to bring the patient to the hospital; the vehicle leaves the scene with the patient on board; the video-audio connection may be kept active on the way to the hospital, keeping on monitoring the patient and environmental conditions (H1C).
- **Step 6**: the vehicle drives back to the highway, when it approaches the intersection again asks for a green-light priority.
- **Step 7**: the vehicle turns left at the intersection and drives on the highway; the scenario ends when the OBU of the vehicle is out of coverage of the 5G Standalone network.

![Figure 4. Test scenario of the combined phase-3 transport and healthcare trials](image)

### 2.3.2 List of key performance indicators

The key performance indicators associated with the T2S1 use case at the start of the 5G-HEART project (see deliverable D4.1 [1]) are summarized in Table 2.

<table>
<thead>
<tr>
<th>Network requirements</th>
<th>Target values</th>
</tr>
</thead>
<tbody>
<tr>
<td>User experienced DL throughput</td>
<td>Medium (10 Mbps)</td>
</tr>
</tbody>
</table>
User experienced UL throughput | Medium (10 Mbps)
---|---
Broadband connectivity / peak data rate | DL: Low (20 Mbps) UL: Low (20 Mbps)
Latency requirements | Low (200 ms)
Interactivity | High (1000 transactions/sec)

### 2.3.3 Measurement and testing tools

For the phase-3 trials, the following measurement and testing tools are used:

- Ping for measuring the round-trip time (RTT) at the network layer.
- iPerf3 for measuring network layer throughput
- Green Light Optimal Speed Advice (GLOSA) application to measure Traffic Light status information application E2E latency.

In order to validate the influence of 5G Standalone slicing on the network performance, the general-purpose traffic is emulated by using a road-side unit (RSU) nearby the intersection, with a relatively short distance from and good radio condition towards the base station.

As we have observed during initial tests, the uplink of the CCAM traffic consumes little data due to it being only one vehicle connected to the network. Next to that, the camera of RedZinc may generate video-audio stream data with a throughput of no more than 15 Mb/s in the uplink, so hence we configured the RSU to send uplink data also with a throughput of around ~15 Mb/s.

To be able to see a significant effect on the network performance when enabling or disabling the slicing configuration, it was necessary to reduce the carrier bandwidth to 20 MHz. This emulates a 5G commercial network where a significant part of the overall bandwidth (e.g., of 100 MHz) is reserved or used by other applications. So, with this reduced bandwidth of only 20 MHz instead of 100MHz, the measured maximum uplink throughput is 15.7 Mb/s.

### 2.3.4 Final results

In this section, we compare the results of two network configurations, one setup with and another setup without network slicing enabled:

1. No priority slicing is configured, the CCAM traffic, the video traffic and the general-purpose internet traffic are scheduled by the base station with the same priority.
2. Three slices are configured, with different priorities, where the CCAM slice is assigned the highest priority, the video slice the 2nd highest priority and the general-purpose internet slice the lowest priority.

For each of the two cases, the vehicle performed four runs following the route and steps as described in Figure 4 and Section 3.3.1. Each run takes about 250-300 second. For the sake of simplicity, in the context below we show and compare the results of one single run of each of the cases. Note that the same/similar behavior in terms of throughput patterns has been observed among the four runs of a certain case.

Figure 5 shows the observed uplink throughput performance for the first case along the route. Here, “All vehicle traffic” refers to the sum of video traffic and CCAM traffic sent from the vehicle. At the start (Steps 1-3 of the route), “All vehicle traffic” only consists of CCAM traffic with a low data transmission demand, and therefore the general-purpose traffic could utilize almost all of the available radio resources (in this case the reduced bandwidth of 20 MHz) and reach an uplink throughput of around 15 Mb/s.
When the video traffic is started (at Step 4 and being turned on until the vehicle runs out of the coverage), “All vehicle traffic” is dominated by the video traffic and competes with the general-purpose traffic in the use of the available radio resources.

The results show that on average the general-purpose traffic is assigned about 50% of the radio resources and reaches an uplink throughput of around 7.5 Mb/s. The video streaming traffic, which could have potentially utilized the remaining 50% of the available throughput, only takes about 1.5 Mb/s. This may be explained by several factors that influence the throughput measurements such as modulation scheme used by the UE (at the vehicle) and parameters used by the video streaming application to adapt to lossy radio conditions. Since these are proprietary software components, further tests would be required to for a more precise analysis. Nevertheless, previous tests in a controlled lab environment using iperf traffic only in both UEs have shown that each UE takes approximately 50% as expected.

Figure 5. Observed uplink throughput of “All vehicle traffic” (H1C + T2S1) and general-purpose internet traffic

Figure 6 shows the observed uplink throughput performance of the second case along the route. In this case, the video traffic and CCAM traffic are explicitly separated since they use two different slices with different priorities.

Similar to the first case, at the start (Steps 1-3), the general-purpose internet traffic could utilize almost all of the available radio resources and reach uplink throughput of around 15 Mb/s. When the video traffic is started at Step 4, it has a higher priority in using the radio resources than the general-purpose internet traffic (note again that the amount of the CCAM traffic is so little that it has almost no effect in radio resource assignment although with higher priority). Therefore, the video traffic can reach a much higher uplink throughput (with higher video quality), at about 10-15 Mb/s at Steps 4-6.

During this period, some general-purpose internet traffic could still be scheduled using (remaining) radio resources not utilised by the CCAM and video traffic. When the vehicle drives away from the base station, the throughput of the video traffic drops although it still consumes most of the slots in the radio spectrum. When the vehicle drives further away from the base station, the received signal strength at the vehicle is so low that no video traffic can be transmitted which results in the general-purpose internet traffic again getting assigned almost all the radio resources.
2.4 Recommendations

These trials have shown that 5G Standalone network slicing is able to guarantee sufficient radio resources for the delivery of time critical CCAM traffic as well as video-audio streams on a 5G network that is used for multiple services simultaneously.

It is recommended to continue similar trial-based evaluations with a commercially deployed 5G network with more challenging network conditions and varying environments, including evaluation of certain network features (e.g., slicing, relaying) which are expected to be able to improve network and radio resource availability.

Latency hasn’t been measured, because our focus on throughput is sufficient to prove whether slicing has an advantage for a real-life mobility scenario where high-throughput streams are required. However, the latency of traffic in high priority slices may be influenced by traffic at the other lower priority slices in a scenario where the RAN is loaded. Hence, future work should also include latency measurements.

We have configured absolute priority slices in our RAN. This priority mechanism always grants all radio resources to the highest priority slice. Relative priority, which should offer more granular control over the radio resources between slices, will be more feasible in real-world scenario’s due to the QoS requirements of multiple real-world services combined in the same network. Dynamic Radio Resource Partitioning is not yet available in our setup at the time of writing. This technique promises control over the radio spectrum with slices and should be explored in future work. A holistic approach may also include business model study (see the first study in D7.4 [14]), since the aimed network availability (i.e. anywhere and anytime) and performance are not only about 5G network capabilities but also about business policies of stakeholders (e.g. who should invest in order to guarantee network availability and performance required by ambulance services).

Lastly, scaling this slicing setup towards a large nation-wide commercially available network is not trivial. The requirements for deploying (priority) slicing for numerous services on a commercially available network are not defined in this project and thus remain to be investigated in the future.
3  T2S4: HUMAN TACHOGRAPH

3.1 Description and motivation

The human tachograph service utilises wearable sensors to monitor the biosignals of professional drivers and provides guidance to prevent fatigue and improve wellbeing. Unlike most of the existing driver fatigue detection systems, human tachograph tracks both the live biosignals during driving as well as sleep and physical activity in long-term. The information from the human tachograph application can also be shared with other drivers and vehicles in the form of anonymised warning messages.

For this purpose, a wearables-based driver monitoring, and traffic warning system framework was implemented, which collects the sensor data and triggers the warning messages towards other road users over 5G based on the human tachograph driver condition analysis. This section describes the final trial setup utilised to measure the performance of the 5G network while serving the users of the human tachograph service.

3.2 Final setup

The final trial setup was deployed on top of the 5GTN-VTT test facility in Oulu, Finland.

3.2.1 Network architecture

Figure 7 presents the high-level network architecture for the final trials of the human tachograph service and use case scenario. The driver monitoring data in the form of live biosignals was collected using wearable sensor devices (heart rate monitors on chest belts) and streamed to the network in the Uplink (UL) direction using a 5G smartphone as Gateway (GW) device. The raw sensor data was received in the edge cloud to be used as an input in the driver condition assessment. The raw data can also be forwarded to the remote cloud and used in the long-term driver condition analysis. By exchanging information with the remote cloud, the edge cloud environment uses a combination of the live and long-term sensor data to provide more accurate assessment of the current status of the driver. The edge cloud environment also hosted the warning message triggering framework, which was used to notify the other road users in the area about increased risk caused by driver fatigue. The warning messages were distributed to the road user in the Downlink (DL) direction.

![Network architecture for the final trials of the human tachograph use case scenario.](image)

All architectural components depicted in Figure 7 were running locally at the 5GTN-VTT test facility in Oulu, Finland. The only remote component was the wearables services ecosystem running on Polar’s research servers, but as the transfer of data between the edge and remote clouds is only related to the maintenance and update of the long-term driver data in the human tachograph service architecture, it
was not part of the measured data path during the final trials. The hardware and software related to
collection and forwarding of the sensor data to the network was implemented and provided by Polar as
was the software related to the analysis of the data at the remote wearable’s services servers. All the 5G
network components and user devices as well as the warning message triggering framework were
implemented and provided by VTT.

3.2.2 User application architecture

As the focus in the final trials was to move the human tachograph service on top of the updated 5G SA
network configuration, the utilised user application architecture remained unchanged compared to the
Phase 2 trials presented in D4.3 [3]. In the network-centric service deployment, depicted in Figure 8,
the service components in the UL direction included the wearable sensor devices with integrated
software forwarding the sensor data from the wearable device to the smartphone as a continuous stream.
In the smartphone, the sensor data stream received from the wearable device was further forwarded to
the 5G network edge cloud and Polar’s research server in the remote cloud using Polar Sensor Data
Logger software. The algorithms running in the remote cloud as well as the API utilised to access the
analysed historical data were developed to support the specific parameters and information required to
assess the driver status. The current driver status analysis and warning message trigger framework was
running in the edge cloud and combined the two data branches and generated the warning messages in
the DL direction. The components listed in the boxes drawn with dashed lines in Figure 8 show other
potential data sources in the vehicle and cloud, but they were not part of the human tachograph trials in
the 5G-HEART project.

Figure 8. User application architecture for the final trials of the human tachograph use case scenario.
3.2.3 Hardware components

The network architecture utilised during the final trials contained the following hardware components:

- **Wearable sensor devices:**
  - Polar H10 heart rate monitor [16] measured the biosignals including Heart Rate (HR), Electrocardiogram (ECG), and Accelerometer (ACC), and broadcasted them continuously over a Bluetooth Low Energy (BLE) link.

- **UEs:**
  - Google Pixel 4 smartphone was receiving the biosignal data from Polar H10 and streamed them to the sender side measurement laptop over a WiFi link.
  - Telewell 5G USB modem was used as the main 5G UE in the final measurements.

- **gNBs:**
  - 5G NR Time Division Duplex (TDD) Rel-15/16 NSA/SA @ 3.5 GHz (band n78), BW = 60 MHz.
    - Macro gNB with 2 horizontal beams was used in the performance measurements.
    - 30 kHz subcarrier spacing, which corresponds to 0.5 ms slot duration.
    - 3/7 DL/UL time slot ratio and UL proactive scheduling with 0.6 ms grant interval for best case performance.
    - 4x4 DL and 1x4 UL MIMO configuration.
  - 5G NR Time Division Duplex (TDD) Rel-15 NSA @ 3.5 GHz (band n78), BW = 60 MHz.
    - Pico gNB was used in the scalability measurements.
    - 30 kHz subcarrier spacing, which corresponds to 0.5 ms slot duration.
    - 3/7 DL/UL time slot ratio and UL proactive scheduling with 4 ms grant interval for more realistic scalability.
    - 4x4 DL and 1x4 UL MIMO configuration.

- **EPC and 5GC:**
  - Software based core network services for the performance and scalability measurements.

- **Wearables services:**
  - A Virtual Machine (VM) server receiving the streaming sensor data in VTT’s edge cloud environment.
  - A server receiving the streaming sensor data and history data in Polar’s remote cloud.

3.2.4 Software components

The following software components were utilised in the final trial setup:

- **Polar Mobile Software Development Kit (SDK) [17]** enabled to read live data (streamed through BLE) directly from Polar sensors, including ECG data, ACC data and HR broadcast.

- **Polar Sensor Logger Android application [18]** implemented decoding of the H10 BLE signalling using the Polar SDK and visualisation of the biosignal measurements. The application was updated to include an MQTT publisher and additional sensor data parameters for the final trials. Polar Sensor Logger published the sensor data from a smartphone to the data brokers at the network edge cloud in the 5GTN-VTT test facility and Polar’s remote research server.

- **Polar Open Test Application Programming Interface (API) [19]** provided a direct information sharing link between the Polar ecosystem and research server as well as between the Polar research server and 5G network edge cloud environment for the historical data.
  - Estimation of fatigue levels for the day can be based on user’s sleep history (recent sleep amount and timing in relation to circadian rhythm).
Fatigue level prediction can also take into account daytime napping (not currently available in history data, but through manual notation).

- MQTT client (publisher) was running on a smartphone for publishing the biosignal data packets to the network.
- MQTT broker was running in the edge cloud for initial reception and forwarding of the published biosignal data packets.

MQTT client (subscriber) was running on a laptop or smartphone for receiving the warning messages in the network.

### 3.3 Testing and verification

In the final trials, the feasibility and scalability of the network-centric human tachograph service deployment and related traffic warning system was assessed using a 5G SA network configuration. The performance was measured mainly in terms of the achieved communication latency and reliability, but additional KPIs such as user experienced throughput, peak data rate, device density, interactivity, and area traffic capacity were also investigated as part of the service scalability tests. The driving route utilised in the outdoor measurements has been presented in section 6.3.4 of D4.3 [3].

#### 3.3.1 Methodology

The performance measurement setup utilised in the final trials is shown in Figure 9. Polar H10 heart rate sensor measured the driver’s biosignals (HR, ECG and ACC) and sent them over the BLE connection to an Android phone running the Polar Sensor Logger application. Utilising the ECG data, heart rate variability and breathing rate were also calculated in real-time in the Polar Sensor Logger application.

The phone published all the biosignals to a MQTT broker running at the network edge in parallel with the 5GC. The MQTT packets were captured by Qosium Probes which sent the relevant metadata to a Qosium Scope for KPI processing. Clock reference for Linux measurement laptops in the field was provided using Network Time Protocol (NTP) that is synchronised with Global Positioning System (GPS) National Marine Electronics Association (NMEA) timestamp and the Pulse Per Second (PPS) signal from the GPS receiver. This kind of setup was able to provide even ~10 µs synchronisation accuracy for different Qosium Probes with stationary vehicles. The synchronisation accuracy was somewhat decreased with moving vehicles but was still below ~100 µs, which was adequate for the conducted measurements.
The raw sensor data and warning messages transferred in the 5G UL and DL, respectively, as well as the measured values of the related one-way latencies between the utilised UEs and edge cloud instances were visualised for monitoring and demonstrations purposes with a Grafana dashboard shown in Figure 10. All live data show at the dashboard were first forwarded from the MQTT broker (sensor data in the middle column) and Qosium Scope (one-way latencies on the right) to an InfluxDB database, from which Grafana pulled the data for visualisation. The 2-week sleep data overview as well as the 24-hour fatigue forecast (shown as static images on the left) are based on the long-term historical data analysed at the remote servers and only occasionally updated.
The scalability measurement setup utilised in the final trials is shown in Figure 11. As the continuous data traffic in the human tachograph service focused in the 5G UL direction, the scalability test was performed by increasing the amount human tachograph users in the UL. The user equipment configuration with the Polar H10 heart rate sensor, smartphone and sender side measurement laptop was the same as in the performance measurements presented above. In addition to the physical user measured during the tests, emulated human tachograph users were added to the network by using Keysight UeSIM [20] that was connected to the same 5G cell as the sender side measurement laptop. A conducted connection was used to guarantee good channel quality also for the emulated UEs.

![Figure 11. Human tachograph final trials scalability measurement setup.](image)

3.3.2 List of key performance indicators

The final trials aimed to verify the functionality of the deployed human tachograph service components and validate the 5G SA performance in both the UL and DL directions when the human tachograph service was used by both stationary and mobile end users. Reliability was defined as the percentage of application packets that are successfully received within the pre-defined target timeframe. The key KPIs and their target values for the human tachograph service based on [10] and the analysis performed in D2.2 [34] were defined as follows:

- E2E message latency (target: 10 ms)
  - One-way UL message latency (target: 5 ms)
  - One-way DL message latency (target: 5 ms)
- UL and DL slice reliability (target: ≥99.99 %)
- User experienced UL and DL throughput (target: <10 Mbps)

The additional KPIs investigated as part of the human tachograph service scalability assessment and their target values based on the analysis performed in D2.2 [34] were:

- Broadband connectivity / peak data rate (target: <100 Mbps)
- Connection (device) density (target: 0.43-4.3*10³ devices/km²)
- Interactivity (target: 1000 transactions/s)
- Area traffic capacity (target: 0.0043-0.043 Mbps/m²)
3.3.3 Measurement and testing tools

The main measurement and testing tools utilised in the final trials were as follows:

- Kaitotek Qosium [21] was used to passively measure the network KPIs (throughput, latency and jitter) from the service traffic in both UL and DL directions. These directly measured KPIs are also used to assess the communication reliability indirectly as a function of the time constraint for a successful packet transfer.
- Keysight Nemo Handy [22] was used to measure the 5G cell coverage and signal strength/quality during the setup of the trials. The tool was also used to record and visualise the driving route used during the trials.
- Keysight UeSIM was used to generate emulated users/UEs to the 5G cell during the measurements. It was specifically used to provide controllable Control Plane (CP) and User Plane (UP) load to the network during the service scalability tests.
- Nokia BTS Site Manager/Web Element Manager was used to record and access the performance counters at the utilised Radio Access Network (RAN) components during the trials.
- Garmin GPS18x LVC [23] as used as the external GPS receiver for synchronising the laptops used as UEs (together with the 5G modems) in the field measurements.
- Trimble Thunderbolt PTP GM200 [24] with an external GPS antenna was used as PTP master for the server running the MQTT broker.

More information on the utilised measurement and testing tools as well as other tools provided by the test facility and utilised in the configuration and debugging of the trial setup during its deployment can be found from [10].

3.3.4 Final results

The detailed final trial results and analysis can be found in D6.4 [9].

3.4 Recommendations

Two major high-level findings were made from the results of the final trials. First, when it comes to the one-way latencies achieved with the human tachograph service traffic, the main challenges with the current 5G technologies were in the UL direction. Even though the mean latencies in the 5G UL were roughly half of those achieved in a 4G network and were in best cases close to the target KPI values set for the human tachograph use case, the latency variation, i.e., jitter, was still too high to reach good latency performance reliably. Secondly, despite the low amount of data generated into the 5G UL direction by each of the human tachograph service users, i.e., roughly 50 kbps, the maximum amount of user that could be supported with adequate service quality by a single 5G cells was 10. This was surprisingly low compared to the peak data rates achieved in the utilised network configuration.

These findings clearly indicate that even though 5G already provides significantly better performance than 4G and makes network edge-based deployments of latency-sensitive services feasible, more effort needs to be put into the optimisation of UL scheduling algorithms for continuous low data rate packet streams. As the packet data scheduling algorithms in the current 5G equipment are still more geared towards DL dominated eMBB traffic, the increasing support for URLLC and mMTC use cases in the most recent 3GPP releases should alleviate the problem when the related functionalities come into large-scale use also in commercial network deployments. In addition, the final trials made it clear that achieved 5G performance still significantly depends on the UE make and model in use. As 5G is still in early stages of its evolution, the capabilities of the chipsets and firmware utilised in the modems can vary drastically. This problem should be alleviated as the technology matures. However, the currently available 5G equipment should be thoroughly tested for performance critical use cases before taken into use in a production environment.
4 T3S1: TELE-OPERATED SUPPORT (TESO)

4.1 Description and motivation

The use-case scenario of Tele-operated support for remote driving refers to the remote control of a vehicle using the available mobile communication infrastructure. It does not assume any Road-Side Units (RSUs) deployed in the streets. A human operator located remotely sends control commands to the vehicle over the network, while at the same time, information about the vehicle’s state and its surroundings is properly transferred and visualized back to the operator. Teleoperated support can be utilized as a stand-alone service to support various applications and scenarios, ranging from mission critical situations under harsh environmental conditions to every-day automated transportation or industrial services. More importantly though, the application of remote driving can be complimentary or serve as a backup service of the autonomous/assisted driving mode. This form of remote driver fallback authority can help to bring autonomous vehicles’ technology to the consumer earlier by providing the desired advanced security and safety level.

To realize the communication chain from the vehicle to the remote operator and then, back to the vehicle, a V2N connection is established between the remotely controlled vehicle and the Remote Operations Center (ROC), where the remote human operator is located. Through the V2N wireless link the secure transmission of real-time data feed from the on-board vehicle's instrumental sensors and High-Definition HD cameras, as well as the GNSS position, is achieved. These data are properly visualized by the appropriately designed and developed user application’s Graphical User Interface (GUI), and, ultimately, utilized by a remote human operator to maneuver the vehicle. At this time, the control commands are transmitted via the V2N connection in the opposite direction of the communications, realizing in this way the TeSo service. Roughly speaking, the human operator analyses the presented video streams and sensor data, decides the desirable actions/manoeuvres, and inputs the appropriate control commands that are transmitted back to the vehicle over the network.

4.2 Final setup

In this section, the finalized TeSo service for remote driving, developed within the framework of the 5G-HEART project, is presented in detail regarding the designed end-to-end system architecture and the complete software implementation.

4.2.1 Network architecture

Figure 12 illustrates the end-to-end system architecture for the proposed TeSo service. The experimentation vehicle is equipped with a number of sensors and actuators capable of measuring and controlling its velocity, steering wheel angle, and throttle/brake position, together with four cameras mounted on each side (i.e., front, back, right, and left). As can be seen, the main components of the employed setup are:

- the Remote Operations Center (ROC), which serves as an interface with the human operator, displaying the received telemetry data/video streams and accepting the remote control/navigation input.
- the On-board Unit (OBU) that interfaces with the sensors, cameras, and actuators of the vehicle at a low level in order to capture operational and ambient data, make it available in a standard format to other HW/SW components, and translate the remote-control commands to signals compatible with the vehicle's actuators.
- the Remote Operations Center-Gateway (ROC-GW) that processes the data published by the OBU and acts as an intermediate point for the communication between the vehicle and the ROC, transmitting in the uplink to the remote location the video streams/sensor data and receiving in the downlink the remote control commands; and
the network infrastructure, which is responsible for realizing the communications between the ROC and the ROC-GW.

Figure 12. High-level overview of the TeSo service's architecture.

The Remote Operations Center (ROC) is located at a remote site and is composed of a GUI application that displays the received video streams and telemetry data to the human operator, while accepting as input the remote-control commands that must be transmitted to the vehicle. At the vehicle side, the ROC-GW, the OBU, and the various sensors/actuators are interconnected in a local mesh network, created by leveraging the capabilities and the features of the DRAIVE Link\(^2\) framework (i.e., node auto-discovery and publish/subscribe messaging pattern). The remote communications between the ROC and the ROC-GW are realized over the public network leveraging, among others, the 5G cellular technology. Specifically, the data transmissions over the network are realized using the publish-subscribe messaging pattern provided by the ZeroMQ asynchronous messaging library, using appropriate sockets (PUB or SUB) at the respective endpoints, and encapsulating the appropriate data objects into ZeroMQ messages.

**4.2.2 User application architecture**

The proposed TeSo service was implemented in C++ using the DRAIVE Link framework as a middleware to publish and subscribe to sensor data and actuator commands. In Link, the communication between nodes that are part of the same local mesh network is realized via messages using a publish-subscribe communication pattern. Messages carry different data as payloads and are sent between the nodes using network transport protocols. The data types have a FlatBuffers\(^3\) table format. Data objects hold the actual data, and they are an instance of the corresponding data types. The same data objects are used for the communication between the ROC-GW and the ROC over the 5G network using the ZeroMQ pub-sub pattern. The Flatbuffers table data types used for the TeSo service are the following:

1. **Camera** containing the JPEG-compressed frames of the four video streams.
2. **Vehicle State** retaining the vehicle's velocity in m/s and the corresponding timestamp.
3. **Automation State** including the currently set throttle percentage, brake percentage, and wheel angle in radians.
4. **GNSS Position** holding the latitude, longitude, and corresponding timestamp.
5. **Throttle Control** denoting the desired throttle percentage.
6. **Brake Control** conveying the desired throttle percentage.
7. **Steering Wheel Control** indicating the desired wheel angle in radians.

The overall TeSo service has two main endpoints which communicate over the 5G network: the ROC-GW node at the vehicle and the ROC GUI application at the remote location. Both these components, incorporate the following three functionalities:

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\(^2\) https://draive.com/docs/link2/

\(^3\) https://google.github.io/flatbuffers/
- Video streaming from the four cameras that are mounted on the vehicle (at the front, back, right and left side).
- Transmission/Reception of sensor and instrumentation data describing the current state of the vehicle and automation system.
- Remote control with appropriate commands based on the input of the human operator.

The ROC-GW node is a Command Line Interface (CLI) application. The required configuration is provided in the form of a JSON file (instance.json) that is given as an argument to the CLI application. The most relevant information is the IP address of the ROC that is needed for establishing the ZeroMQ sockets between the two endpoints and the JPEG compression quality (an integer between 1 and 100, with 100 being the best) corresponding to the cameras' frames. The ROC GUI application is the interface with the human operator.

### 4.2.3 Hardware components

The employed vehicle was a BMW i3 EV. The OBU, a Nuvo-4000 with Intel i7-3840QM 2.80GHz 4-core CPU and 16GB RAM, was interconnected with the following sensors via suitable Link nodes:

- four Allied Vision⁴ machine vision MAKO series cameras and
- a u-blox⁵ AEK-4T GNSS device.

Steering and throttling were remotely actuated by a dSPACE⁶ automation box and servomotors integrated into the vehicle and interfaced with an in-house MATLAB application. The ROC-GW and ROC software agents were hosted on two Dell Optiplex-7070s with Intel i9-9900 3.10 GHz 8-core CPUs and 32GB RAM, additionally equipped with a u-blox EVK-M8T and EVK-6T GNSS device, respectively. Traffic between the ROC-GW and ROC was securely transmitted using a SOC 2 compliant virtual private networking solution. 5G connectivity in-vehicle was realized via a commercial CPE router, from which signal and cell information were collated.

### 4.2.4 Software components

In the following, we provide details about the main software components of the developed solution.

#### 4.2.4.1 Remote Operations Center-Gateway (ROC-GW)

The ROC-GW node acts both as a subscriber with seven input pins and a publisher with three output pins (Figure 13). Generally, output pins assemble the desired data into messages and send them to other nodes by pushing them to the mesh, whereas input pins receive these messages and decompose them into data objects for further processing. In this particular case, the input pins receive the messages that carry data objects of types 1-4 described in Section 4.2.2 and forward them to the ROC over the 5G network. To that end, the respective Flatbuffers tables are encapsulated inside ZeroMQ messages and are transmitted to the ROC using ZeroMQ sockets and the pub-sub messaging pattern, with ROC-GW being the publishing endpoint and ROC the subscribing endpoint. Particularly for the four camera input pins (i.e., front, back, right, and left), the received messages corresponding to individual frames are first suitably processed (i.e., resolution and JPEG-compression) before being sent to the ROC. On the other hand, the output pins pack data objects of types 5-7 that correspond to remote control commands into messages and push them to the local mesh network in order to reach the OBU and, ultimately, the vehicle's actuators. These control data objects are first received from the ROC over the 5G network.

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using ZeroMQ sockets and the pub-sub message pattern in the reverse direction (i.e., this time, ROC is the publishing and ROC-GW the subscribing endpoint).

Figure 13. ROC-GW design.

In the local mesh network, the publisher announces the types of data that are available for subscription. This comprises the publisher's offer. A subscriber can subscribe to this offer either partially or to its entirety according to his demand. A subscription is defined by mapping data fields of the publishers' offers to corresponding data fields of the demand of each input pin. The subscriptions and corresponding mappings for ROC-GW are described in the `instance.json` file, which additionally contains other user-defined variables such as the IP address of ROC and the JPEG compression level that should be applied to the video frames.

4.2.4.2 Remote Operations Center (ROC)

The ROC GUI application (Figure 14) was implemented leveraging the Qt5 framework and its signals and slots mechanism, according to which separate threads are used for receiving data objects of types 1-4 (see Section 4.2.2) from the ROC-GW using ZeroMQ SUB sockets and, after the required processing and data type conversions, suitable signals connected to the appropriate display slots of the main window's widgets are emitted and the respective information is presented to the operator. More precisely, there is a separate thread for receiving:

- the video frames of each camera that are ultimately displayed at the four screens comprising the bulk of the main window,
- the GNSS position coordinates that are used to draw a marker at the 2D map (written in QML by leveraging the Open Street Map Plugin) located at the upper right corner of the window, and
- the vehicle and automation state telemetry data describing the current conditions of the vehicle that are reported in the upper left corner of the window.

The main window with all its component widgets is constructed by the main (or GUI) thread, which is also responsible for obtaining the remote operator's input (either from the push buttons located at the bottom of the window or via the arrow keys of the keyboard) and sending the corresponding data objects of types 5-7 to the ROC-GW, using ZeroMQ PUB sockets. The four widgets displaying the video streams from the vehicle’s on-board cameras comprise the bulk of the application’s main window. In the upper right corner, a 2D map illustrates the trace of the vehicle that is constructed based on the received GPS coordinates. In the upper left corner, telemetry data describing the current state of the

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automation system and the vehicle is updated according to the information received from the ROC-GW. Finally, the bottom part of the window is dedicated to the remote control. In the middle, there are four push buttons for entering the desired brake/throttle and steering input (alternatively, input can be given via the arrow keys of the keyboard). To the left, the user-provided angle is displayed in degrees, along with the respective selected increment step. To the right, a bar displays the user-provided throttle (or brake) percentage in green (or red) colour, together with the respective selected increment step.

Figure 14. ROC GUI application.

Regarding throttle and brake control, taking into account that the actuators remember and maintain the last received value, input is obtained from the operator and transmitted to the vehicle in the appropriate data type by adding or subtracting a predetermined increment every time the respective buttons or arrow keys are pressed. Regarding the steering wheel control, the current (desired) angle is continuously transmitted every 100ms. When the respective button or arrow key is pressed, the angle is increased (for the left direction) or decreased (for the right direction) at a predetermined rate. Finally, when no button/key is pressed the angle is moving towards 0 at a fix rate.

4.3 Testing and verification

In this section, the experimental setup of the TeSo service's validation trials in a real pilot over a commercial 5G NSA network deployment is analyzed together with the measurement methodology followed during experimentation. The field trials took place in a rural environment with a large number of cellular users. The 5G connection between the vehicle and the base station was operating in band n3 (UL: 1770.1 MHz, DL: 1865.1 MHz) and band n77 (UL: 3450.0 MHz, DL: 3450 MHz) of the spectrum. The 5G receiver node emulating the user equipment was deployed inside the research vehicle. The trials were conducted during office hours on weekdays, and the vehicle's velocity was up to 25 km/h. The distance between the BS and the vehicle varied from 60 to 120 meters. The remote operation center was located in Chemnitz, Germany, around 36 km away from the vehicle. Preliminary experimentation was conducted in the field to investigate the KPIs, availability, and reliability and obtain a fine-grain image of the provided 5G performance. Moreover, it should be noted that during the trials, the 5G signal was degraded by many factors such as Non-Line-of-Sight (NLOS) propagation, windows, trees, and house walls penetration. As shown in Figure 15, the trials occurred over a wide RSRP range running from -62 dBm to -87 dBm.
4.3.1 Methodology

Figure 16 depicts the testing and measurement setup employed during the validation trials. As can be seen, the end-to-end chain of the developed TeSo service comprises three parts:

1. the local mesh network at the vehicle side interconnecting the vehicle's sensors and actuators, the OBU, and ROC-GW,
2. the GUI application at the remote location that brings the human operator into the control loop of the vehicle, and
3. the network infrastructure (including 5G functionality) realizing the communications between ROC-GW and ROC.

The typical end-to-end sequence of steps is as follows. First, the four cameras mounted on each side of the vehicle and the rest of the sensors capture ambient and operational data, which are processed and transformed into a predetermined standard format by the OBU and ultimately reach the ROC-GW (i.e., vehicle integration). Then, the data is transmitted over the network to the ROC application using the publish-subscribe messaging pattern of the ZeroMQ library. There, the video streams, and the other telemetry data are presented to the human operator, who processes this information, decides the proper course of action, and issues the corresponding remote-control commands (i.e., human cognitive process). These are transmitted back to the ROC-GW over the network, and they go through the OBU to finally reach the appropriate actuators of the vehicle.

Within the scope of the conducted validation trials, we focus on evaluating the performance of the aforementioned network component. The remaining two components are considered constants and not relevant for our purposes that primarily regard 5G mobile communications. Vehicle integration is fixed at a hardware level and hardwired, whereas the human operator's cognitive process and reaction time cannot be directly measured. Moreover, it is not possible to match the exact data (e.g., video frames) that instigated a specific reaction from the operator. Taking all the above into consideration, we perform measurements (i.e., capture the outgoing and the incoming traffic) separately for each data type on the indicated monitoring points (points 1-2 and 3-4 in Figure 16) in the UL and the DL between the ROC-GW and the ROC.
4.3.2 List of key performance indicators

Remote driving relies on the mobile network infrastructure. The most critical Quality of Service (QoS) parameters include (i) latency (regarding both the execution of the operator’s commands and the transmission of vehicle’s sensor information back to the operator), which can significantly affect cognitive functions such as spatial cognition, sense of presence, and awareness, and (ii) throughput/bandwidth, which is directly related to the ability of the operator to accurately perceive the vehicle’s environment and state. During the field trials, the vehicle was remotely controlled from about 36 km away, and raw measurements were collected, capturing the exchanged traffic between ROC and ROC-GW. Said measurements were later post-processed to calculate relevant KPIs for the downlink (DL) and uplink (UL) communications. Specifically, the quantitative analysis regards the achieved one-way latency, jitter, throughput, and packet loss for each data type stream, defined as follows:

- **one-way latency**: the mean of the time differences of the reassembled ZeroMQ Message Transport Protocol (ZMTP) messages recorded at the respective source and destination endpoints,
- **jitter**: the mean of the absolute time differences between consecutive reassembled ZMTP messages,
- **throughput**: the mean throughput of the underlying TCP streams calculated over the whole duration of each test case iteration, and
- **packet loss rate**: the proportion of lost segments for the respective TCP streams.

Generally speaking, each of the employed data types analyzed in Section 4.2.2 corresponds to a different data stream between ROC-GW and ROC that is realized over distinct ZeroMQ sockets. Separate values for the one-way latency, jitter, throughput, and loss rate can be calculated for every data stream.

4.3.3 Measurement and testing tools

As previously described, the performance of the TeSo service application is evaluated by capturing the outgoing and incoming traffic at the two devices hosting ROC-GW and ROC. To achieve this, we employ the tcpdump command-line packet analyser on the appropriate network interfaces with a Boolean expression that indicates the underlying port range used by the service, and we record the matching traffic in two PCAP files. Moreover, the required clock synchronization of the two hosts is accomplished via their Pulse-Per-Second (PPS) synchronization to the GNSS reference time, attaining a mean PPS signal jitter of 1-20 μs. These raw measurements are post-processed by leveraging the Wireshark network protocol analyser. In particular, the ZeroMQ Message Transport Protocol (ZMTP)
messages exchanged between ROC-GW and ROC are decoded using the ZMTP Wireshark Dissector plugin. The corresponding messages are identified, and the respective one-way latencies and jitter are computed with a Python script based on the Pyshark packet parsing module. Throughput and packet loss are calculated over the underlying TCP streams using the statistics tools provided by Wireshark.

### 4.3.4 Final results

A large number of brief experimental rounds with the research vehicle being actively controlled remotely from a distance of around 36 km were conducted over several weekdays during office hours. During the trials, we collected approximately 500 minutes of raw measurements and video recordings. The measurements captured the traffic exchanged between the vehicle and the remote operation center while conducting different manoeuvring scenarios, i.e., straight course, right turn, lane change, and parking. After proper network and packet analysis, the quantitative analysis of the raw measurements provides numerical results for the main network KPIs and valuable insights into the network's performance and stability. Table 3 provides an overview of the main results of interest for a small subset of those experimental scenarios. The selected rounds pertain to two different days in order to document the proposed service's behaviour under varying environmental conditions.

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<th>Data Stream</th>
<th>Mean Latency (μs)</th>
<th>Jitter (μs)</th>
<th>Mean Throughput (bps)</th>
<th>Loss Rate (%)</th>
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8 https://github.com/whitequark/zmtp-wireshark
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The obtained results reveal that a one-way latency ranging between 20 and 40 ms can be achieved, providing an acceptable and even sufficient performance for slow-speed vehicular use-case scenarios, as empirically evaluated by our conducted trials. The loss rates are kept low, indicating the reliability and availability of the TeSo service when performed over 5G communications. On the other hand, the mean throughput values vary depending on the transmitted data stream and the employed configuration of the TeSo service. At the same time, minor variations can also arise due to the alternation of line-of-sight and non-line-of-sight propagation between the vehicle and the serving base station. More extensive results and comprehensive analysis can be found in the deliverable D6.4 [9].

## 4.4 Recommendations

The conducted validation trials have verified that 5G technology can effectively support tele-operation for slow-speed vehicular use-case scenarios, even when the underlying network infrastructure is non-optimized. In such use-case scenarios, the effect of jitter is more severe than end-to-end delay, directly impacting the stability and consistency of the remotely located operator’s interaction and control over the vehicle. Both the numerical and empirical validation results reveal that an acceptable performance with respect to jitter can be achieved, particularly enabling applications that involve haptic control, such as remote machinery operation. Apart from the optimization and proper configuration of the underlying network infrastructure, the designed and developed TeSo service itself provides several other degrees of freedom that can lead to improved performance, ranging from the hardware, software, and even the employed technologies. A finer vehicle integration combining different nodes within the vehicle in a unified manner over the same device can reduce the measured latency. Moreover, adjusting the JPEG compression level of the camera frames can yield further improvements in the achieved UL throughput. Finally, the use of advanced features of the 5G NR (e.g., network slicing and the deployment of services at the edge of the network) can ameliorate the TeSo service’s performance both from the spectral and response time perspectives.
5 T4S5: END-TO-END (E2E) SLICING

5.1 Description and motivation

The 5GENESIS slicing-as-as-service (SaaS) functionality can be exploited to trial selected 5G-HEART use case scenarios. The trials and measurements in T4S5 therefore focus on the EtE performance of 5G CN-slicing (and will eventually evolve to include also RAN resource slicing).

5.2 Final setup

The initial baseline setup for the slicing experiments have been presented in Section 14.3.4 of the deliverable D4.2 [2]. The initial network setup consisted of the following components:

- Core: Rel.15 4G Core NSA,
- Control Plane: 4G RAN,
- User Plane: 5G RAN (Huawei Commercial),
- UE: 5G CPE.

The 5G CPE, connected to both the eNB and gNB according to an NSA deployment, hosts an iPerf client that is interacting with an Iperf server and controlled via Ethernet using the Test Automation Platform (TAP) from Keysight®. The reader is referred to the Deliverables D6.1 [6] and D2.3 [7] of 5GENESIS for more details about the experimentation methodology and test case description, respectively.

In-house development of Rel. 16 SA core components completed during phase 3 enabling final trials and experiments. Furthermore, deployment Release B of 5GENESIS software components was also completed during phase 3. Also, due to a number of security vulnerabilities (identified & associated with Ubuntu v.16 OS, that was used in Release B of 5GENESIS), the operating systems on a number of servers were upgraded to v.20 and to ensure compatibility, a number of existing software components in Release B, had to be upgraded and tested for correct functionality.

The final trials setup consists of following:

- Core: Rel.16 4G Core SA, eMBB slice
- Control Plane: 5G RAN,
- User Plane: 5G RAN (Huawei Commercial), MU-MIMO capable
- UE: 5G commercial (Huawei P40 pro).

5.2.1 Network architecture

The detailed description of the utilised 5GENESIS architecture can be found from Section 14.2.1 of the deliverable D4.2 [2].

5.2.2 User application architecture

N/A.

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9 https://www.keysight.com/upload/cmc_upload/All/TapDeveloperGuide.pdf
5.2.3 Hardware components

The 5GENESIS test facility offers access to a range of 3GPP and non-3GPP Radio Access Technologies (RATs) available on the UOS campus. Full list of the 5GENESIS supported RATs are reported in Section 14.2.3 of the deliverable D4.2 [2].

5.2.4 Software components

The most relevant entities of the 5GENESIS architecture from the experimenter (i.e., 5G-HEART) perspective, are the Slice Manager, Open API and the Portal, that are detailed in Section 14.2.4 of the deliverable D4.2 [2].

5.3 Testing and verification

5.3.1 Methodology

Detailed description of the testing methodology can be found in Section 14.3.1 of the deliverable D4.2 [2].

5.3.2 List of key performance indicators

The key metrics considered are:
- E2E slice deployment time (a.k.a. “service creation time”)
- DL/UL throughput
- Latency and Jitter

Note however that E2E slice deployment time, according to detailed methodology described in section 4.2 of 5GENESIS deliverable D3.3 [8], is composed of (i.e. is sum of) following components:
- Network Service (NS) placement time
- NS provisioning time
- NS deployment time
- Transport network deployment time (via the WIM)
- Radio configuration time

5.3.3 Measurement and testing tools

The measurement and testing tools of the trial facility are exploited during T4S5 trials. In particular, the following components are used:

- Performance Monitoring tools, incl. PING and iPerf TAP plug-ins
- InfluxDB (storage).
- Grafana (visualization).

Detailed description of the measurement and testing tools can be found from Section 14.3.3 of the deliverable D4.2 [2].

5.3.4 Final results

The final results are reported and discussed in D6.4 [9].
5.4 Recommendations

The trials results as reported in [9] indicate that the slicing mechanism operating together with 5G SA configuration, on the Surrey platform, is fit-for-purpose and provides a reliable service. With the adoption and future deployments on next-generation radios capable of radio-resource slicing, full E2E slicing can be realized, given that latest generation of commercial UEs and 5G modems are already capable of supporting multiple, simultaneous slices.
6 T4S6: VEHICLE SOURCED HIGH-DEFINITION (HD) MAPPING

6.1 Description and motivation

AVs do not only require on-board sensors to perceive the world around them, but also HD maps to aid their decision making. HD maps of roads and infrastructure will take years to capture and consolidate. There is the added issue of dynamic changes to these maps over time.

As such, an innovative means to collect and maintain up to date data would be to crowdsource this information through on-board cameras and sensors which would stream back to a regional or central service, firstly to establish baseline maps and subsequently to manage change detection.

As one of the most important of human inventions, man has been making maps for millennia. People have created and used maps to help them define, explain, and navigate their way through the world and beyond. These maps initially were in the form of two-dimensional drawings and eventually took the form of three-dimensional globes. Modern maps of the old and new worlds were developed during the age of discovery. The last century has ushered in the information age where the power of computing, connectivity and storage has allowed us to digitise maps and transmit real-time location information via satellite technology. These maps are commonly used in smartphones through the use of applications such as Google Maps and also in vehicles (e.g. TomTom and Garmin for road vehicles).

For Lyft, maps are a key component to building self-driving technology. Unlike regular web map services which are in wide use today for turn-by-turn navigation, AVs require a new class of HD maps. Current maps and mass market location-based tracking using GNSS technology provides accuracy within a range of ten meters. HD maps for AVs need to represent the world at a centimetre level resolution, which is orders of magnitude greater than the resolution that map services offer today.

AVs demand such a high resolution because they need to routinely execute complex manoeuvres such as nudging into a bike lane to take a turn and safely passing cyclists. For example, marked bike lanes in Europe are typically 1.2 – 1.5 meters wide at a minimum, but are recommended to be between 1.5-2.5m in width. Other factors such as the type of road or junction, distance from the kerb, road signage as well as other considerations impact the design of these lanes. Centimetre level accurate maps are a must for an AV to be able to confidently reason about its position within a lane, assess distance from vehicles, cyclists, road infrastructure and potentially unique road features (e.g. potholes or other road conditions) to confidently take action.

Several mapping and self-driving companies have already started to produce and consume HD maps. However, it is still early days in terms of how these maps are being built, the richness of information they contain, and how accurate they are. Companies are iterating quickly on making these HD maps better and as such there is little standardisation between various providers and consumers, but this is being investigated in the UK by British Standards Institution (BSI) with Ordnance Survey. Therefore, the creation and management of HD maps forms a specialised function in the autonomy stack of AVs.

6.2 Final setup

This use-case scenario was trialled on the 5GENESIS trial facility located in Surrey, UK.

6.2.1 Network architecture

The considered network architecture during sensor upload is shown in Figure 17. The HD mapping application should be running on both the OBU and cloud mapping server.
6.2.2 User application architecture

The functional architecture on the user application side is shown in Figure 18. The OBU is based on Ubuntu Linux/Robot Operating System and uses a standard Intel SoC. Application is written portably in the C++ language native to the platform. The sensors like LiDAR, GPS and 5G CPE are interfaced, by which the sensors data is streamed to the backend. The server uses standard server HW based on Intel and runs an offline mapping Application.

6.2.3 Hardware components

The required HW components to conduct the trials are the following:

- OBU: This consists of an Intel-based board running Ubuntu Linux.
- LiDAR: SLAMTEC RPLIDAR A3 LiDAR\(^ {10}\). This is a 2D LiDAR capable of gathering scans.
- GPS: A highly accurate GPS module is interfaced to the system.
- 5G CPE: Huawei LF 7880 CPE\(^ {11}\). This is the HW to access the 5G network over WiFi and Ethernet interfaces.
- Server: These are standard datacentre servers running Linux.

6.2.4 Software components

The required SW components to conduct the trials are the following:

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\(^{10}\) [https://www.slamtec.com/en/Lidar/A3](https://www.slamtec.com/en/Lidar/A3)

\(^{11}\) [https://consumer.huawei.com/en/routers/5g-cpe-pro/](https://consumer.huawei.com/en/routers/5g-cpe-pro/)
- **Client App**: This is a C++ application to upload sensor data from LiDAR and other sensors and location info from GPS to the backend server.
- **Upload and Mapping Apps**: Cloud applications to store and analyse uploaded data.
- **Network Middleware**: Uses standard TCP/IP available in the system.
- **Various Drivers** (used to interface LiDAR, GPS and 5G CPE to the system).

### 6.3 Testing and verification

#### 6.3.1 Methodology

Testing was carried out by running the client/server applications and measuring KPIs by inserting logs into the code.

#### 6.3.2 List of key performance indicators

The user requirements associated with this use case scenario have been analysed and converted into a set of network KPIs. Table 4 presents the resulting list of network requirements together with their target values.

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<th>Target values</th>
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<td>User experienced DL throughput</td>
<td>Low (\leq 1) Mbps</td>
</tr>
<tr>
<td>User experienced UL throughput</td>
<td>High (100 Mbps)</td>
</tr>
<tr>
<td>Latency requirements</td>
<td>Low (100 ms)</td>
</tr>
</tbody>
</table>

#### 6.3.3 Measurement and testing tools

No third-party testing tools were used. The measurements are taken by inserting logs into the code.

#### 6.3.4 Final results

The final results are reported and discussed in D6.4 [30].

### 6.4 Recommendations

It was found that the network bandwidth was scalable enough to give the necessary guarantees for sensor data upload. The map generation being a non-real-time activity, latency considerations were not important. As multiple versions of same sensor data were designed for redundancy, reliability was also not of main concern. As the traffic was almost entirely in upload direction the KPI measurements were done in upload direction. Data being continuously uploaded in a streaming mode; roundtrip performance metrics were also not important for this use case. Although it was found that the upload data rates were far lesser than that in reverse direction, it was proven to be sufficient. Further optimizations are possible wherein the sensor data can be better curated, compressed etc.
7 T2S2: SMART JUNCTIONS AND NETWORK ASSISTED & COOPERATIVE COLLISION AVOIDANCE (COCA); SIMULATION TRACK

7.1 Description and motivation

As introduced in deliverable D4.1 [1], this use case focus on improved VRUs/vehicles safety in complex road environments such as urban intersections. Context awareness and cooperation between drivers is a key aspect for the Cooperative Collision Avoidance (CoCA) system to ensure safe and efficient navigation through intersections, lane changing, overtaking, etc. To this end, we consider a CoCA system, where various vehicles carry embedded ranging sensors (LiDAR, RADAR, etc.):

- to construct local probabilistic occupancy maps (which models the local scene perceived by the vehicle with pixels representing a zone occupied by an obstacle) or
- to generate Collective Perception Messages (CPM) which provides a list of obstacles.

The latter are transmitted to a fusion center such as the Road Side Unit (RSU) or gNodeB / Mobile Edge Computing (MEC) through a V2X connectivity for further processing. Thus, the RSU/gNodeB can gather all available information from vehicles to build the global occupancy map / merged CPM and recreate the whole scene of the evaluated zone. This fusion step is described in D4.3 [3] for local occupancy maps and CPM messages. At this stage, the RSU/gNodeB can either share the global map / merged CPM or send a simple DENM to warn the vehicles in case of collision risk.

This simulation work aims to complement the field trials by evaluating large-scale performance. Thus, in the first 2 phases of the project, we evaluated the impact of V2V/V2I 4G LTE-V2X connectivity (sidelink) on CoCA application and we derived the best compromises between the communication configuration and obstacle detection capabilities.

In phase 3, the performance of Vehicle-to-Network (V2N) connectivity based on the 5th Generation - New Radio (5GNR) as a support to CCAM, in light of both network and Multi-access Edge Computing (MEC) deployments is investigated. Focusing on the canonical centralized CoCA use case that involves several vehicles in an intersection environment, we assess the link reliability and the End-to-End (E2E) latency of all the messages involved in the CoCA process (from/to interconnected MECs hosting the centralized CoCA application), while assuming different deployment configurations.

In this phase, we will also show how 5G can contribute to higher Automated Driving (AD) levels and hence, more generally, to better road traffic efficiency and safety with 5G-boosted collective perception capabilities (in comparison with standalone vehicle perception only based on onboard sensors).

7.2 Final setup

7.2.1 Network architecture

Figure 19 shows the overall system architecture supporting a CoCA system assuming the support of Vehicle-to-Network (V2N) 5G NR connectivity with respect to gNodeB, as well as inter-connected Multi-access Edge Computing (MEC) hosting the centralized CoCA application. We consider both UEs and gNodeB as ITS-Stations (ITS-S) following an ITS protocol architecture:

- Facilities Layer to enable the CoCA, CPM, CAM and DENM related services.
- Access layer for the physical (PHY) and medium access control (MAC) based on cellular V2N 5G NR.
Information collected by vehicles is stored and processed by the on-board LDM system. Physical sensors (e.g., radar, camera, Lidar) and navigation system are used to extract a list of obstacles which is then included in CPM message. Then, this high-level information is sent through 5G NR connectivity.

In a 5G-based centralized CoCA application, a CoCA service hosted in a MEC system first interprets the information from side vehicles, before transmitting to all vehicles a merged CPM message containing all detected obstacles. Then, gNodeB can either send event-DENM messages in case of risk of collision or send messages to share the global CPM with the UEs. Note that UEs are assumed to have an on-board CoCA system to interpret the merged CPMs or the warning messages sent from the RSUs. Hence, we assume herein that low-latency interfaces should be available to support information exchanges between services running on neighbouring MECs.

We also consider several MEC deployment configurations, including fully decentralized (i.e., 1 MEC per gNodeB and highly centralized (i.e., one per operator data center) schemes.

7.2.2 User application architecture

N/A

7.2.3 Hardware components

N/A

7.2.4 Software components

A road intersection scenario has been considered, where vehicles transmit CPMs to a fusion center via the cellular 5G NR connectivity. The CoCA service, hosted in a MEC system, executes the fusion of CPM messages in order to generate a merged CPM that will be broadcast, every $T_{CPM} = 100$ms, to all vehicles in the cell. The fusion of CPMs obstacles is important in order to maximize perception gains and obstacles detection capabilities. The fusion algorithm is detailed in D4.3 [3].
In order to simulate this scenario, we consider a simulation framework (Figure 20) that consists of four modules:

- **Physical mobility module**: models realistic road traffic of a real-life urban intersection using Simulation of Urban Mobility (SUMO).
- **V2X connectivity module**: NS-3 simulation of messages exchange between vehicles and fusion center, via 5G NR connectivity, based on mobility traces generated in SUMO. The simulator includes the LENA 5G NR module [12] which is interfaced with the CoCA traffic scenario.
- **CPM generation module**: generates CPMs (following ETSI generation rules), based on Lidar sensor model.
- **CPM fusion module**: the local generated CPMs will be gathered by the fusion center while considering V2X connectivity. The fusion center executes the fusion algorithm such as described in D4.3 [3].

![Figure 20. Simulation modules and the interaction among them.](image)

### 5G NR

In NS-3, the Radio Access Network (RAN) is simulated. At the physical layer level, the numerology is set to 2, which supports shorter frame transmission and thus, low latency communications. A dynamic Modulation and Coding Scheme (MCS) is applied for better link adaptation. Each Time Division Duplex (TDD) slot contains 10 OFDM data symbols that are flexibly shared between UL (higher priority) and DL data scheduling. Regarding propagation, we consider the standardized 3GPP Urban Macro Cell (UMa) channel model defined in [13] including both conditional path loss, shadowing, fast fading parameters. In terms of medium access control, both Orthogonal Frequency Division Multiple Access (OFDMA, for DL only) and Time Division Multiple Access (for UL and DL) are supported. Physical Resource Blocks (PRBs) are evenly allocated to multiple users by a simple Round Robin scheduler. Finally, so as to improve link reliability, the Hybrid Automatic Repeat reQuest (HARQ) protocol is activated with a maximum of 3 re-transmissions (i.e., 4 transmissions).

In NS-3, the RAN latency between a source and a destination (e.g., typically, for an UL CPM message from a vehicle up to the gNodeB) can be simulated up to the application level, while accounting for jitter at the radio level depending on link quality, resource scheduling and network load. Beyond the RAN aspects mentioned above, other latency components on top are not explicitly simulated either but represented in as abstract bounds.
**CPM Structure and generation rules**

According to ETSI standard [4], CPM messages (as illustrated in Figure 21) include an Intelligent Transport Systems Protocol Data Unit (ITS PDU) header and 4 containers: Management Container, Station Data Container, Sensor Information Containers (SICs), and Perceived Object Containers (POCs) with the information about the detected obstacles (speed, type and dimensions). CPM generation rules [4] define when vehicles should transmit a CPM, and what is the information, i.e., the list of obstacles and sensors information, that should be included in a CPM.

Two generation rules have been considered: the periodic and dynamic rules. With the periodic one method, CPMs are generated every \( T_{CPM} \) and they include all the detected objects. The CPM should be transmitted even if no objects are detected. With the dynamic generation rule, the transmitting vehicle checks every \( T_{CPM} \) if the environment has changed in order to transmit a new CPM. More precisely, a vehicle generates a new CPM if:

1) A new obstacle has been detected
2) An obstacle’s absolute position has changed by more than 4m since the last time \( T_{update} \) it was included in a CPM.
3) An obstacle’s absolute speed has changed by more than 0.5m/s since the last \( T_{update} \).
4) The last time the object was included in a CPM was 1 second ago \( (T_{update} > 1 \text{ sec}) \).
5) An obstacle is classified as Vulnerable Road User (VRU) or an animal.

![Figure 21: CPM structure.](image)

**Fusion algorithm overview**

The proposed fusion algorithm in D4.3 [3] can merge Collective Perception Messages in order to generate a global CPM. This latter then contains more reliable information about vehicles environment. The proposed fusion algorithm is simple to implement, with low complexity compared to literature approaches. The algorithm proceeds mainly with three steps. The first step occurs in case the fusion center receives CPMs at iteration \( t \). In this case, the fusion center will check if the obstacles included in the CPMs are new obstacles or an update about already existent obstacle. Moreover, the fusion center will consider also already existent obstacles that are not updated but are still valid \( (T_{update} < 1 \text{ sec}) \). The second step of this algorithm takes place in case the fusion center does not receive any CPM at iteration \( t \). In this case, the fusion includes all valid already existent obstacles without changing their information. The third step of this algorithm consists of analyzing the list of obstacles by first associating obstacles according to their position and by giving a reliability value for each obstacle.

7.3 Testing and verification

7.3.1 Methodology

For the evaluation, we consider the real intersection of two main streets located in Lyon (France). Each street is four lanes wide, with two lanes in each direction. This intersection constitutes the center of a 400mx 400m area. The gNodeB, placed at the north-west corner of the intersection, is connected to the...
MEC hosting the CoCA application (playing the role of the fusion center). Simulated vehicles can reach a maximum velocity of 50 km/h. We setup a 2D LiDAR with a horizontal field of view of 110° (azimuth aperture) for all equipped vehicles. According to the dynamic generation rule policy, CPMs present variable size based on the number of obstacles included in the PoCs and other containers included in the CPM. In this work, containers are included in CPMs according to ETSI dynamic generation rule. Moreover, concerning packets headers, due to the use of 5G NR, we are considering MAC, RLC and PDCP layers headers for a total of 15 Bytes.

We compared the following scenarios:

1. Dynamic generation rule with perfect connectivity and with V2X connectivity, i.e., in this scenario, packets losses induced by V2X connectivity are considered and calculated based on simulated NS-3 traces.
2. Periodic generation rule with perfect connectivity and with V2X connectivity.

For each considered scenario, we run 20 NS-3 simulations with a duration of 60 seconds each.

7.3.2 List of key performance indicators

To assess the impact of CPMs processing, messages periodicity and 5G NR radio configuration, we consider the following KPIs:

- **Packets Delivery Ratio (PDR):** The PDR of Vehicle to Network (V2N) is calculated. First, we study the communication link from vehicles to gNodeB (denoted by UL), to evaluate the capacity of the CoCA application hosted in the MEC to collect CPMs from the vehicles, and second, we evaluate the communication link from gNodeB to vehicles (DL), to evaluate the capacity of the CoCA application to share merged CPMs with all the vehicles in the intersection. We define the PDR in UL as the ratio between the number of packets received (decoded) by the gNodeB and the number of packets sent by the vehicles. The PDR in DL is the number of received packet by the vehicles over the total number of transmitted packets from the gNodeB.

- **Latency:** Latency is highly critical in CoCA application. The latency (U-plane) is the delay of a packet transmission in a cellular network and can be contributed by the Radio Access Network (RAN), backhaul, core network, and data center/Internet. The latency simulated at RAN level is first evaluated independently and then integrated within an overall latency budget, given various assumptions and educated guesses regarding both MEC deployment and core network. For the latency evaluation above, we derive either the empirical Cumulative probability Density Function (CDF), or both the median and « worst-case » characteristic values (e.g., showing performance at say, 50% and or 95% of the CDF, resp.). These values allow us to capture both the global trends (necessary in such a dimensioning study) but also system robustness. Both unconstrained and latency-constrained reliability (PDR) at link level is also assessed. For the latter, we typically evaluate that the messages are correctly received within an a priori target latency requirement (typically 10 ms, as the usual reference for the GBR data traffic). In other words, for latency-constrained reliability, we evaluate the joint probability Pr(Successful Reception and Latency<10ms) = Pr(Latency<10ms / Successful Reception) x Pr(Successful Reception), whereas for unconstrained reliability, we simply evaluate Pr(Successful Reception) regardless of latency. Packet reception success is assessed here through the PDR. Note that the latency evaluation is herein restricted to RAN contributions only. Further considerations regarding extra-latency contributions (from backhaul, core network, or inter-MEC connections/switches) in light of MEC deployment assumptions can be found in [15].

- **Obstacle Misdetection Rate:** The OMR accounts the number of mis detected obstacles compared to the real scenario. An obstacle is considered as mis detected if it is missing compared to the real scenario or whenever the difference between the detection position and the real obstacle position is higher than a predefined threshold Th.
7.3.3 Measurement and testing tools

N/A

7.3.4 Final results

In the following tables, we summarize the main parameters used in our focused simulations for 5G-NR radio (V2N) and related transmitted messages (in terms of both format and rate), respectively.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency (GHz)</td>
<td>3.5</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>100 MHz (50 MHz in option)</td>
</tr>
<tr>
<td>Propagation model</td>
<td>Standard Urban Macro Cell, TR 38.901</td>
</tr>
<tr>
<td>(UE, gNodeB) Antenna height (m)</td>
<td>(1.7, 15)</td>
</tr>
<tr>
<td>(UE, gNodeB) Antenna</td>
<td>Isotropic</td>
</tr>
<tr>
<td>(UE, gNodeB) Transmit power (dBm)</td>
<td>(23, 49)</td>
</tr>
<tr>
<td>Modulation and Coding Scheme (MCS)</td>
<td>Adaptive (AMC) (MCS 5 in option)</td>
</tr>
<tr>
<td>Numerology</td>
<td>2</td>
</tr>
<tr>
<td>Channel Access (DL, UL)</td>
<td>Time Division Multiple Access (TDMA)</td>
</tr>
<tr>
<td>Duplexing scheme</td>
<td>Time Division Duplex (TDD)</td>
</tr>
<tr>
<td>Medium Access Control</td>
<td>Round Robin (RR) Scheduler</td>
</tr>
<tr>
<td>Hybrid Automatic Repeat reQuest (HARQ) IR</td>
<td>Enabled</td>
</tr>
</tbody>
</table>

Table 6. Main messages parameters in focused CoCA simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Messages size (bytes)</td>
<td>From 171 to 836 Bytes (UL CPMs)</td>
</tr>
<tr>
<td></td>
<td>From 171 to 1396 Bytes (DL CPMs)</td>
</tr>
<tr>
<td>Tx frequency (Hz)</td>
<td>10 (periodic) or dynamic (UL CPMs)</td>
</tr>
<tr>
<td></td>
<td>10 (DL regular CPMs)</td>
</tr>
</tbody>
</table>

Remark: Given the evaluation of this use case (T2S2) been based solely on simulations, the results are not therefore reported in the vertical’s trials work package WP6 (D6.4 deliverable) and instead, all T2S2 KPIs are presented in this document.

CoCA traffic
We first analyse the CoCA traffic scenario with the number of CPM messages per second and per user/vehicle (Figure 22 - left) and the resulting packet size (Figure 22 - right) with the dynamic and the periodic generation rules. Figure 22 (left) shows that the frequency of CPM transmission decreases strongly with the traffic density for the dynamic traffic (It is divided by 2 when going from 10 vehicles to 100 vehicles in the intersection). Indeed, in case of high vehicle density, the speed will decrease and thus the frequency of changing the position and speed will decrease accordingly. This low mobility limits the generation of CPM messages in the dynamic case. For the periodic traffic, the number of messages transmitted per vehicle decreases more slowly from 8.9 messages per second with 10 vehicles to 7 messages per second for 100 vehicles. Figure 22 (right) presents the empirical Cumulative Distribution Function (CDF) of CPM packets size for the dynamic/periodic generation rules and for two vehicles densities (10 and 100 vehicles in the intersection). First, we can notice that the size of CPM messages is larger if we use the periodic generation law. This difference with the dynamic law increases with the number of vehicles (obstacles). This is due to the periodic generation of CPM messages which systematically includes all detected obstacles. Obviously, the CPM messages are larger when the number of vehicles/obstacles is important (up to around 800 Bytes for the periodic law).

These two figures show the interest of the use of the dynamic generation law of CPM messages with a lower number of transmitted messages and smaller packet sizes.

**Latency**

Figure 23 and Figure 24 present (on the left), the evolution of the median UL latency at the RAN level (with the quantile at 5% and 95%) and, on the right the empirical Cumulative Distribution Function (eCDF) of E2E latency at RAN level for UL and DL respectively and for 10 and 100 vehicles.

The UL RAN latency remains well below the targeted 10 ms requirement in terms of the median which is between 4 ms and 5 ms. However, in the worst cases (represented by the 95% quantile of the received packet) the latency can reach 18 ms regardless of the traffic (dynamic/periodic and from 10 to 100 vehicles). We can note that 85% of the received packets have a latency lower than 10 ms. The empirical CDF of the RAN latency is represented in Figure 23 (right) for 10 and 100 vehicles. The calculation of the CDF takes into account all the messages transmitted whether they are well received or not. A message not received is then considered to have infinite latency. With this fair approach, we can directly observe the average PER corresponding to the maximum of the CDF. We can then observe that the UL latency is very slightly lower when there are 10 vehicles in the intersection compared to 100 vehicles. It is also interesting to note that the influence of HARQ is directly observable on these eCDF curves.
Indeed, we can see that the eCDF of the latency is staircase shaped for which each step corresponds to one transmission.

The RAN latency in DL, illustrated in Figure 24, is lower than in UL under a low UEs density in Tx. Higher network loads have a more significant deleterious impact on the DL CPM messages, whereas the impact is quite transparent in UL, with a very marginal latency increase (See Figure 23 and Figure 24). The TDD flexible scheme indeed tends to prioritize UL transmissions, whenever the traffic demand drastically increases. However, the degradation remains globally contained below the 10ms requirement.

We can also observe in Figure 24 (right) that, unlike UL, the HARQ process is only marginally used. This is mainly explained by the difference in transmission power with 49 dBm in DL and 23 dBm in UL. This emphasizes that the increase in latency observed in DL is related to the scheduler and its resource allocation process.

The performance with a bandwidth reduced by half to 50 MHz was also evaluated and is shown in Figure 25 (UL on the left and DL on the right). The UL latency is then slightly impacted by this bandwidth reduction. We can observe a very slight increase in terms of latency. This increase is rather accentuated
for the 5% of the worst cases which present a latency higher than 16 ms. The impact of the bandwidth reduction is more pronounced for the DL link. Indeed, we can observe an increase in terms of latency up to 4 ms for periodic traffic with 100 vehicles. For the 5% of the worst cases, the increase in latency is even more pronounced and can exceed 20 ms. It is also interesting to note that with 50 MHz of bandwidth we can observe a rather marked difference of about 2 ms between periodic traffic and dynamic traffic.

Figure 25. Evolution of the RAN latency with a bandwidth of 50 MHz. On the left, we have the median UL RAN latency (with the quantile at 5% and 95%) and on the right the median DL RAN latency (with the quantile at 5% and 95%) from 10 to 100 vehicles in the intersection.

Figure 26 shows the evolution of the RAN latency (UL and DL) as a function of number of vehicles with an MCS fixed at 5 for the transmission of CPM messages. We then observe that the strategy of fixing the MCS involves a significant increase in terms of median latency both in UL and in DL. This increase is about 12/14 ms for UL depending on the network load and traffic type. In DL, the increase in latency from 1ms (for 10 vehicles) to 20 ms (for 100 vehicles) is directly related to the network load (total number of messages transmitted). This median DL latency exceeds 10 ms from 50 vehicles in the intersection. Thus, fixing the MCS does not provide low enough latencies for the COCA service.

Figure 26. Evolution of the RAN latency with MCS=5. On the left, we have the median UL RAN latency (with the quantile at 5% and 95%) and on the right the median DL RAN latency (with the quantile at 5% and 95%) from 10 to 100 vehicles in the intersection.
Both MEC deployment architectures have been considered, including fully decentralized (i.e., 1 MEC per gNodeB and highly centralized (i.e., one per operator data center) schemes. For instance, under a highly centralized MEC hypothesis, the overall E2E latency integrates extra delays related to backhaul and core network. The mapping between the considered MEC deployment hypotheses and the resulting latency terms that must be accounted in the overall E2E latency budget is:

- Decentralized (1 MEC per gNodeB) in the same cell
  - The E2E latency is the RAN latency
- Centralized (1 MEC per data center) in the same cell
  - The E2E latency is given by the addition of the RAN latency with the backhaul latency and the core network latency

For backhaul latency (e.g., between a gNodeB and a regional concentration site) and core network latency (i.e., between a radio access regional aggregation site and a data center), which are mainly distance-driven, we assume 2 ms for each component [15]. This corresponds to lower bounds (typically, under the coarse assumption of 1ms/100km for fiber transport).

Figure 27 illustrates the median UL latency for the decentralized and centralized MEC deployment strategy with a bandwidth of 100 MHz and the adaptive MCS. Whatever the type of deployment, the UL latency remains below the 10 ms target. However, it is still more interesting to prefer a local deployment of the MEC to minimize this latency.

![Figure 27](image.png)

Figure 27. Evolution of the latency (median) for the decentralized and centralized MEC deployment as the function of the number of vehicles.

**Unconstrained and constrained Packet Delivery Ratio**

Figure 28 shows the evolution of the PDR for unconstrained reliability and constrained reliability (i.e., rate of packets delivered with a E2E RAN latency < 10ms), respectively.

Dually, similar curves of constrained reliability are shown in Figure 29 for a reduced bandwidth of 50 MHz and then for a fixed MCS (MCS = 5).

We thus remark that:

- The unconstrained reliability, shown in Figure 28, remains at a quite high level close to 100% in DL. This implies that the merged CPM messages will be perfectly transmitted to the vehicles in the intersection thus maximizing the level of road safety.
- In UL, the PDR is relatively stable for periodic traffic between 80% and 85% while for dynamic traffic it tends to increase from 80% to 90% with the number of vehicles in the intersection. This increase in PDR is mainly due to the topology. Indeed, when there are few vehicles in the...
intersection, the vehicle/base station distance is on average greater than if there were a large number of vehicles. For periodic traffic, we do not observe this phenomenon because it is balanced by the significant increase in packet size when there is a large number of vehicles (CPM messages include all obstacles).

- In comparison with the latter, the latency-constrained reliability is degraded in UL and DL (Cf Figure 28 right). In UL, the degradation is of the order of 10% regardless of the type of traffic. For the DL, the latency being always lower than 10ms there is no degradation of the failure rate if the number of vehicles is lower or equal to 40. Beyond 40 vehicles in the intersection, the reliability progressively decreases to 65% (resp. 60%) for dynamic (resp. periodic) traffic with the increase of the number of vehicles and thus of the network load.

- The unconstrained reliability when the bandwidth is 50 MHz or with MCS=5 is the same as with the classical configuration (BW = 100 MHzs and adaptive MCS).

- The constrained PER for a bandwidth of 50 MHz illustrated in Figure 29 (left) shows a more pronounced performance degradation for the UL and DL link. In UL, the constrained PER slowly progresses with the number of vehicles in the intersection from 64% to 73% (resp. 64% to 66%) for dynamic (resp. periodic) traffic. For the DL, we can observe the same behaviour as for BW=100 MHz, i.e. an increase of the failure rate from 40 vehicles in the intersection with a PDR decreasing up to 37% (resp. 25%) for the dynamic (resp. periodic) traffic.

- Due to the high RAN latency, the constrained PDR for MCS=5 has the poorest performance. The constrained PDR in UL for MCS=5 is zero. In DL, the constrained PDR decreases from 100% for 30 vehicles to 10% (resp. 2%) for 100 vehicles and for the dynamic (resp. periodic) traffic.

![Figure 28. Evolution of the unconstrained PDR (left) and of the constrained PDR (right)](image-url)
OMR

In order to demonstrate the effectiveness of the proposed fusion algorithm and to highlight the impact of 5G NR connectivity on the merged list of obstacles, the OMR KPI is assessed. Results are shown in Figure 30 for different values of obstacles position error threshold \( Th \) (4m (a), 2m (b) and 1m (c)). This threshold can be seen as a tolerance on the position error.

Figure 30 highlights the fusion algorithm advantages in terms of obstacles detection capabilities and confirm the relevance of using CPM messages. Figure 30 (a) shows the OMR evolution for a tolerance threshold \( Th \) of 4m which is considered in the CPM generation policy (Cf section 7.2.4). In order to show that the fusion algorithm works correctly, we showed the performance with a perfect connectivity. In fact, with the dynamic policy, information about obstacles is included in a CPM each time the obstacle changes its position by 4m or more. Therefore, in case of perfect connectivity, all obstacles should be updated, and no obstacle should be mis detected. Figure 30 (a) shows that OMR in this case is null, which confirms our analysis and highlights the effectiveness of the proposed algorithm. With the 5G NR connectivity, the OMR decreases as the number of vehicles in the intersection increases from 5% to 0.8% (resp. from 5.3% 1.7%) for dynamic (resp. periodic) traffic. This trend can be explained by the impact of a lost packet (containing the CPM message) on the merged obstacle list. When there are only 10 vehicles, the loss of a packet is more detrimental because there is little redundancy in the obstacles that are fed back to the fusion algorithm unlike the case with 100 vehicles. We can also note that dynamic traffic outperforms the periodic in terms of OMR.

For a tolerance threshold reduced to 2m and 1m (Figure 30 (b) and (c) respectively), the trend is opposite. The OMR obtained from the periodic traffic shows then the best performance. Indeed, the rules for dynamic generation of CPM messages include an obstacle in the list when it has moved more than 4 meters. With the periodic approach, CPM messages must include all obstacles in visibility. The obstacles are then updated more regularly which makes the approach more robust even if the network is more loaded in terms of message numbers. For \( Th=2m \), the OMR decreases from 15% to 7% (resp. from 6% to 2%) for the dynamic (resp. periodic) traffic. For a tighter tolerance \( Th=1m \), the performance is still degraded, and the OMR decreases from 30% to 17% (resp. from 6% to 2%) for the dynamic (resp. periodic) traffic.
Figure 30. (a) OMR with $Th=1m$, (b) OMR with $Th=2m$, (c) OMR with $Th=4m$. 
7.4 Recommendations

In this study, we have accounted for a variety of simulation results illustrating the performance of V2N 5G-NR connectivity to support a CoCA service in a city intersection, while varying the number of connected vehicles. These simulation-based evaluations at radio link level mainly concern the reliability and the end-to-end latency of the critical messages involved in CoCA service transactions (i.e., CPM). These results are discussed in light of network deployment, MEC deployment and network load. Finally, we showed the effectiveness of our fusion algorithm in terms of obstacles detection capabilities.

The advantage of using a 5G NR-based cellular network for a delay-sensitive application like CoCA service is to have a very low latency, less than 10 ms on average, even if the network is heavily loaded. Moreover, the reliability of such a network is very good because the radio resources are scheduled by the base station (no packet collision). The impact of these good performances on connectivity is then highlighted through the good results on the cooperative detection of obstacles in the intersection.

We then recommend the use of 5G NR cellular connectivity with CPM messages for CoCA-like services. However, in case of lack of cellular coverage, the V2X sidelink approach (such as C-V2X or NR sidelink) would be an excellent complement (Cf D4.3 [3]).
8 T2S3: QUALITY OF SERVICE (QOS) FOR ADVANCED DRIVING

8.1 Description and motivation

This scenario involves the dynamic selection of the appropriate driving mode based on the context at-hand. According to [42] the driving mode is mainly characterised by the Level of Automation (LoA), which reflects the functional aspects of the technology and affects the system performance requirements. This specific scenario considers the situation where an autonomous vehicle reaches the end of its operational design domain (ODD) by entering an urban area. Under normal circumstances it would need to switch to a low LoA. Instead, it leverages the support of a cloud-based service that enhances the vehicles perception and therefore allows it to stay in a high LoA.

Since the availability of that service highly depends on the expected QoS over the planned trip the service might or might now accept that request. If it does accept, it then continues to monitor the connection and might abort the manoeuvre if the link degrades.

![Figure 31. T2S3 scenario. An automated vehicle approaches the end of its ODD (green). To continue with a high LoA, vehicle requests maneuvre support from the cloud and can continue with high LoA through the non-ODD area (orange).](image)

8.2 Final setup

At the time of submitting deliverable D4.2, the pandemic situation that evolved as a result of COVID-19 made travelling temporarily impossible. Further, the evolving Brexit situation introduced legal and fiscal uncertainties. The perspective of shipping the Carai vehicles to Surrey, UK became very unclear. Therefore, development to implement own trial facilities started at TUC with the goal of hosting smaller-scale trials involving the Carai vehicles at the TUC and associated premises started. This removed the need for travelling and shipping circumventing unclear situations.

Therefore, this use case scenario’s final trials were held at the newly developed test-site “Schlettau”, near Chemnitz, Germany. This test site hosts a dedicated base station operated by Vodafone Germany offering 5G NSA and 4G.

8.2.1 Network architecture

Figure 32 presents the network architecture for this trial. The vehicle is connected to the network via a 4G/5G CPE while the remote service is deployed to a cloud connected PC. The software and hardware used at the user as well as the cloud-plane are developed by TUC. The access network as well as the core are being used from Vodafone Germany. The access network configuration has been adjusted to be 4G or 5G NSA, depending on the testcase.
8.2.2 User application architecture

This section describes the user application, their components, and the communication scheme. While the client runs in the vehicle, the server is deployed in a cloud to leverage their computing power. Both communicate over two distinct communication channels: control and video (see Figure 33).

Figure 33. T2S3 application architecture. Green: software components developed by TUC; Orange: external hardware devices

The control channel is being realised over by communication over plain UDP and allows for the initial scenario negotiation as well as the active QoS monitoring via a ping-acknowledgement functionality. A typical communication sequence for an accepted request is presented in Figure 34.

Figure 34. T2S3 message flow for an accepted scenario.
Once the request has been accepted by the server, the client emits continuous pings and expects timely acknowledgements. Once the channel worsens, the client can then abort the ongoing manoeuvre in a timely manner and therefore go to a safe state.

The video channel is used to transmit the vehicle’s front camera to the server application via RTP with encoded h264 video. It only gets established once a successful manoeuvre negotiation took place and provides the server application with a continuous video stream. The timely arrival of video frames is crucial as the vehicle depends on the incoming detected objects for safe navigation.

### Server Application

The server application models is a service that offers remote assistance to an automated vehicle. It determines the expected network coverage over a requested trip, monitors the active connection with the vehicle and performs object detection and classification in incoming video streams.

Once an assisted manoeuvre request arrives, the server first checks whether the requested route for the manoeuvre lies within an area of sufficient coverage. It has a map of previously approved areas with its expected RSSI values available. It decides whether the requested trip can be supported or not by applying a threshold, when the RSRQ is greater than -18dbm. The resulting map for the Schlettau area is presented in Figure 35.

![Figure 35. T2S3 network coverage map for assisted maneuver. Green denotes area where the reception is expected to be good while red areas are known to have bad reception](image)

If the request has been accepted, the server opens an RTP port to receive an incoming video stream from the vehicle. For every frame that arrives it performs object detection for relevant objects like vehicles, trucks and motorcycles as well as VRUs like pedestrians and bicycles. Object detection is performed with the yolo framework, a sample frame from the preparational trials is presented in Figure 36. Once the relevant objects have been detected, they are sent back to the client application.
Client Application

Upon reaching the end of the vehicle’s ODD, the client application gets activated. It requests active manoeuvre support by the cloud service. The request includes the current GNSS position of the vehicle (start) and the target position (end of non-ODD area). After receiving the answer from the cloud service, it either indicated the OBU to switch to a lower LoA or proceeds with an active supported manoeuvre.

If that request gets accepted, it then proceeds to capture the front-camera’s video stream, encodes them to h264/RTP and sends them to the cloud service. In return, it receives the detected object list and forwards them to the trajectory planning application leveraging a Frenet planning algorithm as described in [32]. While the manoeuvre is active, it actively monitors the connection by sending pings and receiving acknowledgments (see Figure 34). Late acknowledgments enable the application to stop the manoeuvre and switch to a safe mode.

8.2.3 Hardware components

The following hardware is used and deployed as part of the experimentation setup at and have been used for the trials of this scenario.

- Base Station test-site “Schlettau”
- Carai 3 vehicle (BMW i3)
  - Huawei CPE 2 Pro 5G
  - OBU Nuvo industrial; client software is deployed here
  - uBlox NEO M8T Global Navigation Satellite System (GNSS) receiver
  - AVT Mako 235G camera
- Cloud application service (TUC)
  - Dell OptiFlex 7070 server (hosting software)

8.2.4 Software components

The following software is used and deployed as part of the experimentation setup and have been used for the trials of this scenario.
- DRAIVE Link2 SDK [36] for developing reusable software parts (node) on client and server side in C++ and Python, modelling the communication between them over TCP and UDP and for record & playback of measurement data
- Yolov5 AI object detection software [37] for object detection and classification in camera images
- GStreamer [38] for video encoding (H264) for transmission and reception of video frames
- Chrony [39] and gpsd [40] for time synchronisation

8.3 Testing and verification

This section describes the test and measurement setup to develop and verify the functionality as well as to derive the final KPI measurements. The final KPI results, and their evaluation are reported as part of D6.4 [9].

8.3.1 Methodology

Development and Validation

As a first step, the trials were developed and setup at the TUC premises before moving to the trial site in Schlettau. The initial development in phases 1 and 2 had been setup on one single computer with localhost communication. That methodology facilitated the fast prototyping of all the critical application parts: video encoding, control channel, object detection and trajectory planning. After the full functionality has been validated, the setup has gradually been moved to the final hardware and the vehicle.

![Figure 37. T2S3 Research vehicle Carai 3 used for development and validation trials.](image)

The Carai 3 test vehicle was modified to host the necessary hardware. It was equipped with a Nuvo industrial PC as OBU, 4x AVT GigE cameras, uBlox NEO M8T and a Huawei 2 Pro CPE. Software deployment included the setup of the client application and the time synchronisation with chrony and gpsd. For the cloud deployment a “Dell Optiflex 7070” has been used. It was deployed and setup in the TUC leveraging the institution’s gigabit backbone. The functionality of the whole deployment was verified by running the application with previously recorded data – played back via DRAIVE.Link2 player – over ethernet. Finally, the Huawei CPE 2 Pro 5G has been installed and towards the end of phase 2, sample trials have been performed at the backyard at the TUC premises. The full functionality of all parts has been successfully validated.
Final Trials

As a second step, the setup was then moved to the TUC test site in “Schlettau”, where a dedicated Vodafone base station was used (see Figure 39). The specifications of this base station are presented in Table 7.

Table 7. T2S3 access network configuration

<table>
<thead>
<tr>
<th>Network</th>
<th>Vodafone.de</th>
</tr>
</thead>
<tbody>
<tr>
<td>gNB</td>
<td>Sector Antennas</td>
</tr>
<tr>
<td>Band 1</td>
<td>TDD on 3450.0 MHz (band n77)</td>
</tr>
<tr>
<td>Band 2</td>
<td>FDD on UL: 177.1 MHz and DL: 1865.1 MHz (band n3)</td>
</tr>
</tbody>
</table>
In Schlettau, the trial has been set up on the roads marked in Figure 39. As these roads are public, for legal reasons the vehicle was operated in passive mode. In this mode the application runs as designed, grabs sensor data and performs trajectory planning, but the vehicle is still driven manually to ensure safety. Further, adjustment for Schlettau included the change of road- and RSSI map for trajectory planning (client) and RSSI mapping (server) as well as IP configurations.

After the preparation phase had finished and the functionality had been validated, the final trials have then been performed on 3 consecutive days. First the 4G trials have been performed to collect baseline measurements of the application for comparison to 5G NSA. From the second day on the trials have been performed with 5G NSA. A total of 23 scenario runs with a net duration of 2.75 hours of measurement data has been recorded for evaluation.

8.3.2 List of key performance indicators

The main KPIs for the “QoS for Advanced Driving” test case are as follows:

- TC05: E2E message latency
- TC06: User experienced DL throughput
- TC07: User experienced UL throughput
- TC09: Reliability
- TC11: Mobility
- TC13: Interactivity

These are to be measured on application layer between the OBU of the vehicle and the cloud service. The latencies do not include the time for signal processing on both, the OBU and the service as these are very implementation dependent and do not affect the scaling of the system.

8.3.3 Measurement and testing tools

The following tools were used to capture and evaluate the applications KPIs:

- DRAIVE Link2 [41]: A middleware library for message exchange between independent nodes. This tool offers a recorder that is able to accurately record every message exchange on application level and write that into a binary file. This binary file can be examined with various tools or converted into other formats (plain text, SQL, etc.)
- Tcpdump: a tool to record raw network packages on OSI layer 2 and above.
- Wireshark: a tool to analyze files created by tcpdump containing tools for bisecting various protocols on various layers. Can provide throughput, latency and reliability estimates for some protocols.
- Microsoft Excel, MATLAB, PlotJuggler as well as some Link2 tools and plug-ins have been used to calculate statistics out of raw values and print plots.

8.3.4 Final results

The final results are reported and analyzed in D6.4 [9].

8.4 Recommendations

Based on the trial setup presented here and the measured KPIs as presented in D6.4 [9], it can be concluded that the deployed service is working as expected. The service can match the requested trip with an a-priori known RSSI map and accept or deny that request based on the static QoS estimate. If accepted, the remotely detected objects can subsequently be used for trajectory planning in the vehicle.
Further, the QoS monitoring mechanism for live manoeuvres gives an early indication of link degradation.

Unfortunately, the extensive trials revealed that the performance and stability of the 5G NSA network used is not yet able to support the requirements of this application. The detailed analysis of the correlation between RSSI on the UE side with the measured KPIs show that whenever the received signal strength drops, all KPIs degrade to unacceptable levels. This applies especially to latency and reliability.

In the trial, a typical one-way latency of 44.3ms over 5G has been measured. Since the server processing time is typically around 30ms for a single camera frame in our setup, the total RTT for that frame adds up to at least 118.6ms under best network conditions. Under worse network conditions (lower RSSI), that latency rises up to 8000ms (measured) or even total signal loss. A similar behaviour was observed with reliability. While we were able to observe up to 100% reliability under best conditions, the degradation of the RSSI resulted in a significant drop of packages, as low as 8.8% reliability in some test cases.

Given the safety-critical nature of this scenario and the unpredictability of the available QoS for a given route it must be concluded that the trialled network is not able to support this kind of application yet. Nevertheless, it is expected that the provisioning of 5G SA with NR as well as a dedicated URLLC will provide the reliability necessary for the network to host such application.
9 T4S1: VEHICLE PROGNOSTICS

9.1 Description and motivation

An application running at the network edge and having the capability to access the Internet enables any vehicle passing the coverage area of a 5G-enabled roadside unit to report its current functional state to a local or remote diagnosis service and receive just-in-time repair notifications. A vehicle service application linked to repair centres needs to obtain and analyse data from the vehicle periodically and an edge cloud or Road-Side Unit (RSU) application can provide this data by collecting it from the passing cars on the road. Based on the outcome of the analysis, the repair centre will notify the vehicle owner with any identified issues.

The vehicle prognostics use case trials focused on the validation of the 5G UL performance with test traffic based on typical On-Board Diagnostics – Second Generation (OBD-II) messages. By emulating the vehicle prognostics service data with software and hardware-based traffic generators, the validation trials were configured to focus on the UL data throughput, end-to-end latency of the data path from the user device to the network edge. Based on the achieved 5G UL performance, the specific focus of the final trials described in this section was to assess the scalability of the trialled service when the amount of service users increased inside a single 5G cell.

9.2 Final setup

The final trial setup was deployed on top of the 5GTN-VTT test facility in Oulu, Finland.

9.2.1 Network architecture

Figure 40 presents the high-level network architecture for the final trials of the vehicle prognostics use case scenario. The test traffic emulating the vehicle prognostics service was generated at the 5G UEs and transmitted to the network in the UL direction. The application receiving the emulated test traffic was running on a VM server in the edge cloud environment. From the point-of-view of an end user, the most critical part of the service was the upload of the vehicle status data from the moving vehicle to receiving application at the network edge, as the vehicle was inside the coverage area of the 5G cell only for a limited period of time.

![Network Architecture Diagram](image)

Figure 40. Network architecture for the final trials of the vehicle prognostics use case scenario.

All network architecture components related to the generation, transmission, and reception of the test traffic in Figure 40 were developed and configured for the trials by VTT. All other 5G network and test tool components were provided for the trials by the 5GTN-VTT test facility.
### 9.2.2 User application architecture

For the most parts, the user application architecture remained the same as in the Phase 2 trials presented in D4.3 [3], but more advanced hardware based Keysight UeSIM test traffic generator [20] was used in parallel with the software tools to assess the scalability of the vehicle prognostics service in a more realistic manner. The measured user application in the final trials of the vehicle prognostics use case scenario was still emulated with a software-based traffic generator, which generated test traffic based on the OBD-II message format and payload sizes. All test traffic was transferred between the 5G UE (publisher) and edge cloud server (subscriber) using the MQTT protocol. The other users/UEs in the 5G cell during the scalability tests were emulated by using Keysight UeSIM with same test traffic characteristics.

### 9.2.3 Hardware components

The network architecture utilised during the final trials contained the following hardware components:

- **UEs:**
  - Telewell 5G USB modem was used as the main 5G UE in the final measurements.

- **gNBs:**
  - 5G NR Time Division Duplex (TDD) Rel-15 NSA @ 3.5 GHz (band n78), BW = 60 MHz.
    - Pico gNB was used in the scalability measurements.
    - 30 kHz subcarrier spacing, which corresponds to 0.5 ms slot duration.
    - 3/7 DL/UL time slot ratio and UL proactive scheduling with 4 ms grant interval for more realistic scalability.
    - 4x4 DL and 1x4 UL MIMO configuration.

- **EPC and 5GC:**
  - Software-based core network services for the scalability measurements.

### 9.2.4 Software components

The following software components were utilised in the final trial setup:

- MQTT client (publisher) was publishing the generated test traffic data packets to the network.
- MQTT broker was running in the edge cloud and receiving the published test traffic data packets.

### 9.3 Testing and verification

In the final trials, the scalability of the vehicle prognostics service was assessed using a 5G NSA network configuration. The performance was measured mainly in terms of the achieved user experienced UL throughput and communication latency, but additional KPIs such as communication reliability, peak data rate, device density, interactivity, and area traffic capacity were also investigated as part of the service scalability tests.

#### 9.3.1 Methodology

The scalability measurement setup utilised in the final trials is shown in Figure 41. The measured test traffic data packets related to the emulated vehicle prognostic service were transmitted using MQTT. The MQTT packets at the sender side measurement laptop and at the receiving end network edge VM server were captured by Qosium Probes, which sent the relevant metadata to a Qosium Scope for further KPI processing. The scalability tests were performed by gradually increasing the amount of simultaneous vehicle prognostics service users in the 5G UL. The emulated users were added to the network by using Keysight UeSIM that was connected to the same gNB as the sender side measurement.
laptop. A conducted connection was used to guarantee good channel quality also for the emulated UEs transmitting the test traffic.

![Figure 41. Vehicle prognostics final trials scalability measurement setup.](image)

### 9.3.2 List of key performance indicators

The key KPIs and their target values for the vehicle prognostics service based on the analysis performed in D2.2 [34] were defined as follows:

- E2E/UL message latency (target: >100 ms)
- User experienced UL throughput (target: 1-10 Mbps)

The additional KPIs investigated as part of the vehicle prognostics service scalability assessment and their target values based on the analysis performed in D2.2 [34] were:

- UL slice reliability (target: 99.999 %)
- Broadband connectivity / peak data rate (target: 100 Mbps)
- Connection (device) density (target: 0.5-4.3*10^3 devices/km^2)
- Interactivity (target: <100 transactions/s)
- Area traffic capacity (target: 0.005-0.043 Mbps/m^2)

### 9.3.3 Measurement and testing tools

The main measurement and testing tools utilised in the final trials were as follows:

- Kaitotek Qosium [21] was used to passively measure the network KPIs (throughput, latency, and jitter) from the service traffic in both UL and DL directions.
- Keysight UeSIM was used to generate emulated users/UEs to the 5G cell during the measurements. It was specifically used to provide controllable CP and UP load to the network during the service scalability tests.
- Nokia BTS Site Manager/Web Element Manager was used to record and access the performance counters at the utilised RAN components during the trials.
- Trimble Thunderbolt PTP GM200 [24] with an external GPS antenna was used as PTP master for the server running the MQTT broker.
More information on the utilised measurement and testing tools as well as other tools provided by the test facility and utilised in the configuration and debugging of the trial setup during its deployment can be found from [11].

9.3.4 Final results

The detailed final trial results and analysis can be found in D6.4 [9].

9.4 Recommendations

The main high-level finding from the results of the final trials was the limited scalability of the current 5G UL implementations. In the case of the vehicle prognostics service, the target UL latency of 100 ms could be achieved with the associated 99.999 % reliability when the number of simultaneous service users was 8 or less in a single 5G cell. At this threshold, under half of the total cell capacity was in use when it comes to the amount of data transferred by the users. This clearly shows that the packet data scheduling algorithms in the current 5G equipment are not yet optimised for UL traffic, which can create performance problems even for services with low and moderate KPI requirements when the number of simultaneous users begins to increase.

Currently, the majority of the services offered over commercial 5G networks are focusing on DL dominated eMBB traffic, which also means that the commercial equipment currently in use is optimised for this specific usage scenario. The increasing support for URLLC and mMTC use cases in the most recent 3GPP releases should alleviate the problem when the related functionalities come into large-scale use also in commercial network deployments. In addition, as enhancing capabilities of the UE chipsets and firmware should alleviate the identified problems as the technology matures. Meanwhile, when deploying a service such as vehicle prognostics, the capabilities and performance of the currently available 5G equipment should be verified in advance for UL-oriented traffic.
10 T4S2: OVER-THE-AIR (OTA) UPDATES

10.1 Description and motivation

Engine Control Unit (ECU) is a generic term for a hardware module with corresponding software in a vehicle that controls some electronic functions within the on-board systems. It can control anything from the steering wheel to the brakes and is in key role in automated driving. The engine control unit is a critical part of the vehicle and, as the vehicles become more and more automated, needs regular software updates. Over-the-air updates provide significant cost-savings, as the vehicles are not required to be recalled and updated in a dedicated physical location by a manufacturer or service centre.

The Over-the-Air (OTA) update use case trials focused on the baseline performance of the 5G DL for generic data transfer as well as the assessment of the applicability of 4G Evolved Multimedia Broadcast Multicast Service (eMBMS) -based cellular broadcasting functionality as a backup method for the distribution of the engine control unit software updates. Based on the achieved 5G DL and 4G broadcast/multicast performance, specific focus of the final trials was to assess the scalability of the trialled service when the amount of service users increases inside a single 5G cell.

10.2 Final setup

The final trial setup was deployed on top of the 5GTN-VTT test facility in Oulu, Finland.

10.2.1 Network architecture

Figure 42 presents the high-level network architecture for the final trials of the OTA updates use case scenario. The test traffic emulating the OTA updates service was generated at the service cloud, residing in close proximity of the 5GC, and transmitted directly to the 5G UEs in the DL direction. From the point-of-view of an end user, the most critical part of the service was the download time of the provided software update package.

Figure 42. Network architecture for the final trials of the OTA updates use case scenario.

The configurations related to the generation, transmission, and reception of the emulated test traffic in the final trials were performed by VTT. All 5G network and test tool components in Figure 42 were provided for the trials by the 5GTN-VTT test facility.
10.2.2 User application architecture

A hardware based Keysight UeSIM test traffic generator was used to assess the scalability of the vehicle prognostics service. All test traffic was transferred between the service cloud server and emulated 5G UEs as full buffer IP packet streams. Compared to, e.g., real File Transfer Protocol (FTP) downloads, this approach provided a best-case estimate of the OTA updates service scalability as the protocol overhead is lower.

10.2.3 Hardware components

The network architecture utilised during the final trials contained the following hardware components:

- **UEs:**
  - Telewell 5G USB modem was used as the main 5G UE in the final measurements.

- **gNBs:**
  - 5G NR Time Division Duplex (TDD) Rel-15 NSA @ 3.5 GHz (band n78), BW = 60 MHz.
    - Pico gNB was used in the scalability measurements.
    - 30 kHz subcarrier spacing, which corresponds to 0.5 ms slot duration.
    - 3/7 DL/UL time slot ratio and UL proactive scheduling with 4 ms grant interval for more realistic scalability.
    - 4x4 DL and 1x4 UL MIMO configuration.

- **EPC and 5GC:**
  - Software-based core network services for the scalability measurements.

10.2.4 Software components

The final trials did not contain any special software components.

10.3 Testing and verification

In the final trials, the scalability of the OTA updates service was assessed using a 5G NSA network configuration. The performance was measured mainly in terms of the achieved user experienced DL throughput and related software update package download time, but additional KPIs such as communication latency, reliability, peak data rate, device density, interactivity, and area traffic capacity were also investigated as part of the service scalability tests.

10.3.1 Methodology

The scalability measurement setup utilised in the final trials is shown in Figure 43. The scalability tests were performed by gradually increasing the amount of simultaneous OTA updates service users in the 5G DL. The emulated users were added to the network by using Keysight UeSIM that was connected to the 5GC on the transmitting side as well as to the gNB on the receiving side. A conducted connection was used to guarantee good channel quality for the emulated UEs receiving the test traffic.
10.3.2 List of key performance indicators

The key KPIs and their target values for the vehicle prognostics service based on the analysis performed in D2.2 [34] were defined as follows:

- User experienced DL throughput (target: 10-100 Mbps)

The additional KPIs investigated as part of the vehicle prognostics service scalability assessment and their target values based on the analysis performed in D2.2 [34] were:

- E2E/DL message latency (target: >100 ms)
- DL slice reliability (target: 99.999 %)
- Broadband connectivity / peak data rate (target: 1000 Mbps)
- Connection (device) density (target: 0.5-4.3*10^3 devices/km^2)
- Interactivity (target: <100 transactions/s)
- Area traffic capacity (target: 0.005-0.043 Mbps/m²)

10.3.3 Measurement and testing tools

The main measurement and testing tools utilised in the final trials were as follows:

- Keysight UeSIM was used to generate emulated users/UEs to the 5G cell during the measurements. It was specifically used to provide controllable CP and UP load to the network during the service scalability tests.
- Nokia BTS Site Manager/Web Element Manager was used to record and access the performance counters at the utilised RAN components during the trials.

More information on the utilised measurement and testing tools as well as other tools provided by the test facility and utilised in the configuration and debugging of the trial setup during its deployment can be found from [11].

10.3.4 Final results

The detailed final trial results and analysis can be found in D6.4 [9].

Figure 43. OTA updates final trials scalability measurement setup.
10.4 Recommendations

The main high-level finding from the results of the final trials was that in the 5G DL direction the achievable performance was already close to the theoretical values and under an increasing load, the performance also deteriorated in a much more predictable way than what was recorded in the 5G UL direction. Purely from a download performance perspective, the 5G unicast was able to outperform the 4G eMBMS-based multicast/broadcast still with tens of simultaneous users, which in most cases is well beyond a typical usage scenario for the trialled OTA updates service. Hence, the utilisation of 4G eMBMS-based multicast/broadcast instead of 5G unicast as the distribution medium for software update packages is meaningful only in very specific usage scenarios and environments. Examples of such usage scenarios could be situations where the number of users simultaneously downloading the same content is very large or when something else than download performance, e.g., spectral or energy efficiency, is wanted to be optimised at the network level.
11 T4S3: SMART TRAFFIC CORRIDORS

11.1 Description and motivation

This use case is motivated by the fact that vehicles can utilize selected routes in order to reduce pollution or congestion, especially in areas that suffer the most. This solution focuses on providing a routing/navigation service, which minimizes the impact of pollution for most of the Air Quality Management Areas (AQMAs) due to the vehicle’s emissions, while simultaneously minimizing the travel time and the respective travel costs for the driver. This scenario looks at how historical and real-time data gathered from air quality sensors and information related to vehicle-emissions can be intelligently utilized and combined to control the routes that a vehicle is recommended or mandated to take in any given journey. This can be achieved through monitoring of emissions and guiding individual, or groups of vehicles to be routed based on locally implemented emissions corridors. Vehicles such as lorries, trucks and buses, or older vehicles with high emissions may be guided through a high emissions corridor whilst low emissions or electric vehicles may be given more flexibility on routes to their destination. The possible gain resulting from implementing such a service is:

- Reduction of the pollution levels especially in urban areas which is becoming increasingly crucial.
- More effective routing for the drivers resulting in saving time and fuel costs.

11.2 Final setup

This use-case scenario is being trialled on the 5GENESIS trial facility located in Surrey, UK

11.2.1 Network architecture

The network architecture as depicted in Figure 44 consists of:

- The 5G gateway node which receives the air-quality sensors information
- The 5G access and core network (5GENESIS)
- The Cloud

![End User App - Dashboard](image)

![Vehicle OBU](image)

![Air quality sensors](image)

![Internet-Cloud](image)

Figure 44. Network architecture.
11.2.2 User application architecture

The user application architecture consists of:

- A UDP-server feeding the data from the air-quality sensors into the database system.
- The cloud infrastructure containing the software components listed in Section 10.2.4.
- The end-user application (Web dashboard)

11.2.3 Hardware components

The following section presents information regarding the developed sensors (by WINGS). The devices installed form a low-cost multi-sensor station deployed over the area of “Agios Kosmas” in Attica region, calibrated to produce accurate measurements of the following quantities:

- Gases: Ozone (O3), Carbon monoxide (CO), Sulphur Dioxide (SO2), Nitrogen Monoxide (NO), Nitrogen Dioxide (NO2)
- Particulate Matter (PM): PM1, PM2.5, PM10
- Other metrics: Noise, Temperature, Pressure and Humidity.

In terms of network and local connectivity, the supported technologies are ZigBee, LoRA, Narrowband Internet of Things (NB-IoT), Global System for Mobile Communications (GSM) and SigFox. The evaluation of the installed devices has been made by comparing the measurements with the Greek Ministry of Environment and Energy data.

11.2.4 Software components

In the current phase the software components are the ones mentioned in D4.2 as well as a dedicated web dashboard developed and finalised in phase III to serve the end-user visualization purposes:

- The UDP server feeding the sensor to the Database system.
- The software component (Java server) responsible for the Air Quality Index (AQI) calculation processing the supplied entities from the sensor side.
- The Relational Database Management System (RDBMS) maintaining the sensor data.
- The python server, where the Central Decision-Making system resides.
- A web-dashboard to visualize the proposed route.

The developed dashboard consists of a map as showed in Figure 45 displaying the user's current location and an address search field. The application is developed in Angular 10. The main map of the website is based on OpenStreetMap and Leaflet, an open-source JS library for mobile-friendly interactive maps. The address search field has an autocomplete feature, based on Geoapify Geocoder Autocomplete [31], a JavaScript (TypeScript) library that provides autocomplete functionality for the Geoapify Geocoding API.
11.3 Testing and verification

11.3.1 Methodology

The methodology to test the validity of the afore-mentioned scenario, as well as the network capabilities, was based on the simulation of the user requests. As a first step, the streaming latency of air quality data from the installed sensors to the cloud infrastructure, was measured and evaluated after integrating them with the rest of the service components. In terms of application metrics, as described in the plans of D4.2 [2], the end-to-end latency of a single request from the end user has been measured and evaluated (Section 10.3.3). Regarding the network metrics the measurement and testing tools are described in the following section.

11.3.2 List of key performance indicators

The key target KPI for the final trials is the E2E latency as shown in Table 8. The full target KPIs list for the use case scenario is presented in Section 12.3.2 of the deliverable D4.2 [2].

<table>
<thead>
<tr>
<th>Network requirements</th>
<th>Target values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latency requirements</td>
<td>Low (25 ms)</td>
</tr>
</tbody>
</table>

11.3.3 Measurement and testing tools

On the network side, the measurement and testing tools of the 5GENESIS trial facility are exploited. In particular, the following components are used:
- Infrastructure Monitoring, which focuses on the collection of data that synthesize the status of architectural components, e.g., end-user devices, radio access and networking systems, computing and storage distributed units.
- Performance Monitoring, which is devoted to the active measurements of performance indicators.
- Storage and ML Analytics, which enables efficient management of large sets of heterogeneous data and drives the discovery of hidden values and correlation among them.
- InfluxDB (storage).
- Grafana (visualization).

11.3.4 Final results

The detailed final trial results and analysis can be found in [30].

11.4 Recommendations

The smart traffic corridor scenario has been proven a valuable one since it can provide a routing plan to vehicles leading to less congestion and polluted routes. The latency of the service is minimum, only a few seconds, if we consider the benefits of low traffic and less pollution in the roads.
12 T4S4: LOCATION BASED ADVERTISING

12.1 Description and motivation

With vehicle and passenger information readily available, location-based servers can be implemented to stream content (upon request, if required) as well as local advertising or traffic guidance to vehicles and road users. This becomes especially useful in car-sharing models where vehicles are not owned, and the origin and destination of each journey may vary depending on the passengers.

As the adoption of AVs rises, millions of eyes will be off the road. This creates a world of opportunity where content like games, movies and news will be consumed in vehicles. If music streaming apps were successful at luring millions of radio listeners, self-driving cars and the accompanying new scores of passengers will not just listen to music, but they’ll also have the opportunity to binge watch video content, work collaboratively and play video games whilst on route to their destinations.

According to Forbes, cross-channel advertising opportunities in this fully immersive environment could combine the offline mediums, where commercial ads would sponsor your video content or streaming TV series. Of course, there would be digital banners and pay-per-click (PPC) targeting on your computer and mobile devices. While it may seem like it could be a further invasion to personal space, the in-vehicle experience will actually be more customised with personalised content based on past likes and online activities and histories. Imagine restaurant or activity recommendations made on the fly. The vehicle might even be programmed to take passengers directly to recommended destinations upon opt-in from the passenger. Eventually, the vehicle might even be able to be commanded to suggest a customised day, curated entirely by the AV. It’s also easy to imagine a future in which our subscription car services have two tiers: ad-supported and ad-free. Riders looking to save money could choose to be exposed to video/audio ads during their travel. It is possible that brands will “takeover” select vehicles to create “experiences” for lucky few passengers, who in turn share on their social channels, promoting the brand organically.

The initial stages of automated and connected vehicles will be a boon for traditional out-of-home (OOH) — when drivers are still behind the wheel, but with more time to look around. This could be achieved using geolocation and geo-fencing targeting individuals but also groups of travellers in separate vehicles travelling to a common destination or event (e.g. picking up their children from school or attending a football game or concert). With opportunities abound the vehicle will become a new target for advertisers who can target and identify success of their advertising with detailed information of riders becoming available.

12.2 Final setup

This use-case scenario was trialled on the 5GENESIS trial facility located in Surrey, UK.

12.2.1 Network architecture

The considered network architecture is shown in Figure 46 below. The implementation shows a GUI application running on the OBU, which displays the advertisement data streamed from the server. The application platform has the required decoders to process the received contents.

![Figure 46. Network architecture of T4S4.](image-url)
12.2.2 User application architecture

The functional architecture on the user application side is described in Figure 47. The OBU is based on Android OS and uses a standard automotive grade system on a chip (SoC). The application is written portably in the Java language native to the platform. The server uses standard server HW based on Intel and runs HTTP Live Streaming (HLS) Application. A 5G CPE was used to provide 5G connectivity.

![User application architecture with 5G connectivity, T4S4.](image)

12.2.3 Hardware components

The required HW components to conduct the trials are the following:

- OBU: This consists of an ARM based automotive board running Android.
- 4G Frontend: This is the RF HW to access the 4G network.
- 5G CPE: Huawei LF 7880 CPE\(^\text{12}\). This is the HW to access the 5G network over WiFi and Ethernet interfaces.
- Server: These are standard datacentre servers running Linux or Windows.

12.2.4 Software components

The required SW components to conduct the trials are the following:

- Client App: This is a Java application to playback HLS streamed from the server.
- Streaming App: This is a Personal Home Page (PHP) application to serve HLS file segments.
- Network Middleware: Uses standard TCP/IP and Point-to-Point Protocol (PPP) SW available in the system.
- USB Driver: This is the device driver to interface the 4G Frontend to the system.
- Network Driver: These device drivers provide WiFi and Ethernet access to the application software in the case of 5G.

\(^{12}\) [https://consumer.huawei.com/en/routers/5g-cpe-pro/](https://consumer.huawei.com/en/routers/5g-cpe-pro/)
12.3 Testing and verification

12.3.1 Methodology

Testing was carried out by running the client/server applications and measuring KPIs by inserting logs into the code. A screenshot of the test application used for taking measurements is shown in Figure 48 below. Note that the measurement logs are shown alongside.

![Screenshot of the multimedia playback application.](image)

12.3.2 List of key performance indicators

The user requirements associated with this use case scenario have been analysed and converted into a set of network KPIs. Table 9 presents the resulting list of network requirements together with their target values.

<table>
<thead>
<tr>
<th>Network requirements</th>
<th>Target values</th>
</tr>
</thead>
<tbody>
<tr>
<td>User experienced DL throughput</td>
<td>High (100 Mbps)</td>
</tr>
<tr>
<td>User experienced UL throughput</td>
<td>Low (1 Mbps)</td>
</tr>
<tr>
<td>Latency requirements</td>
<td>Medium (5 ms)</td>
</tr>
</tbody>
</table>

12.3.3 Measurement and testing tools

No third-party testing tools were used. The measurements were taken by inserting logs into the code.

12.3.4 Final results

The detailed final trial results and analysis can be found in [30].
12.4 Recommendations

It was found that the network bandwidth was scalable enough to give uninterrupted multimedia playback. The latency offered by the network along with application side buffering was able to provide good user experience. As the traffic was almost entirely in download direction, only the few bytes GPS location data being in upload, the KPI measurements were done in download direction.
13 T4S7: ENVIRONMENTAL SERVICES

13.1 Description and motivation

Local, regional and national weather offices source their data through satellite earth observation maps and local weather stations. These are generally used for weather forecasts. Vehicles may provide a rich and real-time source of weather and environmental information through existing on-board sensors such as:

- Light sensors for external light conditions such as cloud cover and fog.
- Wiper data for intensity of rain.
- Suspension data for monitoring road conditions such as potholes.

These can be consolidated to create hyper local weather maps aiding drivers and AVs in day-to-day driving but also to assist local authorities to improve road maintenance.

This scenario focuses on collection and consolidation of weather and environmental sensor data which can be used to create hyper local weather maps aiding drivers and AVs in day-to-day driving but also to assist local authorities to improve road maintenance.

Vast amounts of environmental sensors exist both on board vehicles as well as in roadside infrastructure, but currently that data is not consolidated, integrated and used outside very specific and isolated applications for which each sensor is deployed. With the availability of 5G capabilities and infrastructure the opportunity for massive transfer and consolidation of on-board and roadside environmental sensor data and the utilisation of that data in different scenarios and applications becomes possible.

Key for the implementation for this use case would be a centralised hub or exchange that would consolidate, process, translate and make available the collected data and information. Some distributed processing and consolidation might be desirable for some applications, e.g. either at the vehicle OBU or RSU.

In vehicles, a wealth of environmental data can be accessed and collected using an OBU integrated or connected to the vehicle systems, including light sensors, wiper data and suspension sensors. Roadside infrastructure will include air quality sensors, non-ionizing radiation sensors, acoustic noise sensors which could be integrated into the same system for data collection and integration.

Weather and environmental sensor data can be used to create hyper local weather maps aiding drivers and AVs in day-to-day driving. Driver warnings and advisory speed limits would be an example of applications of such data from a vehicle point of view. External transportation systems would also use such data for proactive traffic management in real time.

Additionally, environmental information could be used in planning and management systems with data collected over time, for example for road maintenance by local authorities, weather forecasting by the Met Office, emergency services planning and response, asset inventory and management planning by authorities responsible for road conservation, pollen monitoring and mapping as well as water and sewage monitoring and maintenance.

13.2 Final setup

This use-case scenario was trialled on the 5GENESIS trial facility located in Surrey, UK.

13.2.1 Network architecture

The network architecture during sensor data upload to cloud is shown in Figure 49. An OBU is installed in a vehicle with integration to the on-board environmental sensors. The collected data was transferred using the 5G network to a centralised hub.
13.2.2 User application architecture

The functional architecture on the user application side is shown in Figure 50. The OBU is based on Android OS and uses a standard automotive grade SoC. The Application is written portably in the Java language native to the platform. Air quality sensors measuring PM and 5G frontend HW are interfaced, by which the sensor data is uploaded to backend. The server uses standard server HW based on Intel and runs computer an IoT oriented server Application, using the MQTT protocol.

13.2.3 Hardware components

The required HW components to conduct the trials are the following:

- **OBU**: This consists of an ARM based automotive board running Android.
- **4G Frontend**: This is the RF HW to access the 4G network.
- **5G CPE**: Huawei LF 7880 CPE\(^\text{13}\). This is the HW to access the 5G network over WiFi and Ethernet interfaces.
- **Server**: These are standard datacentre servers running Linux or Windows.

13.2.4 Software components

The required SW components to conduct the trials are the following:

- **Client App**: This is a Java application to broadcast PM2.5 and PM4.0 readings over MQTT to the backend server.
- **MQTT Server**: Provides the data bus using MQTT via publish/subscribe methods

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\(^{13}\) https://consumer.huawei.com/en/routers/5g-cpe-pro/
• Network Middleware: Uses standard TCP/IP and PPP SW available in the system.
• USB Drivers: These device drivers interface the 4G Frontend and PM X.Y sensor to the system.
• Network Drivers: These device drivers provide WiFi and Ethernet access to the application software in the case of 5G.

13.3 Testing and verification

13.3.1 Methodology

Testing was carried out by running the client/server applications and measuring KPIs by inserting logs into the code. A screenshot of the test application used for measurement is shown in Figure 51.

![Screenshot of sensor data capture application](image)

Figure 51. Screenshot of sensor data capture application

13.3.2 List of key performance indicators

The user requirements associated with this use case scenario have been analysed and converted into a set of network KPIs. Table 10 presents the resulting list of network requirements together with their target values.

<table>
<thead>
<tr>
<th>Network requirements</th>
<th>Target values</th>
</tr>
</thead>
<tbody>
<tr>
<td>User experienced DL throughput</td>
<td>Low ≤ 1 Mbps</td>
</tr>
<tr>
<td>Latency requirements</td>
<td>Low (100 ms)</td>
</tr>
</tbody>
</table>

13.3.3 Measurement and testing tools

No third-party testing tools were used. Measurements were taken by inserting logs into the code.

13.3.4 Final results

The final results are reported and discussed in D6.4 [30].
13.4 Recommendations

The use case was IoT oriented with very few bytes of data transmitted. Hence bandwidth was not an important metric and was not measured. The data being present periodically, reliability and acknowledgement was not of major concern and roundtrip metrics were not collected. The settling time of sensor was longer and hence data was sampled only once in few second, resulting in the actual traffic volume being low.
14 CONCLUSION

This deliverable described the final Phase 3 solutions adopted for the transport vertical use cases as well as the final trial setups and application-level results.

In Phase 2, the focus was on the extended implementations of the use case service components, i.e. evolved solutions, as the solution design work progressed from individual components trialled in Phase 1, towards integrated trial deployments. The performance of the Phase 2 implementations was mainly verified on top of the early 5G test facilities (5G NSA) and the intermediate results reported in D4.3 [3].

During Phase 3, the focus of the work shifted from basic functional testing and performance verification to end-to-end solutions deployed on top of 5G networks, in order to trial and demonstrate the extended capabilities of the final solutions and applications. The final Phase 3 implementations and solutions described in this deliverable have been mainly deployed and trialled over 5G SA, supported by the various partner’s testbed facilities.

The final trials were conducted on a per scenario basis, coordinated by the scenario leaders, utilising the 5GENESIS (Surrey, UK), 5Groningen (Groningen, Netherlands) and 5GTN (Oulu, Finland) trial facilities, except for scenario T2S2, which was fully based on simulations, and for T2S3 and T3S1, which were been trialled at the TUC test site (Chemnitz, Germany) utilising a commercial 5G network. The results of trials, pertaining to the measured network KPIs are reported in deliverable D6.4 [9].
REFERENCES


[13] 3GPP TR 37.885; Study on evaluation methodology of new Vehicle to-Everything (V2X) use cases for LTE and NR. 2018.


[25] https://www.etsi.org/deliver/etsi_ts/103300_103399/103301/01.01.01_60/ts_103301v010101p.pdf

[26] https://www.etsi.org/deliver/etsi_ts/103300_103399/103301/01.01.01_60/ts_103301v010101p.pdf

[27] https://www.etsi.org/deliver/etsi_ts/103300_103399/103301/01.01.01_60/ts_103301v010101p.pdf


[36] https://draive.com

[37] https://doi.org/10.5281/zenodo.3908559

[38] https://gstreamer.freedesktop.org/

[39] https://chrony.tuxfamily.org/

[40] https://gpsd.gitlab.io/gpsd/

[41] https://draive.com