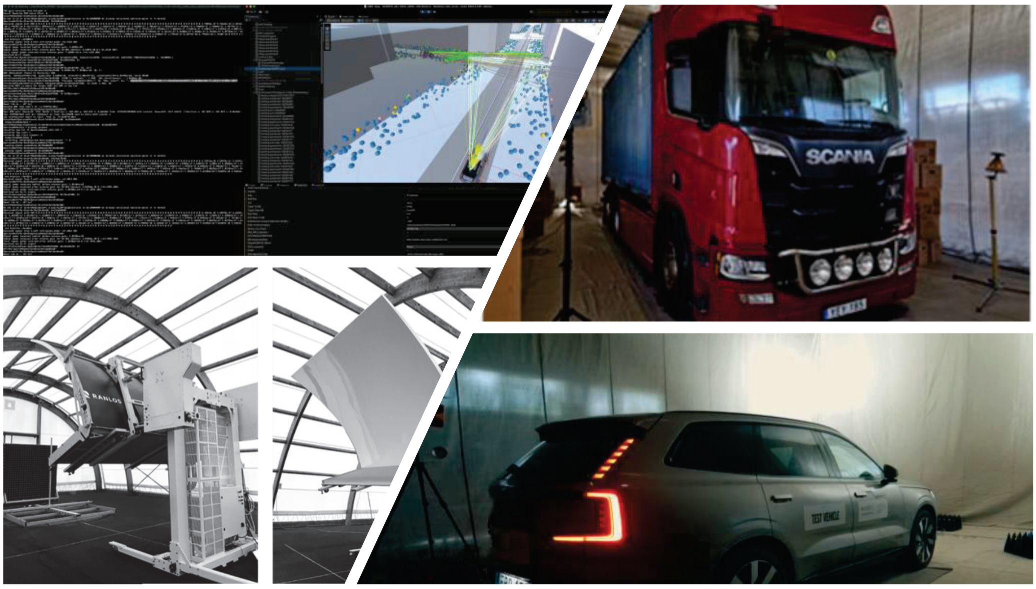
SImulation and VErification of wiReless Technologies 2 (SIVERT2)

Public report



Author: Ida Hagström, Volvo Cars Corporation

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Project within FFI elektronik, mjukvara och kommunikation för fordonsindustrin

Fordonsstrategisk
Forskning och
Innovation

Executive summary

SImulation and VErification of wiReless Technologies 2 (SIVERT2) commenced in April 2022 and was finalised in September 2025. The project is a continuation of the work in FFI SIVERT [*1*]. The project management has been handled by three persons from Volvo Cars: Christian Lötbäck, Anton Skårbratt and Ida Hagström. All project partners in the original application have been involved in the project until the end, the project partners are Volvo Cars, Scania, Lunds University, RISE, RanLOS and Tietoevry.

The project has comprehensively validated vehicle connectivity, spanning Vehicle-to-Network (V2N) 4G and 5G networks, alongside Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). The project has addressed three different stages of verification; simulations, full vehicle verification on a radio frequency (RF) level and End-to-End (E2E) verification. The main vision behind these three stages is to continue exploring the "shift left" philosophy developed in SIVERT1, where verification of vehicle connectivity is done as early as possible in the vehicle development projects.

In SIVERT1 an extensive simulation framework was developed for V2V communication, covering signal propagation and communication stack etc. to enable a full system simulation of V2V communication. In SIVERT2 this framework was extended to also cover V2N communication, thus enabling early-stage validation of 4G and 5G communication systems. Important features for the V2N communication were added, such as multiple distributed antennas, as well as the possibility to add electromagnetic interference. Significant work has been done to incorporate the channel model, the communication stack and MIMO antenna patterns.

For full vehicle verification on an RF level, one main focus area has been to extend the reverberation chamber test method developed in SIVERT1 for 4G communication, to also cover 5G communication. Significant work has been made to adapt and verify the test method for this new communication standard. In SIVERT2 full vehicle verification of V2V communication has also been investigated, building on the wireless cable and RanLOS measurement system developed in SIVERT1. Significant progress has been made to combine the V2V simulation framework with the wireless cable test setup to enable a red thread in the validation steps. Proof-of-concept measurements have been performed to compare simulation, measurement and field test data with good results. Also, the RanLOS measurement system, developed within SIVERT1, has been upgraded to support the V2V frequency bands and now provides semi-3D radiation pattern measurements, expanding beyond its original 2D capabilities.

Finally, one main objective of SIVERT2 was to expand the testing beyond the RF level and increase understanding of the complete E2E performance. Vehicle E2E use cases have been investigated from a quality of experience and quality of service point of view in the project. Test methods for selected use cases have been developed and several test environments investigated.

Comparing the outcome from the project with the defined scope in the FFI application, most of the milestones have been met. The scope of the objectives in work package 3 (E2E verification) was quite ambitious and the complexity of creating generic test methods for E2E was underestimated. To address the complexity, use case-specific test methods were developed and with limited effort the methods can be expanded to new use cases.

The findings from the project have been widely shared in the industry through publications and disseminations, and the simulation tool will be publicly shared.

Contents

1 Background

The adoption of wireless communication in vehicles is expanding rapidly, playing an important role in enhancing road safety and user experience. V2V, V2I communication and cloud based cellular systems allows vehicles to exchange critical information about traffic congestion, hazardous road conditions and accidents in real time. Additionally, modern infotainment systems are becoming increasingly dependent on internet connectivity to deliver premium user experience. The 5G Network expansion creates new possibilities for the vehicle industry but poses more challenges in relation to testing and verification.

To ensure the quality and reliability of the wireless systems in the vehicles, rigorous testing is needed throughout the development process. It is of high importance to replace as much of the field testing as possible, as this is time-consuming, challenging to replicate, and typically occurs at the final stage of a project. Hence, there is a need for lab test methods that can be applied earlier in the development process and with higher reproducibility, this approach is known as the shift-left philosophy.

The FFI SIVERT project has addressed verification of vehicle connectivity modules in a comprehensive manner, from simulations in early phases of a vehicular project to final verification of implemented systems in complete vehicles [*1*], in the report the project will be referred to as SIVERT1 to avoid confusion with the SIVERT2 project. The findings from SIVERT1 have been important in forming the FFI SIVERT2 project.

One important deliverable from FFI SIVERT1 is the simulation framework for V2V communication. This has been found to be a useful tool for validation of communication systems even before any hardware becomes available. This deliverable was an important foundation for expanding the framework to also cover V2N communication

Another important part of the connectivity performance evaluation in SIVERT1 was the development of the complete vehicle OTA test methods. Several methods were prototyped and carefully analysed in terms of accuracy and feasibility to automotive use cases. The project investigated test methods for 4G LTE communication for both component and full vehicle. Building on this foundation, some of these test methods are utilized in SIVERT2 to expand the testing to 5G and V2V communication systems, including additional frequency bands and 4x4 MIMO.

With the increased SW complexity of vehicles and their growing dependency on connectivity, E2E testing has become a critical component of the development process. E2E testing ensures that all integrated systems; hardware, software, and communication interfaces, work together seamlessly under real-world conditions. This holistic approach is essential for identifying integration issues early, validating system behaviour, and enabling continuous software updates with confidence. As vehicles evolve into connected platforms with features like Over-The-Air (OTA) updates and autonomous driving capabilities, the scope of E2E testing expands significantly. Now, it must account for dynamic environments, varying network conditions, and interactions between multiple subsystems. The challenge is further amplified by the need to maintain reliable, low-latency connectivity while the vehicle is in motion, often across different regions and network infrastructures. These complexities underscore the importance of ongoing research and innovation in E2E testing methodologies.

2 Purpose, Research Questions and Method

The project scope is outlined in the project application [2] and aims to continue the study from SIVERT1 [1] of how verification of wireless technologies in vehicles can be done more efficiently in earlier phases of vehicle projects. An overview of the project scope of SIVERT1 and SIVERT2 can be seen in Figure 2-1.

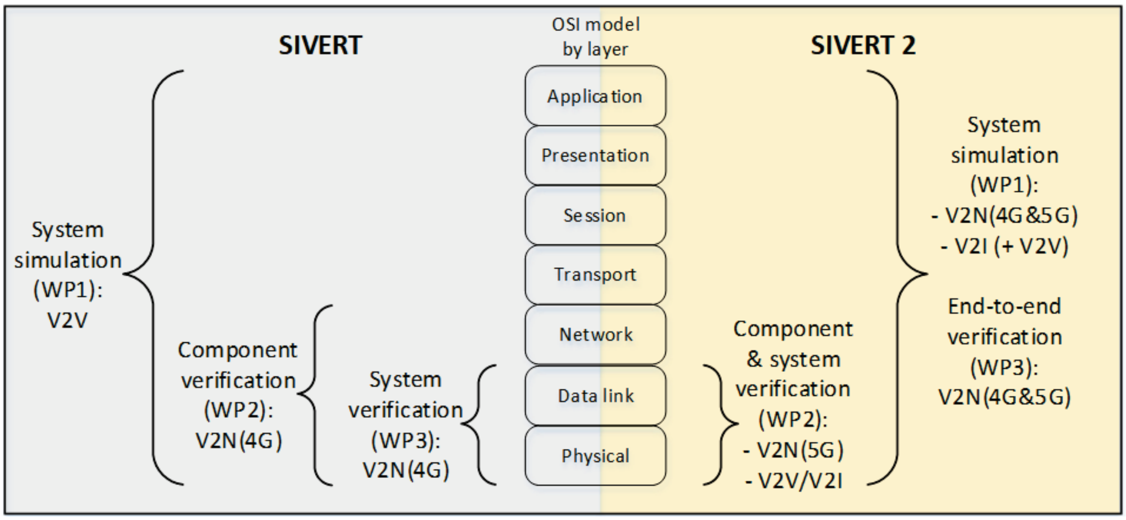


Figure 2-1, SIVERT1 vs SIVERT2 regards to the open systems interconnection (OSI) model.

Utilizing controlled lab environments would facilitate the assessment of device performance by eliminating variables from a live network. Additionally, the tests would be performed in a controlled and repeatable way, increasing the test efficiency, quality and reducing development cost. The project has addressed three different stages of verification; simulations, full vehicle verification on an RF level and E2E verification.

The project aim can be summarized into three research questions:

- Shift left: how to do testing earlier in vehicle development projects?

Earlier testing means issues can be found earlier in the development cycle leading to mitigation at a lower cost, more R&D loops can be done, and it also reduces risks of development delays. Additional testing also leads to better quality of the final product. This research question will be addressed by setting up appropriate simulation and lab measurement tools and test cases. The different work packages will also cooperate to make sure there is a "red-thread" throughout the verification process.

- How to get a more data driven connectivity design?

Simulations before and during the development process can improve the connectivity design and estimate the performance of the full system. For example, the simulation tool from WP1 that can incorporate simulated or measured antenna radiation patterns, as well as propagation conditions representative to real vehicle use cases, will help determine the best antenna placement. Another example is to use data from the current vehicle fleet to feedback into the lab test scenarios, which will be addressed in work package 3 (WP3).

- How can we bridge the gap between vehicle applications and connectivity requirements?

Connectivity is an enabler for many vehicular applications. Understanding the final end-user experience in various connectivity conditions is important to ensure a seamless experience. WP3 will address this by developing test setups for application testing for different connectivity environments, enabling lab testing of applications in a controlled and repeatable way. The goal is also to find a link between selected use cases in WP3 and the lower-layer requirements evaluated in WP1 and WP2, such as throughput.

The project is organized into three main packages.

- The first work package (WP1) is focusing on the **early concept phases** of the vehicle project where no hardware is available. The goal here is to further develop the simulation framework from SIVERT1, which can be used to improve system design before specifications are finalized.
- The second work package (WP2) focuses on the **engineering phases** of the vehicle project where prototyping has started, and verification measurements can be performed. This work package will build on the component and complete vehicle test methods developed in SIVERT1 and extend them to support verification of wireless technologies that will be included in vehicles in the future, such as 5G and ITS-G5/LTE-V2X.
- The third work package (WP3) is focusing as well on **engineering phases** of the vehicle project, where the component and complete vehicle is interacting in an E2E system, i.e., the TCU connected to the cloud through a test core network.

The details of the objectives can be found in Chapter 3.

3 Objectives

The project covers a wide range of verification aspects and thus has been divided into three main work packages. For each of these work packages, clear objectives were defined. These are summarized in the following subsections.

3.1 Work Package 1 – System Simulation

WP1A: Antenna Characteristics

- **Objective**: To implement realistic impact from multiple antenna systems for V2V, V2I and V2N scenarios and operating frequencies up to 7.2 GHz. The efforts will be targeting a minimum of 4 receiving antennas and 4 transmitting antennas supported in the simulation framework. The target is to have a complete chain of simulation, including also simulated antenna characteristics for antennas mounted on vehicles, possibly in a distributed fashion.
- **Comments**: 3D antenna patterns for system simulations were incorporated in the SIVERT2 simulation framework. Any source of the antenna radiation pattern data (analytical, simulated, measured in the lab) can be used and reconstructed using the EADF (Effective Aperture Distribution Function) in 3D. Antenna simulations on the vehicle CAD (Computer Aided Design) body structure were prototyped and compared with antenna patterns from the antenna measurement performed in antenna labs (antenna mounted on the vehicle body). The simulation framework was also extended to support calculation of the multiple simultaneous links between arbitrary Tx/Rx antenna constellations to enable MIMO (Multiple-Input Multiple-Output) simulations.

WP1B: Electromagnetic Interference (EMI)

- **Objective**: To include impact from EMI on V2X communication performance in the SIVERT1 simulation framework.
- **Comments**: We studied the literature on the EMI system modelling in automotive wireless communications. We identified the need for the dynamic unintentional wide and narrow band EMI (incl. frequency-selective) for the future automotive needs, since the amount of potential EMI emitters (high-speed clocks, high-speed transmission lines, etc.) is growing in modern vehicles. We also reviewed the Link-to-System Block-Error-Rate (BLER) packet errors calculations in the modern system level wireless simulators (with emphasis on ns-3) and decided on the approach to introduce EMI into the SIVERT1 simulation framework. As an EMI source we focused on the EMI levels measured in the EMI lab using probe antenna installed next to the telematic unit (this is how the EMI levels can be dynamically measured in the future) – for the research purposes the EMI levels were artificially synthesised using the signal generator and emitted in the EMC lab over-the-air. With spectrum analyser in dynamic waterfall mode, we recorded EMI files that captured the frequency and time resolution of the EMI patterns. This was done for both V2X short range and 5G bands. We Implemented a dynamic EMI injection using what was read from the EMI lab measurement files (preserving frequency and time scale and resolution). We also validated adaptation loop behaviour under EMI – demonstrated that adaptive Modulation and Coding Scheme (MCS), rank, and channel quality reporting respond to EMI levels, showing the sensitivity and capability of the simulation framework to measure degradations caused by measured EMI values.

WP1C: End-to-End (V2I/V2N implementation for E2E performance analysis)

- **Objective**: Extension of the SIVERT1 simulation framework with V2I and V2N communication scenarios and frequencies up to 7.2 GHz to support simulative evaluation of V2X technology evolution.
- **Comments**: This sub-WP develops the extension of the IRACON GSCM (Geometry-based Stochastic Channel Model) to V2N elevated general scenarios. The model was extended to

cover all typical propagation scenarios in the frequency range 1 (FR1 - 410 MHz to 7.125 GHz), but also benchmarked against channel sounding data covering up to mmWave FR2 spectrum, demonstrating a good agreement. The GSCM was extended for the V2N scenario in Unity3D game engine using ray-tracing approach for channel calculation enablement. Implementation on the system level was also verified against the Line-of-Sight (LoS) and Non Light-of-Sight (NLoS) field measurements executed in Gothenburg and has shown a very good agreement. The SIVERT1 simulation framework was extended to accommodate the 5G/5G-V2X Vehicle-to-Vehicle/Vehicle-to-Infrastructure/Vehicle-to-Network and EMI scenarios. A GSCM model for V2X communications was implemented and verified in WP1. Similar to SIVERT1 architecture, the Unity3D – ns-3 coupling via API was extended to accommodate new network access technologies and scenarios. API was extended to support EMI data introduction and injection, as well as new GSCM data. On the ns-3 (network side) 5G-Lena ns-3 5G extension module was used as a baseline and extended/modified to introduce the GSCM channel, which replaces the standard 3GPP 38.901 Cluster Delay Line (CDL) model used in 5G-Lena, while keeping other 5G Radio Access Network (RAN) functionality (channel estimation, adaptive modulation and coding, spatial properties and precoding, etc.) intact to leverage the spatially consistent properties of ray-tracing calculated GSCM to achieve advanced system level simulation results.

3.2 Work Package 2 – Component and System Verification

WP2A: Wideband channel emulation

- **Objective:** Investigate state-of-the-art of wideband channel emulation and extend the existing test setups developed in SIVERT1 to cover relevant bandwidths and frequencies used by 5G and V2V/V2I systems.
- **Comments:** This work summarizes the state-of-the-art in 5G OTA test of User Equipment (UE), including both vehicles, like cars and trucks, as well as vehicular components. It reviews recent research, standardization updates, and highlights test methods relevant to channel emulation. Key test setups explored include Reverberation Chamber (RC) with/without channel emulator, and wireless cable test setups for V2N and V2V/V2I. The test setups implemented in WP2B and WP2C were defined based on this state-of-the-art analysis.

WP2B: V2N

- **Objective:** Extend the test setups developed in SIVERT1 to also include 5G.
- **Comments:** The results extend the SIVERT1 test setups to support 5G, using insights from WP2A on current wireless technologies and channel emulation. The focus was on enhancing RC OTA testing for V2N in Standalone (SA) 5G at FR1. Efforts include increasing bandwidth, analysing power levels, Doppler and delay. The method supports testing of higher-order MIMO, antenna integration, throughput, Block Error Rate (BLER), sensitivity, and various bandwidths. It also enables scenario-based and Virtual-Drive-Test (VDT) testing.

WP2C: V2V/V2I

- **Objective:** Extend the test setups developed in SIVERT1 to cover V2V and V2I communication.

- **Comments:** This work summarizes progress in WP2C, which extends SIVERT1 test setups to cover V2V communication. V2I was also in the scope, but the main efforts have been spent on V2V scenarios. Key outcomes include the definition of relevant channel models and the selection of the wireless cable method as the preferred test method. This method has also been evaluated in a rooftop box version with a conductive textile. A major focus has been the implementation of a versatile scenario tool where simulated data from WP1 were converted into a re-playable format to the channel emulator: a VDT tool. This process was verified for power, Doppler and delay. The tool enables realistic, repeatable testing and supports both V2V and V2I. WP2C has also included the development of the RanLOS measurement system. This has included extending the frequency range to cover the V2V and V2I frequencies by upgrading the system with a new feed array covering the range 3 GHz-6 GHz. The test system was also upgraded to semi-3D measurements, former only 2D, by developing a lift and tilting device for the system. Both the new feed array and the lift-and tilt device have been extensively verified, both in terms of test zone accuracy and real vehicle V2V antenna pattern performance.

WP2D: V2X use cases & Quality of Service (QoS)

- **Objective:** Understand the requirements on QoS from the customers regarding V2X functions. Cascade the QoS identified in WP3A for V2N to NFRs on the lower layers in the OSI model that can be verified by the test methods developed within WP2B. Identify the core use cases for V2V/V2I and cascade them in the same way as for V2N, which can be tested by the methods in WP2C.
- **Comments:** The results from the WP3 have shown that it is not easy to cascade one parameter in order to find the "breaking point" of user functions. The use cases identified and tested throughout the WP3 have shown a significant interdependency between parameters.

3.3 Work Package 3 – End-to-End verification

WP3A: V2N use cases & Quality of Experience (QoE)

- **Objective:** To understand the QoE by the customers regarding cellular connectivity functions. Cascade the QoE to NFRs that can be verified by the developed test methods.
- **Comments:** The investigation has identified several use cases in vehicles using cellular connectivity. The use cases have different connectivity requirements, and the quality of experience is affected differently when the connectivity is inadequate. The requirements have been cascaded from quality of experience to non-functional requirements for some selected use cases.

WP3B: Network Behaviour

- **Objective:** Even if the Telematics Control Unit (TCU) in a vehicle is certified according to legal requirements and different Mobile Network Operators (MNO) test procedures, this is not a guarantee that the module will work perfectly in real life. There is a need to identify and define test scenarios beyond existing certification tests by learning from existing data from live networks, with the aim to define test cases used in the next vehicle project.
- **Comments:** An investigation into network behaviour has been conducted and several network behaviours studied in more detail. The typical network characteristics and behaviour of the connectivity service have been described and documented. An analysis of the network influence factors (NIF) has been made using the statistical test method Design of Experiment (DoE) The NIF analysis was used to quantify the importance of the different network parameters.

WP3C: HIL Setup

- **Objective:** To enable E2E verification of the TCU in lab setups so that E2E verification can be performed earlier in the vehicle projects and performed with a higher degree of control. This allows testing of "What-if" scenarios, which are not possible or desirable to test in field/live networks.
- **Comments:** Several test setups were evaluated with either a vehicle TCU or a commercial unit. The first round of tests was done on the OTA Software Download (SWDL) use case. Later, four test setups were evaluated with additional use cases. A Measurement System Analysis (MSA) evaluation was performed to determine the accuracy and precision of the test setups. The test setups are divided into four groups: Controlled IP Data Throughput, Network Simulators, Private Lab Networks and Private Live Networks. Some testing was also done in Public Live Networks as a reference.

WP3D: Complete Vehicle Setup

- **Objective:** To enable E2E verification on complete vehicle level for cars and trucks. This will enable E2E verification of the complete vehicle including sub-systems and, e.g., Electromagnetic Interference (EMI).
- **Comments:** Full vehicle E2E testing was never performed during the project. There are several reasons for this outcome. During the project the complexity of E2E testing became apparent. In a E2E setup with many use cases, the partners in the project do not control the full chain, with external servers etc. Another reason to test sub-systems instead, is the complexity of fault tracing in a complete vehicle E2E test setup. It would require expertise from many technical areas and is in the end, it is impractical to add it to a vehicle verification strategy. This is an important conclusion from the project, that several sub-system tests, rather than one full E2E test scenario for complete vehicle, are more appropriate. For these reasons, the objective was not completed, and more focus was put on the sub-systems and other objectives.

4 Results and Deliverables

This section summarizes the most important results from the project.

4.1 Delivery to FFI Goals

The table below summarizes the main targets defined in the application [2] and their status after the completion of the project, Table 4-1.

Table 4-1, Delivery to FFI Goals

Defined Target [2]	Project Conclusion	Comment
Promoting cooperation between industry (Volvo Cars, Scania), university (**Lunds University**) and research institute (RISE) through joint research and development of frameworks and methods.	Fulfilled	The collaboration between the partners have strengthened throughout the project. Volvo Cars and Scania have shared insights into respective companies testing strategies, which has strengthened and improved the overall wireless testing knowledge and methods in the companies. RISE and Lund University has provided valuable knowledge within wireless communication and shared state-of-the-art research on channel modelling and industry standards outlook, which has been the foundation for the simulation framework and the development of verification methods.
Promoting cross-industrial cooperation and knowledge transfer through the project's collaboration with the cellular testing industry (Tietoevry, RanLOS AB), but also with instrument suppliers when applicable (e.g., Keysight, R&S, Spirent, and Bluetest).	Fulfilled	The collaboration between the partners have strengthened throughout the project. RISE, RanLOS and Tietoevry have shared valuable testing knowledge to increase accuracy and efficiency in the industry verification frameworks. By using test instruments from the major suppliers (e.g. Amarisoft, R&S and Spirent), it has been possible to develop easy-to-use test procedures and perform valuable benchmarking. RanLOS has performed the majority of the verification and other measurements at Volvo Cars, as well as partly together with Volvo Cars. This has been of great value to understand the measurement needs and wishes from the industry. RanLOS has also gotten valuable input, based on the need from the industry, to both the mechanical and software development of the BeamTilt device.

Increasing the Swedish capacity for research and innovation within the wireless simulation and testing field.	Fulfilled	In the project we have gathered Swedish competence in wireless simulation and testing for vehicular scenarios. Papers have been published and dissemination have been performed to disseminate the knowledge gained in the project both internally within the companies and outside the consortium. Publishing the simulation framework will give Swedish researchers access to it, enabling them to build upon and extend it in the fields of wireless propagation, wireless systems, and other related domains. Partners such as RISE have maintained their position as relevant contributors in OTA test research, both nationally and internationally.
Developing state-of-the-art measurement solutions for complete vehicles enables RISE to setup internationally competitive commercial validation solutions, which also can contribute to international standards.	Fulfilled	The project deliverables include several state-of-the-art measurement solutions for complete vehicle. The RC has been verified with a 5G network simulator and is commercially available for testing. The 2-stage methods have been setup and proof-of-concept measurements have been performed. The RanLOS measurement system has been extended to support higher frequencies and semi-3D measurements. Several test setups for E2E testing have also been developed.
Promoting cooperation between universities and industry by offering an extended simulation framework to the public.	Fulfilled	The simulation tool has been extended and will be made public[1]. 6G simulation and emulation activities at the WiTECH research centre will build on the results from WP1 and WP2 in this project.

[1] *As of this moment the simulation framework is pending approval for publication.*

4.2 Work Package 1: System Simulations

This section presents the SIVERT2 simulation framework, an advanced 5G V2X network simulation framework that integrates Unity3D's [*3*] ray-tracing capabilities with ns-3 LENA [*4*] for enhanced channel modelling accuracy. The system introduces novel approaches to MIMO integration, real-time electromagnetic interference (EMI) modelling, and Geometry-based Stochastic Channel Modelling (GSCM). Our implementation replaces traditional 3GPP TR 38.901 channel models with Unity3D-computed channel matrices, enabling advanced realism in vehicular communication scenarios while maintaining computational efficiency for real-time applications.

The evolution of 5G New Radio (NR) technology has introduced complex Multiple-Input Multiple-Output (MIMO) systems that demand increasingly sophisticated simulation environments. Traditional channel models, while mathematically sound, often fail to capture the intricate electromagnetic propagation characteristics present in real-world vehicular scenarios.

Specifically, the standardized 3GPP TR 38.901 [*5*] channel models, while providing statistical accuracy for general scenarios, exhibit significant limitations when compared to the spatially consistent GSCM [*6*] approach. On the UE side where antenna design is severely constrained by space limitations, complex vehicle geometry, ECU placement requirements, and the need to satisfy aesthetic and aerodynamic requirements. Although arbitrary antenna radiation patterns, array geometries, and mounting positions can be provided to a 3GPP 38.901-based simulator, the underlying multipath, delay, angular spread, and correlation statistics still come from standardized stochastic distributions. In vehicular environments, antenna radiation patterns are dramatically influenced by surrounding materials, metallic vehicle structure, and constantly changing orientation caused by vehicle motion - effects that cannot be captured by stochastic models alone. Furthermore, 3GPP models have only limited spatial consistency required for advanced MIMO techniques and are not linked to the geometry of the propagation environment, as they generate channel coefficients independently in so-called drops rather than accounting for the underlying geometric relationships that govern real electromagnetic propagation. SIVERT1 addresses these fundamental limitations by creating a hybrid simulation architecture that leverages Unity3D's advanced ray-tracing engine for realistic channel computation while maintaining the robust protocol stack implementation of ns-3 LENA [*4*]. This approach enables researchers to study 5G performance in complex electromagnetic environments with enhanced realism, capturing both the geometric complexity of real-world environments and the sophisticated antenna patterns that characterize modern vehicular communication systems.

The work performed includes:

- A novel integration architecture between Unity3D and ns-3 LENA
- Real-time channel matrix injection replacing 3GPP TR 38.901 models
- Advanced EMI modelling using laboratory-measured interference spectra
- Pre-configured beamforming preservation with static beam patterns throughout simulation duration, while still enabling LENA to determine optimal transmission strategies including rank selection, modulation schemes, and power allocation that reflect true electromagnetic propagation conditions.
- Antenna simulation and measurement solutions for system level simulation environments.

4.2.1 SIVERT2 simulation framework architecture

The progression from deterministic to stochastic channel models has been driven by the need to balance computational complexity with accuracy. Traditional approaches include:

Deterministic Ray-tracing Models: Based on Maxwell's equations, these provide high accuracy but at prohibitive computational cost for large-scale simulations. Also the EM properties and precise geometry features of the environment is difficult to get for deterministic simulations.

Stochastic Models: 3GPP TR 38.901 defines statistical channel models that capture key propagation phenomena through parameterized distributions. While computationally efficient, these models lack spatial correlation accuracy required for advanced MIMO systems.

Geometry-Based Stochastic Channel Models (GSCM): These models, employed in our Unity3D implementation, combine geometric ray-tracing with stochastic elements, providing a balance between accuracy and computational feasibility.

The SIVERT architecture implements a distributed simulation environment where Unity3D serves as the channel computation engine while ns-3 LENA [7] handles the 5G/5G-V2X protocol stack simulation.

The Unity3D component creates a comprehensive 3D digital twin environment that forms the foundation for spatially consistent GSCM modeling. This digital twin encompasses:

Detailed Environmental Modeling:

- **Building Infrastructure**: Complete 3D geometric representation of buildings with accurate dimensions, typically imported from OpenStreetMap databases or similar geographic information systems.

- **Road Infrastructure**: Precise modeling of road networks, including elevation changes, surface materials, and roadside infrastructure elements.

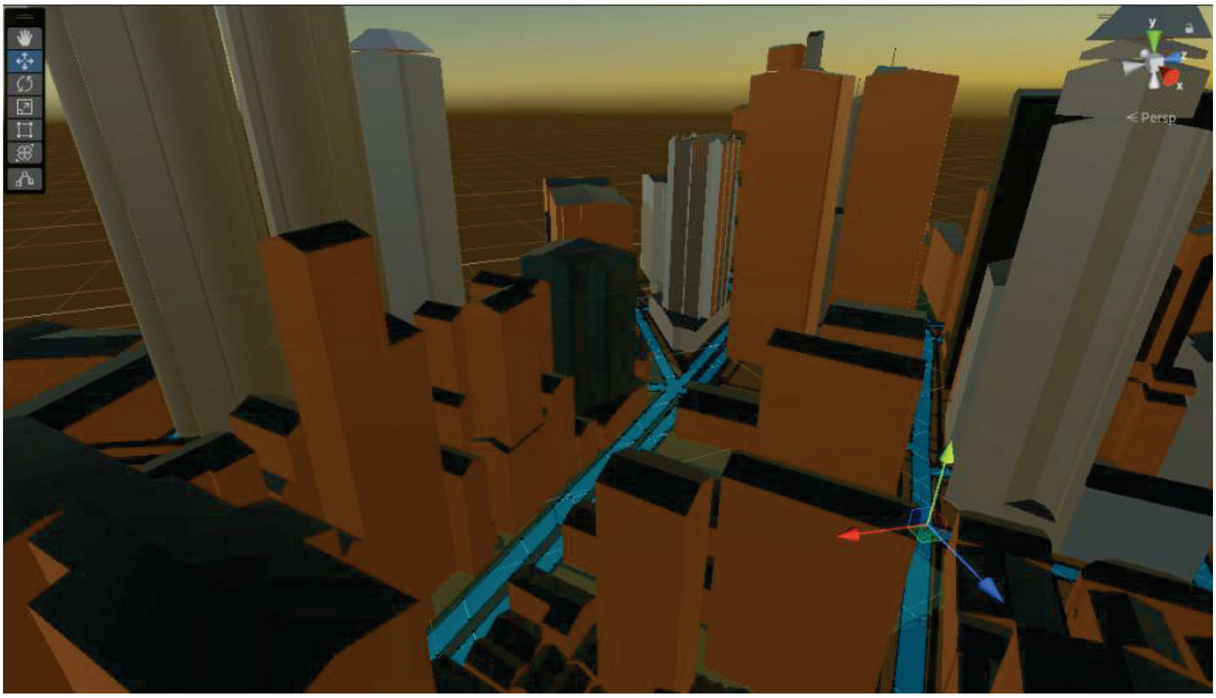


Figure 4-1, Digital twin in Unity3D

- **Vehicular Representations**: Detailed 3D models of vehicles serving as UE platforms.

Advanced Antenna System Integration:

- **gNB 3D Antenna Patterns**: Full three-dimensional radiation patterns for base station antennas, including both co-polarized and cross-polarized components.

- **UE Antenna Modeling**: Complex vehicular antenna patterns that account for vehicle body effects, mounting locations, and nearby ECU interference.

- **Pattern Orientation**: Real-time tracking of antenna orientation as vehicles move through the environment.

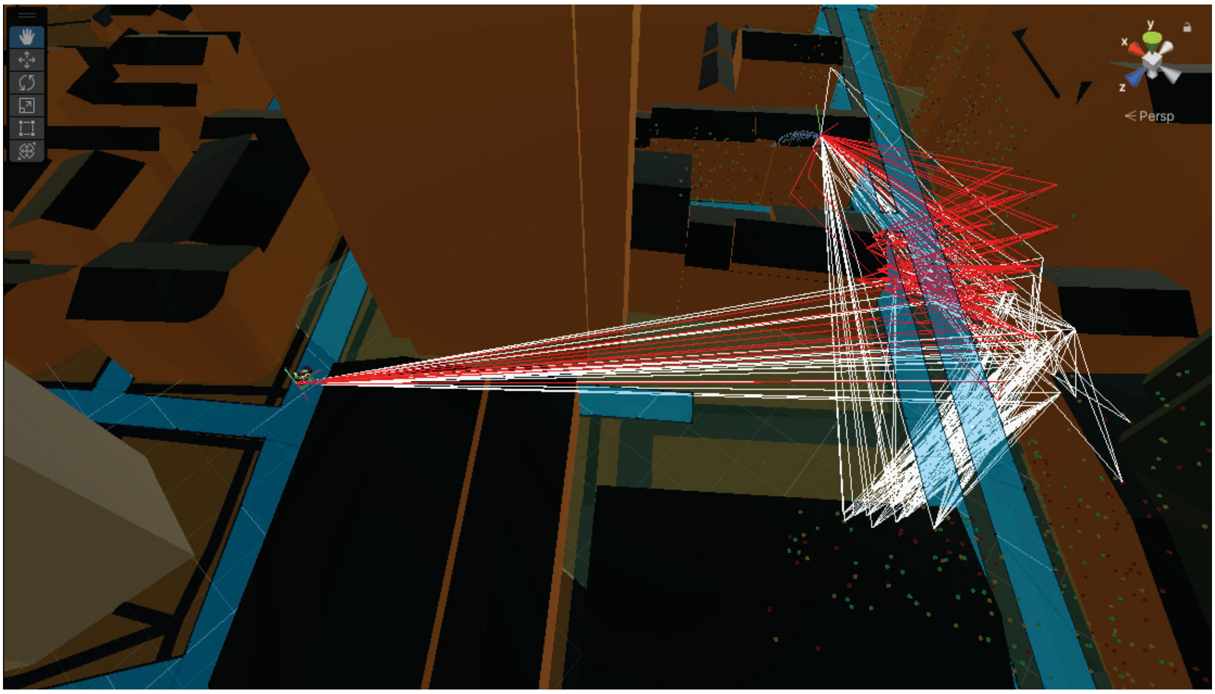


Figure 4-2, Vehicle (UE) with simple 2-antenna installation

Spatial Consistency Requirements: This 3D digital twin representation is essential for the operation of ray-tracing enabled GSCM spatially consistent modeling because:

- **Geometric Accuracy**: Ray paths must reflect actual electromagnetic propagation through real geometric structures.

- **Dynamic Environment Updates**: As vehicles move, the electromagnetic environment changes, requiring real-time updates to channel characteristics.

- **Multi-path Component Tracking**: Individual propagation paths can be traced and their contributions to the overall channel response calculated precisely.

The accuracy of this 3D digital twin directly impacts the fidelity of the GSCM channel modeling, making it a critical component for realistic 5G network simulation in complex environments.

Figure 4-3, UE-gNB 2x2 MIMO wireless links propagation example

On the overall architectural level (Figure 4-4) the SIVERT2 framework combines a Unity3D - a game engine that allow to manipulate 3D structures natively, has powerful capabilities of Raytracing and processes parallelization and rich documentation of the development API. In Unity we build a 3D digital twin that includes buildings and road infrastructure (from OSM), add the UE and gNB nodes, handling the UE mobility using the embedded Unity3D navigation meshes and, most importantly, via ray-tracing and parallelization capabilities combined with environmental Digital Twin representation we calculate the wireless channel using GSCM in the Unity engine. Technical details of this process will be presented in later sections of this report.

The ns-3 [*8*] LENA [*4*] project is a mature and comprehensive open-source LTE/5G-NR/V2X stack simulator, providing state-of-the-art implementations of advanced MIMO algorithms and complete protocol stack modeling that has been extensively validated by the international research community. As an open-source framework with active community support and continuous development, LENA ensures simulation transparency, reproducibility, and access to sophisticated 5G features while allowing reasonably complex integration with our Unity3D ray-tracing engine. LENA 5G and other ns-3-based modules are constantly updated and extended, which will allow to extend the SIVERT2 functionality in the future. For instance, as of now the intra- and inter-cell handover (HO) is not implemented in Lena, which slightly limits the current functionality, however, to the best information available to the authors of this report at the moment of writing, HO is expected in the next major distribution of the Lena, and can be integrated with SIVERT2 concept right away.

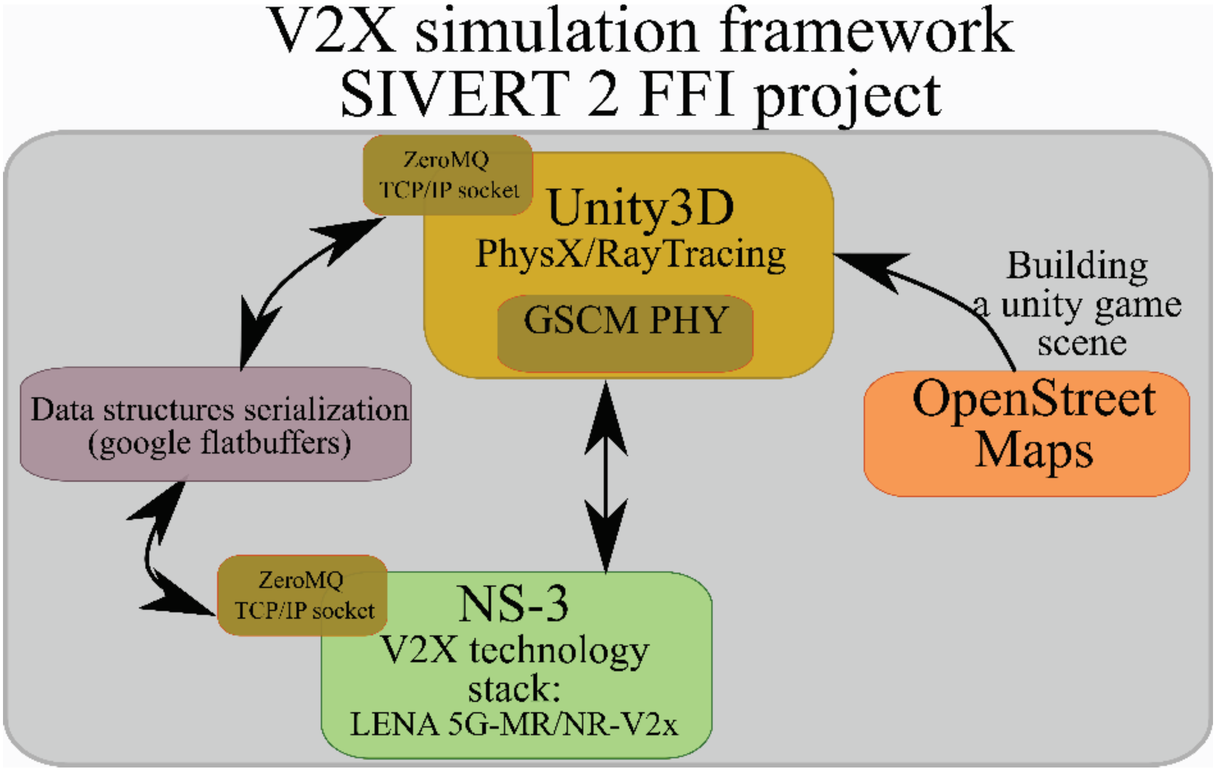


Figure 4-4, SIVERT2 simulation framework architecture

To link Unity3D and ns-3 processes we build a bi-direction connection. The system employs ZeroMQ [*9*] for inter-process communication with FlatBuffers [*10*] for efficient serialization:

- Publisher-Subscriber Pattern: Unity3D publishes channel updates; ns-3 subscribes to receive them
- Request-Reply Pattern: Synchronization and configuration exchange
- Update Frequency: configurable, dictated by the wireless channel model needs and is controlled by Unity3D FixedUpdate system physics calculation variable.

4.2.2 Vehicle-to-everything wireless channel modelling in Unity3D

Our Unity3D implementation utilizes the COST IRACON Geometry-Based Stochastic Channel Modelling (GSCM) [*6*] principles, which provide several advantages over traditional statistical models:

1. **Spatial Consistency**: Ray-tracing accounts for actual geometric reflections, diffractions, and scattering
2. **Dynamic Environment Support**: Real-time adaptation to moving objects and changing environments
3. **Multi-path Component Tracking**: Individual ray paths are tracked for precise MIMO channel matrix computation

The GSCM approach in Unity3D follows this computational flow:

Construction of 3D environment: buildings, other outdoor objects, roads, and their corresponding meshes are generated using the real-world data defined in OpenStreetMap data. This data incorporates accurate building geometries, such as elevation information and their shapes.

Scatterers distribution around interacting objects: objects are volumetrically enveloped by the scatterers following the SIVERT1 scatterers' distribution methodology, by, in addition, accounting for the objects' elevation.

Ray Casting: Multiple rays are cast toward scatterers from both sides: transmitter to receiver.

Interaction Modelling: Each ray interaction with a scatterer is computed using appropriate scattering models calibrated against measurement data. The model applies angle-dependent scattering coefficients calculated from a non-isotropic angular gain function, which considers angles in 3D.

Path Loss Calculation: The combined effect of all rays determines the overall channel response. Each multipath component contributes to the total received power according to its path loss, which includes free-space propagation, interaction losses, and antenna pattern gains.

MIMO Channel Matrix Formation: Individual antenna element responses are finally combined to form the full MIMO channel matrix and are fed to ns-3 for the MIMO calculations. The resulting complex-valued channel matrices capture the full spatial-temporal characteristics required for accurate MIMO performance evaluation.

The GSCM model in SIVERT2 enables comprehensive V2N channel characterization with high accuracy and computational efficiency, providing a robust foundation for system-level simulations and network performance analysis.

4.2.2.1 GSCM principles and implementation specific features

The SIVERT2 GSCM operates by volumetrically distributing scatterers around 3D objects in the environment, where each activated scatterer (in our case reachable by the ray casting procedure) enables a propagation path, and, by incorporating 3D antenna gain, contributes to the total propagation channel. This approach enables the generation of spatially consistent channel realizations while maintaining computational efficiency suitable for real-time simulations.

The GSCM paradigm fundamentally differs from pure ray-tracing approaches in several critical aspects. While traditional ray-tracing methods attempt to model electromagnetic wave propagation through exhaustive geometrical optics calculations, GSCM compensates for unknown environmental details through the stochastic distributions of scatterers, the statistical characteristics of which are derived from extensive channel sounding experiments [*6*]. This compensation mechanism addresses the inherent limitations of pure ray-tracing models, including missing material properties, unknown surface roughness characteristics, and the computational complexity of modelling diffuse scattering from irregular surfaces.

The SIVERT2 GSCM utilizes the Unity3D game engine as its core computational platform since it is a convenient software with specific technical features for real-time channel modelling. Unity's integrated physics engine provides native support for efficient ray-casting operations, enabling rapid visibility evaluation and path calculations that are essential for dynamic channel simulations. Additionally, the engine's built-in parallel computing capabilities significantly accelerate multilink channel calculations, enhancing overall system performance.

The implementation of GSCM in the game engine enables using the digital twin's approach for mimicking real surroundings. The created virtual environments integrate accurate 3D building geometries extracted from OpenStreetMap data, detailed elevation models, and realistic infrastructure layouts that mirror real-world deployment scenarios with high accuracy. This digital twin approach facilitates systematic validation against field measurements while providing a controlled, reproducible environment for testing different communication systems, equipment compatibility, antenna design, etc.

SIVERT2's GSCM implementation significantly extends SIVERT1's GSCM by incorporating the concept of 3D angular spread, which is a vital component for modelling V2X scenarios. Due to the lack of channel sounding measurements that could describe the multipath propagation behaviour in 3D and to adhere to well-known established standards, SIVERT2 incorporates the 3GPP 38.901 angular spread parameters - Azimuthal angular Spread of Arrival/Departure (ASoA/ASoD) and Zenith angular Spread of Arrival/Departure (ZSoA/ZSoD) [*5*]. Hence, SIVERT2's GSCM maintains spatial consistency and incorporates the angular spread concept defined in 3GPP 38.901 models.

4.2.2.2 GSCM V2N extension in SIVERT2

The extension of the SIVERT1 GSCM from vehicle-to-vehicle (V2V) to vehicle-to-network (V2N) scenarios represents a significant technical advancement in SIVERT2. This extension addresses the fundamental differences in propagation characteristics that arise when one terminal is elevated, as is typical in cellular network deployments.

4.2.3 Scatterer distribution for V2N

Although SIVERT1's GSCM was explicitly developed for V2V scenarios, it took into account a 3D environment to validate the impact of vehicle mobility and body dynamics on the channels. Slight variations in the communicating antennas' heights on the vehicles were assumed to have a negligible effect on the channel realizations. However, SIVERT2's GSCM addresses V2X scenarios where antenna placement heights can vary significantly, making the SIVERT1 model inadequate for V2N communications.

To address this limitation, the scatterer distribution approach from SIVERT1 was extended to a volumetric scatterer distribution approach. In SIVERT1, scatterers were distributed on an antenna level of the communicating vehicles. In SIVERT2, the volumetric scatterers distribution approach means that the number of scatterers increases proportionally with the height of buildings and other interactive objects, allowing scatterers to cover entire volumes of structures, see Figure 4-5. This enhancement enables the model to accurately capture the propagation characteristics in scenarios where significant height differences exist between communicating terminals, as is typical in V2N deployments with elevated base stations or infrastructure nodes.

4.2.3.1 Angular parameters and clusters

SIVERT2's GSCM incorporates 3D angular spread functionality essential for realistic V2X modelling through a 3D Angular Gain Function (AGF) that extends the COST IRACON GSCM 2D angular gain method used in SIVERT1. This extension leverages the angular spread parameters from 3GPP 38.901: the Azimuthal angular Spread of Arrival/Departure (ASoA/ASoD) and Zenith angular Spread of Arrival/Departure (ZSoA/ZSoD) [*5*]. SIVERT2's GSCM uses these parameters to compensate for the lack of comprehensive 3D channel sounding measurements in V2X scenarios.

The transition from 2D to 3D presented several technical challenges. In the original COST IRACON model, the 2D angular gain method operates as a weighting function for scatterers, activating them for channel calculations when specific angular-dependent conditions are met. Extending this to 3D required addressing three key problems: interpreting incoming and outgoing angles that do not lie in the same plane, utilizing 3GPP 38.901 angular spread parameters to form ellipsoidal clusters based on azimuthal and zenith angular spread, and establishing the interconnection between scatterers, building surfaces, and scatterer clusters through the 3D angular gain function.

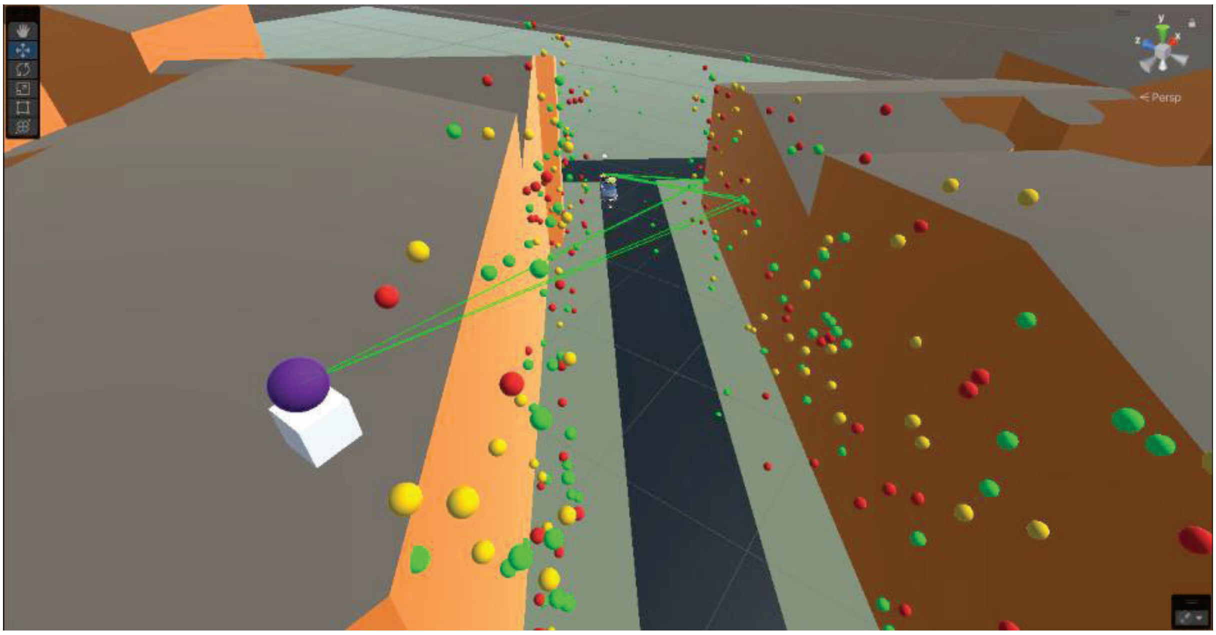


Figure 4-5, Volumetric distribution of the scatterers

Unlike conventional 3GPP cluster models that explicitly define scatterer clusters, SIVERT2's GSCM generates clusters organically through environmental geometry, the positioning of communicating objects, and angular spread parameters. Scatterers falling within the angular spread range naturally form clusters, see Figure 4-6, creating a geometry-based clustering approach that reflects the physical propagation environment. This method ensures that clusters emerge from the interaction between the scatterers, which represent roughness and unknown shapes of a 3D environment structure, and the angular spread characteristics, providing a more realistic representation of multipath propagation behaviour in V2X scenarios.

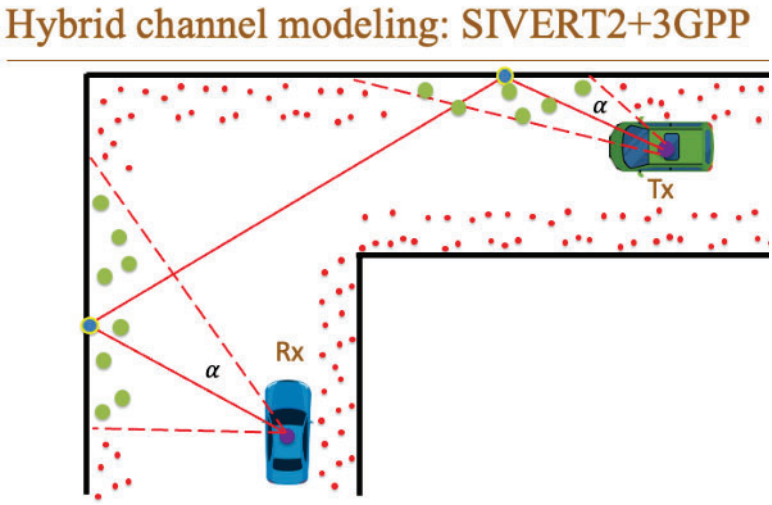


Figure 4-6, The idea of how clusters appear based on geometry and angular spread parameters.

In 3D space, angular spread is described by two parameters (φ, ϑ), where φ is ASoA/ASoD, ϑ is ZSoA/ZSoD according 3GPP 38.901. However, clusters formed by two parameters have non-ellipsoidal forms as depicted in Figure 4-7 left, while if a single angle ψ used, then the cluster has an ellipsoidal form. In SIVERT2 GSCM, it is assumed that $\psi = \vartheta$ since, in the majority of cases, buildings are more straight in the vertical direction and have more variations in the horizontal plane.

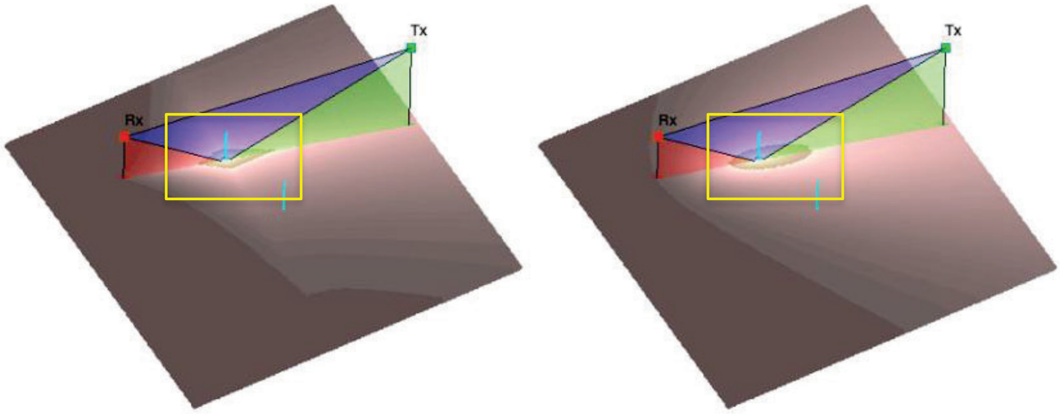


Figure 4-7, left – scatterers cluster defined by (φ, ϑ), where φ is ASoA/ASoD, ϑ is ZSoA/ZSoD; right – scatterers cluster defined by a single angle ψ (in SIVERT2 GSCM ψ = ϑ)

In the example from in Figure 4-6, clusters are defined around reflection points on surfaces based on angular spread parameters. However, in Unity3D environments, all objects are constructed from triangular mesh elements Figure 4-8, making the theoretical approach of finding specular reflection points using smooth plane assumptions impractical. Complex geometries consisting of numerous triangular elements create computationally prohibitive scenarios, particularly in dynamic V2X environments were communicating objects continuously move and incident/outgoing angles constantly change.

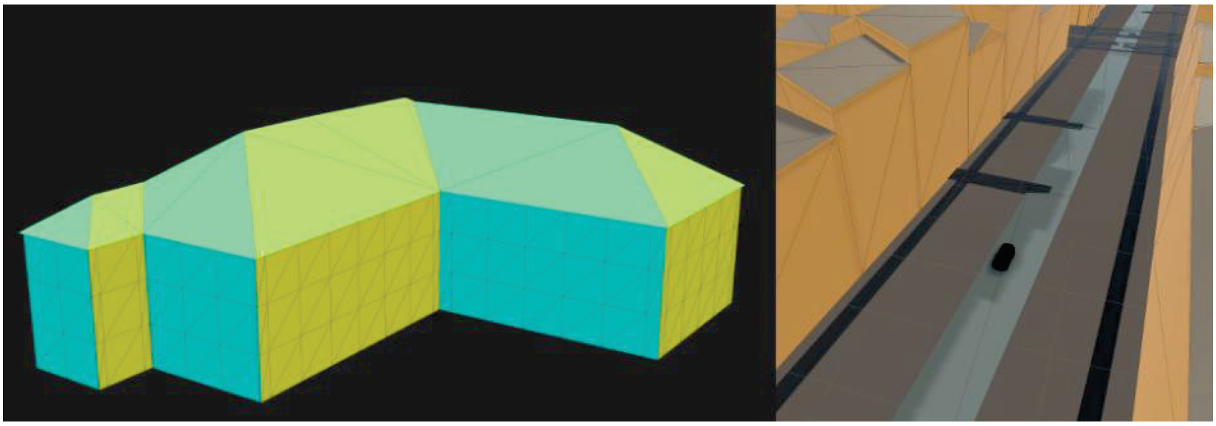


Figure 4-8, Unity3D Objects are made of meshes that consist of triangles

The conventional triangle-based approach requires a computationally intensive procedure:

1. Consider each triangle element
2. Calculate the specular reflection point
3. Verify if the reflection point lies within the triangle boundaries
4. Define an area of interest around the reflection point (distance-dependent)
5. Select scatterers located within the area of interest that belong to the triangle

To overcome this computational complexity, SIVERT2's GSCM leverages the inherent properties of scatterers, which already represent surface elements with defined positions and normal vectors indicating their associated surfaces. This direct scatterer analysis enables efficient computation since the environment's mesh is not involved in the calculation, which significantly reduces the complexity, and some required operations are already performed during the scatterer reachability test. The optimized scatterer activation procedure follows a streamlined algorithm:

1. Consider a scatterer (identified during ray-casting)
2. Determine the reflection point (utilizing the scatterer's surface representation)
3. Calculate the divergency angle between the incident direction and direction to the reflection point, which can be decomposed further into azimuth and zenith angles if needed
4. Activate the scatterer if the divergency angle falls within the angular spread range

This optimization significantly reduces computational overhead while maintaining accuracy in cluster formation and scatterer activation, making the model suitable for real-time V2X channel simulation in complex 3D environments, Figure 4-9.

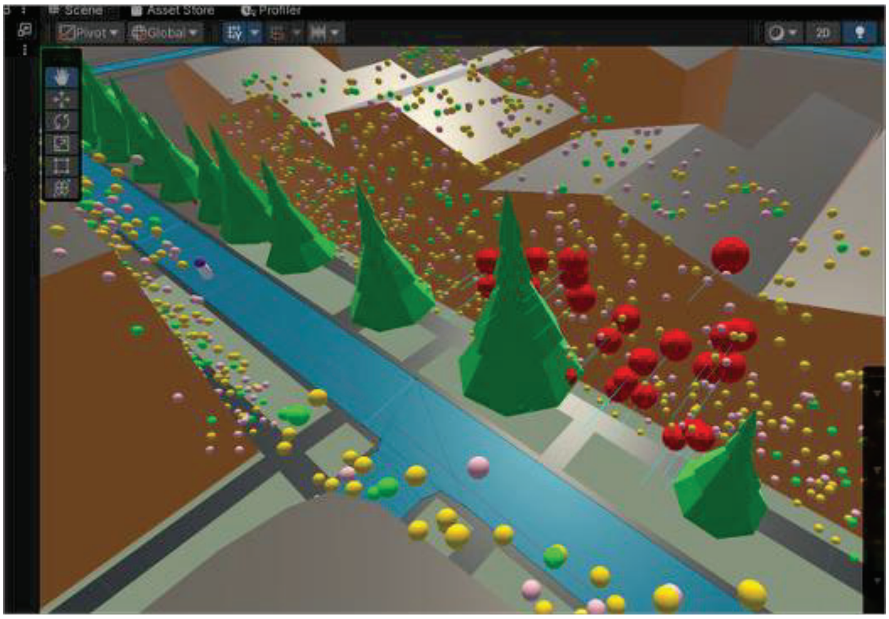


Figure 4-9, Cluster formation following the SIVERT2 GSCM 3D Angular gain function

4.2.3.2 3D antenna patterns in EADF and optimisation with Look-up parallel hash-maps

Building upon the limitations identified in the SIVERT1 project, where 2D antenna measurements were naively extended to 3D using exact values on the horizontal plane with gradual attenuation toward zero at elevation angles, SIVERT2 implements a comprehensive full 3D EADF approach [*11*] that addresses both accuracy and computational performance requirements.

The enhanced implementation follows a two-phase development approach. Initially, full 3D EADF was implemented in Matlab/python to provide an analytical framework for evaluation and antenna diagram conversion. For verification purposes, measured 3D pattern data from V2X front and rear antennas (measured on full vehicles in laboratory conditions in Belgium) are utilized. The complete dataset is extracted from a CSV file and converted to EADF representation. Subsequently, the EADF is reconstructed back to pattern data to verify the integrity of the conversion process, confirming that the antenna diagrams remained unaffected by the transformation, except for numerical errors Figure 4-10.

The transition to the Unity3D game engine, as well as most game engines, introduces an additional burden related to the coordinate systems' orientation mismatch. The implementation requires careful transformation of coordinate system projections to ensure consistency between the analytical framework and the real-time simulation environment. This axis alignment process is critical for maintaining the accuracy of the 3D antenna pattern representations across platforms.

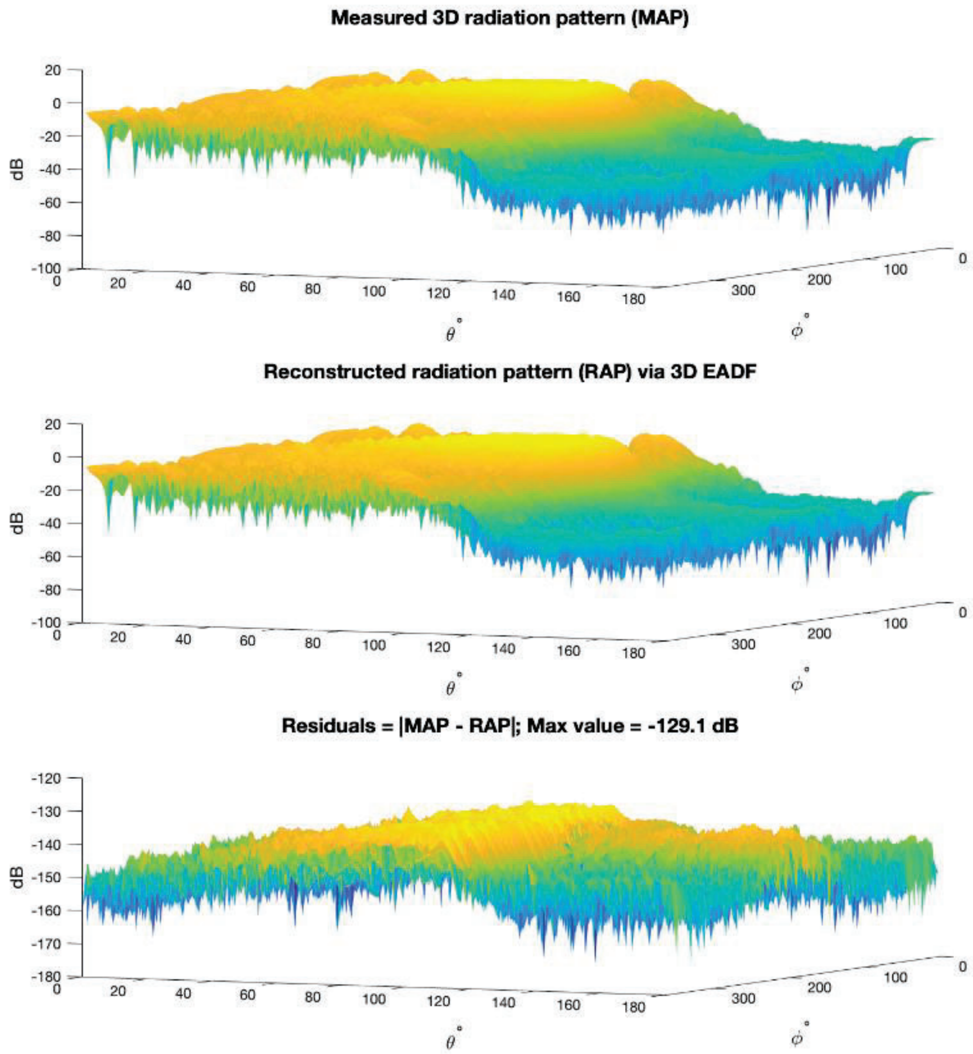


Figure 4-10, 3D antenna radiation pattern: Top – measured; Middle – reconstructed from an EADF representation; Bottom – the difference between measured and reconstructed radiation patterns.

4.2.3.3 Computational Complexity and Optimisation

The computational complexity of 3D EADF operations significantly exceeds that of 2D implementations. To address this challenge, the SIVERT2 framework implements a three-stage optimization approach centred on efficient lookup structures.

First, the measured 3D antenna radiation pattern is converted to its EADF representation, with optional signal processing applied as needed. Second, the 3D antenna radiation pattern is reconstructed from the EADF coefficients using a configurable angular resolution: high resolution for maximum accuracy or reduced resolution for computational efficiency. Third, the reconstructed 3D antenna pattern is stored in Unity3D's NativeParallelHashMap structure, which enables extremely efficient distributed access by parallel threads during runtime operations.

This approach leverages Unity3D's Job System and Entity Component System (ECS) architecture, converting traditional C# arrays to NativeArrays to enable parallel processing on the CPU side. The parallel implementation transforms sequential FOR loops into job system tasks that execute concurrently, providing substantial performance improvements. This parallelization extends to ray-casting and channel computing functions, significantly reducing computational resource requirements. Cross-validation between Matlab (theoretical) and Unity3D implementations was performed through step-by-step manual verification, ensuring that axis rotation and vectorization maintained correct EADF application for randomly selected angles.

This architectural decision in SIVERT2 involves shifting computationally intensive EADF operations from the runtime to the initialization phase. Rather than performing complex 3D antenna pattern reconstruction via EADF during each channel realization, the system precomputes the complete 3D antenna radiation pattern during simulation startup. These precomputed pattern files are loaded once at initialization and persist in memory as fast-access lookup structures throughout the simulation run.

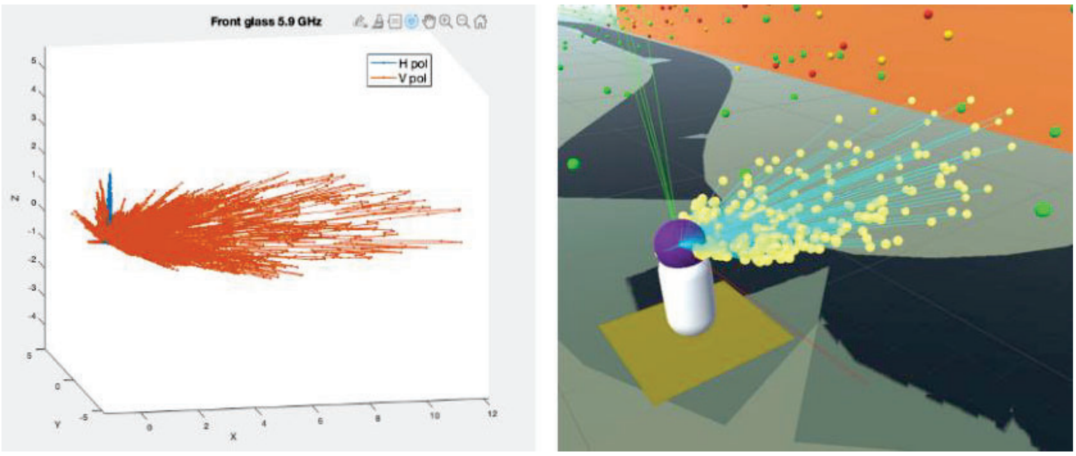


Figure 4-11, Left – Measured 3D antenna radiation patter in Matlab; Right – The same antenna after reconstruction and reading from its NativeParallelHashMap in Unity3D

As an additional verification mechanism, SIVERT2 includes a 3D antenna visualizer implemented directly in Unity3D. This tool provides a real-time representation of the antenna diagrams used for specific antennas, enabling immediate visual verification of pattern accuracy and facilitating debugging of complex 3D antenna configurations. The visualizer serves both as a development tool and a means for validating the correct application of antenna patterns within the simulation framework.

The integration of 3D EADF into the complete SIVERT2 framework has been successfully completed, and validated confirming correct operation across all simulation scenarios. The lookup table optimization has proven essential for maintaining real-time performance requirements while providing the accuracy benefits of full 3D antenna pattern representation. This implementation establishes a foundation for future enhancements, including support for distributed antenna systems and advanced beamforming scenarios.

4.2.3.4 GSCM V2N Validation

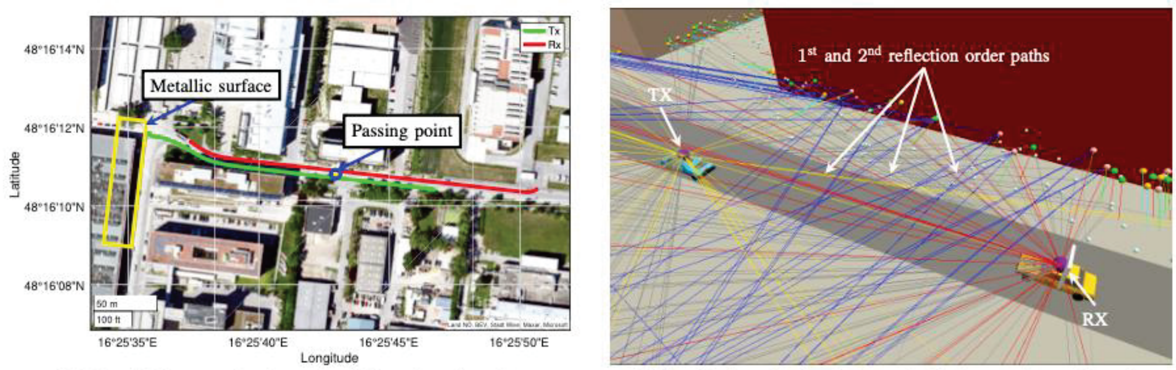
The WP1 originally committed to extending the SIVERT simulation platform by incorporating 3D elevation characteristics from existing V2I/V2N channel models and, from V2I/V2N channel measurement campaigns to be conducted at Lund University using a massive MIMO antenna setup. We successfully delivered on all major commitments with minor deviations except for the V2I/V2N measurement campaigns and their subsequent analysis. Throughout the project it was decided to focus the efforts on the 3D extension of the model rather than performing extensive measurement analysis. Instead we decided to perform validation with measurement results from the literature.

Given the absence of the planned measurement campaign, we adapted our validation approach while maintaining the core technical deliverables. We implemented a hybrid COST-IRACON + 3GPP 38.901 approach where we introduced a new 3D angular gain function. The 3D angular gain function is utilizing well-validated angular spread parameters including ASoA, ASoD, ZSoA, and ZSoD directly from 3GPP 38.901 standards. We validated our implementation against existing high-quality Vienna channel sounding data, demonstrating excellent correlation in delay spread and Doppler characteristics. Furthermore, we conducted verification tests in Gothenburg with elevated Tx/Rx configurations to confirm simulation-measurement consistency at the system level.

This approach ensured that all core platform capabilities were delivered while providing robust validation through established standards and available measurement data, compensating for the resource constraints at Lund University that prevented the originally planned measurement campaigns.

Comparison against Vienna Channel Sounding Data

The comparison against Vienna channel sounding data served as a validation to ensure that SIVERT2 model produces realistic channel characteristics after incorporating the 3D angular gain function. The Vienna scenario involved two vehicles approaching and passing each other on an urban street Figure 4-12, providing a well-characterized reference case with known propagation characteristics [*12*]. This validation was conducted to verify that the implementation of the 3D angular gain functionality did not compromise the model's ability to generate physically realistic channel evolution patterns.



(a) TX and RX pass each other at the indicated passing point. (b) Visualization of a simulation run in Unity near the passing point.

Figure 4-12, Vienna scenario [refer to Methodologies for Future Vehicular Digital Twins]: Left – measurement's scenario; Right – digital twin scenario in Unity3D

We utilized comprehensive Vienna measurement data that includes Power Delay Profile (PDP) and Doppler Spectral Density (DSD) measurements. The dataset includes temporal evolution of channel characteristics as vehicles travel through various propagation conditions, from line-of-sight through multipath-rich environments near the vehicle passing point. The primary objective was to verify that SIVERT2, with the newly integrated 3D angular gain function, still generates realistic channel behaviour when compared against real-world measurement data, ensuring that the model did not introduce computational artifacts or unrealistic channel characteristics.

The comparison results demonstrated that SIVERT2 successfully reproduces realistic channel evolution patterns. The PDP, DSD, and statistical parameters including delay and Doppler spreads showed good agreement with the Vienna measurements, with minor deviations attributable to limited hardware specifications and real-world motion information, as depicted in Figure 4-13, Figure 4-14, and

Figure 4-15. The model accurately captures line-of-sight components, multipath reflections, and diffuse scattering contributions. Notably, channels were generated using default simulation parameters without model tuning, which accounts for slight distinctions observed between measured and simulated results.

Additional deviations stem from incomplete knowledge of the measurement antennas' radiation characteristics. In the SIVERT2 framework, we emulated the receiving patch antenna as an omni-directional antenna with a blocking plane behind it, as shown in street Figure 4-12 (right side). This simplified representation cannot accurately recreate the actual RX antenna properties, highlighting the critical importance of detailed antenna radiation patterns for precise channel modelling.

Figure 4-15 demonstrates the trend of increased delay spread as the TX and RX vehicles approach each other, observable in both measured and simulated channels. In the SIVERT2 implementation, vehicle motion was controlled by Unity3D's built-in Navigation package, which applies its own acceleration and collision avoidance algorithms. Consequently, vehicles rapidly accelerate to high speeds initially, approach the passing point quickly, then decelerate sharply to avoid collision. These motion dynamics contribute to the observed discrepancies between simulation and measurement results.

Overall, this validation confirmed that the 3D angular gain function integration preserved the model's fundamental capability to generate physically realistic channel characteristics. The results provide confidence that SIVERT2 maintains its modelling accuracy and can be reliably used for both V2N and V2V channel simulation with enhanced 3D angular gain functionality.

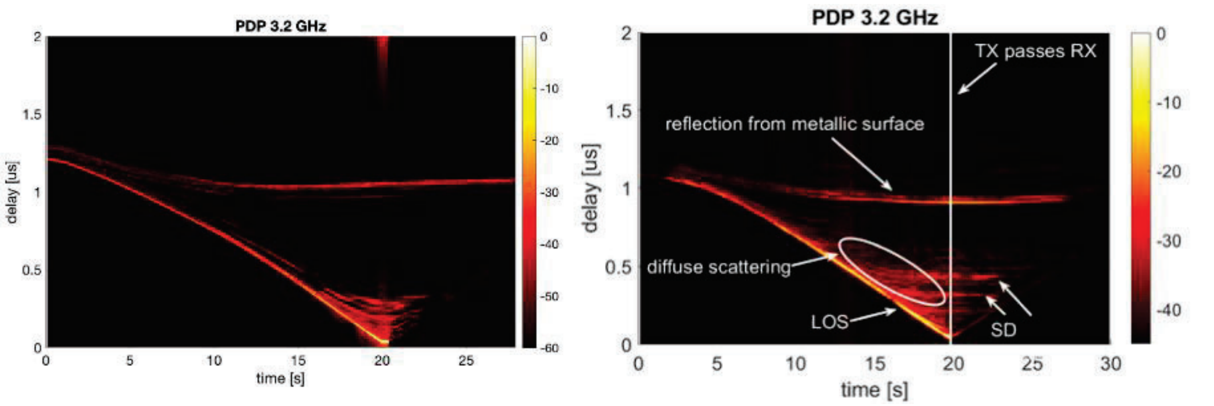


Figure 4-13, PDP comparison: <u>Left</u> – a SIVERT2 GSCM result; <u>Right</u> – the Vienna measurements [12]

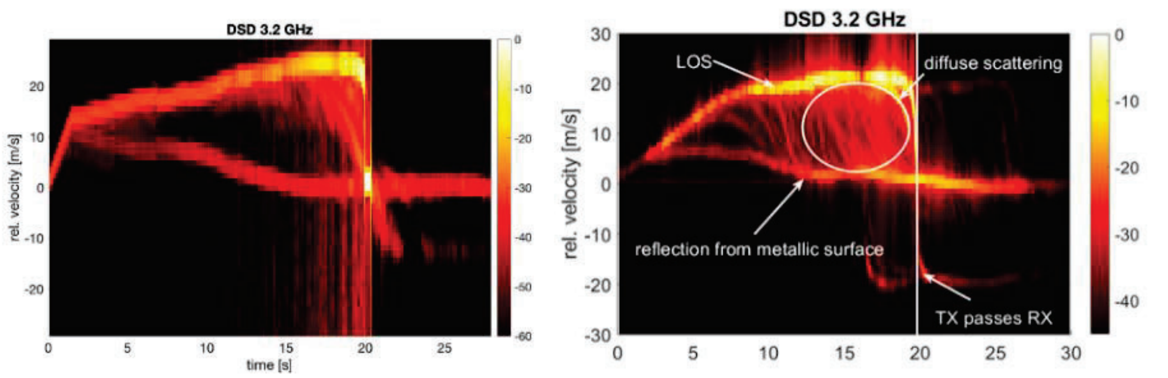


Figure 4-14, DSD comparison: <u>Left</u> – a SIVERT2 GSCM result; <u>Right</u> – the Vienna measurements [12]

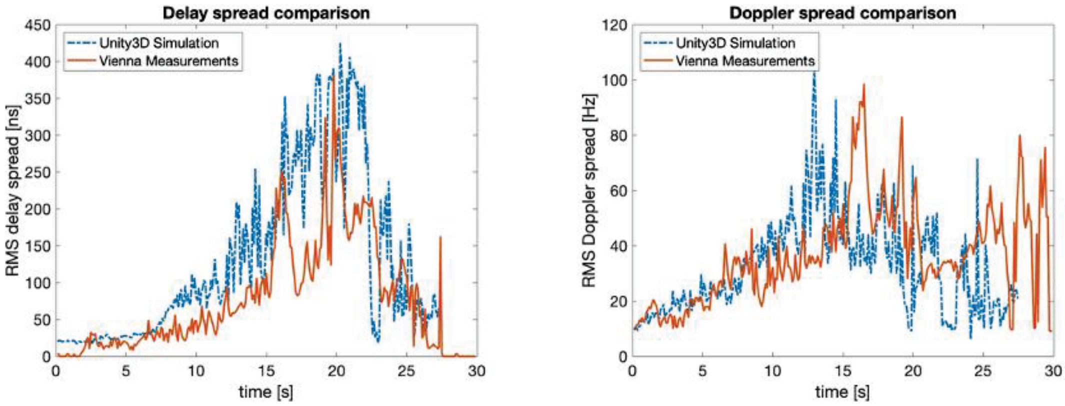


Figure 4-15, Statistical parameters comparison: Left – delay spread comparison; Right – Doppler spread comparison. Vienna measurement - [12].

4.2.3.5 *Field tests in VASA and V2N verification on the RSS level*

The Gothenburg Vasa Downtown field test was conducted at the intersection of Chalmersgatan and Kristinelundsgatan to validate SIVERT2's performance against real-world V2N propagation characteristics. The test setup involved an elevated transmitter configuration and mobile receiver to replicate typical V2N communication scenarios.

The Tx node was installed at an elevated position on a mast, as illustrated in Figure 4-17, providing the vehicle-to-infrastructure geometry characteristic of V2N communications. The Rx antenna was mounted on a Volvo XC90 test vehicle, which followed multiple predetermined routes through the intersection to capture diverse propagation conditions and geometric relationships.

Both transmitter and receiver utilized dipole-over-reduced-ground-plane antennas, ideally characterized by smooth, nearly omnidirectional radiation patterns in the forward direction. However, the rear-side radiation patterns exhibit unknown characteristics due to cable attachment and mounting constraints, with design parameters visible in Figure 4-16. The operational frequency was 5.9 GHz with a bandwidth of 700 MHz.

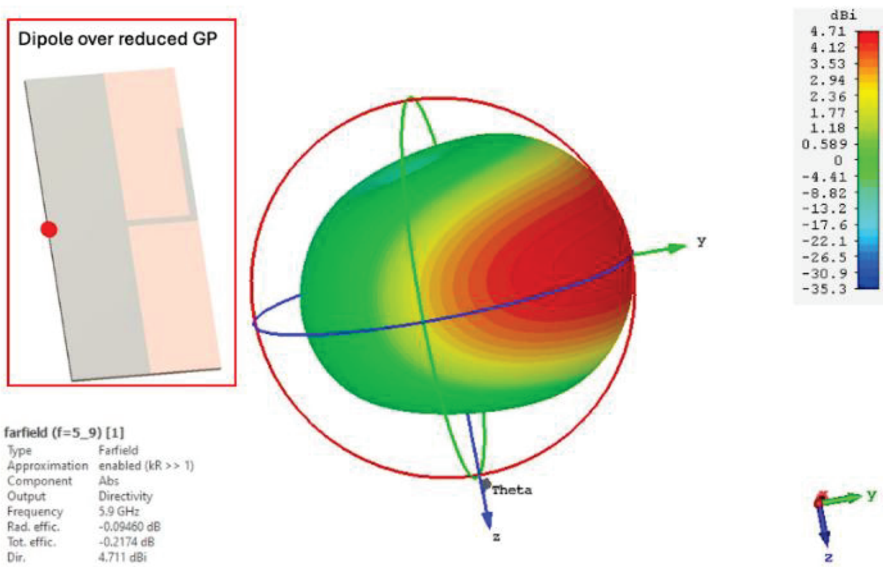


Figure 4-16, Description of the exploited dipole antennas from RISE.

Antenna Mounting and Orientation

As shown in Figure 4-17 (right), the Rx antenna was rear-mounted with sufficient clearance from the vehicle body to minimize automotive structure influence on the radiation pattern. This rear-mounting configuration was specifically chosen to reduce vehicle body coupling effects, though front-mounting remains feasible when adequate ground clearance can be maintained.

The Tx antenna orientation, visible in Figure 4-17 (left), is directed toward the intersection center. Given the geometric layout shown in Figure 4-18, this positioning was chosen to cover the intersection.

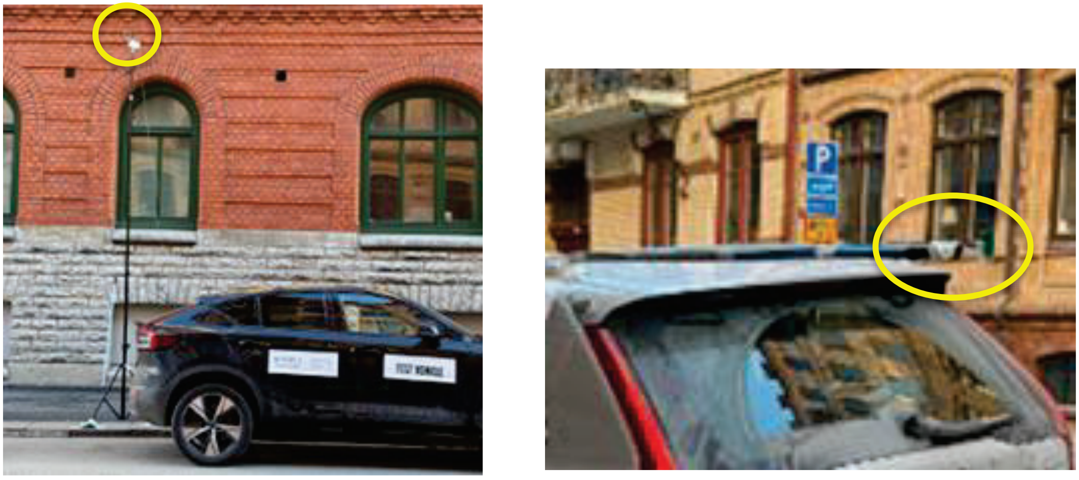


Figure 4-17, Vasa scenario setup: Left – elevated BS transmitting continuously; Right – rear-mounted antenna UE

In total, four scenarios were considered:

1. Front-mounted Rx antenna
    a. The car moves away from the BS while maintaining LOS visibility, as illustrated in Figure 4-19 (Left).
    b. The car travels along Kristinelundsgatan street Figure 4-19 (Right)), moving perpendicular to the BS's street and transitioning from an NLOS region to a LOS region, then back to an NLOS region.
2. Rear-mounted Rx antenna
    a. The car moves away from the BS while maintaining LOS visibility, as illustrated in Figure 4-19 (Middle).
    b. The car travels along Kristinelundsgatan street, moving perpendicular to the BS's street and transitioning from an NLOS region to a LOS region, then back to an NLOS region.

As shown in Figure 4-18 (left), the digital twin consists of two vehicles with appropriately mounted antennas. The vehicle with the rear-mounted Rx antenna is positioned on the left side, moving away from the BS, while the vehicle with the front-mounted Rx antenna is positioned on the right side, also moving away from the BS. SIVERT2's computing capabilities enable all four scenarios to be executed simultaneously.

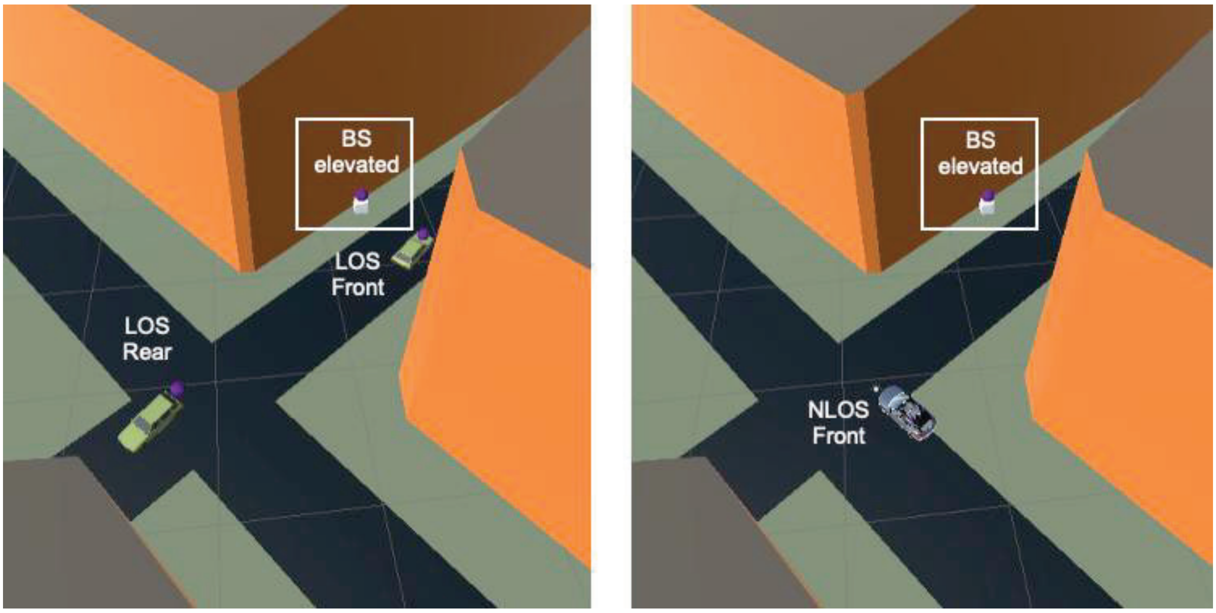


Figure 4-18, Vasa V2N scenario: Left illustrates two scenarios – LOS scenario with a rear-mounted antenna and LOS scenario with a front-mounted antenna; Right – NLOS scenario with front-mounted antenna

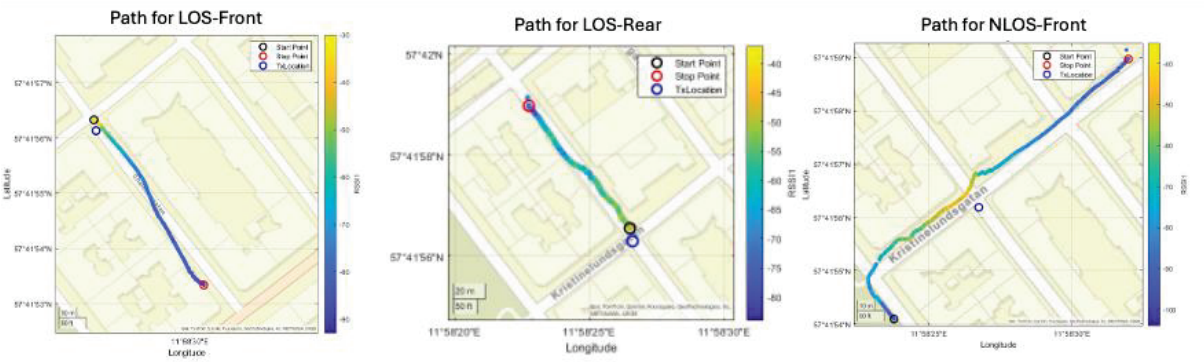


Figure 4-19, GPS captured trajectories: Left – LOS scenario with a front-mounted antenna; Middle – LOS scenario with a rear-mounted antenna; Right – NLOS scenario with front-mounted antenna

Figure 4-20 presents a comparison between SIVERT2 simulation results and field test measurements. The top plot, the LOS scenario with a rear-mounted antenna, shows excellent agreement between the SIVERT2 simulation framework output and field test results, while the middle plot, the LOS scenario with a front-mounted antenna, reveals significant discrepancies. These differences can be attributed to antenna placement and orientation effects.

In the rear-mounted LOS scenario, both antennas are oriented toward each other in their forward directions, utilizing their near-omnidirectional radiation patterns (as shown in Figure 4-16). This configuration allows SIVERT2's omnidirectional antenna model to accurately represent the real-world behaviour, producing realistic results.

Conversely, in the front-mounted LOS scenario, the transmitting and receiving antennas are oriented away from each other, making the actual radiation patterns highly unpredictable. Under these conditions, the omnidirectional model used cannot accurately capture the realistic channel evolution behaviour. Furthermore, SIVERT2's lack of a diffraction model means that the vehicle body completely blocks the LOS connection between antennas in the simulations, whereas in reality, some signal propagation would occur through diffraction effects. As a future extension, a simplified diffraction model could be implemented.

The bottom plot of Figure 4-20 demonstrates good agreement between simulation and field test results, with the exception of the transitioning region where diffraction effects occur. This agreement is in-line with the proper antenna installation on a sticking pole in this front-mounted configuration scenario – making component antenna radiation pattern a proper approximation of the antenna in this drive scenario. When the antenna mounted on the vehicle is obstructed by the vehicle body structure, the effects of the body structure on the antenna radiation pattern should be included in the pattern diagram dataset (i.e., simulation of the antenna diagram on the full vehicle CAD structure, antenna mounted on the vehicle using antenna laboratory measurements or measurements of the antenna mounted on the vehicle using RanLOS measurement system).

As the vehicle approaches the intersection, its front-mounted antenna is oriented toward the BS antenna, which is directed toward the intersection center. This positioning results in an angular separation of less than 90 degrees between the antennas' forward directions, placing both antennas within their near-omnidirectional radiation regions. Consequently, the omnidirectional model accurately represents the real-world channel behaviour during the approach phase.

However, once the vehicle passes through the intersection, the antenna orientations become obstructed by the vehicle body itself, for which the component antenna diagram does not account. This lack of proper antenna pattern data mounted on the vehicle body causes the increase discrepancy between simulation and measurement results. For matching results, as explained above, antenna

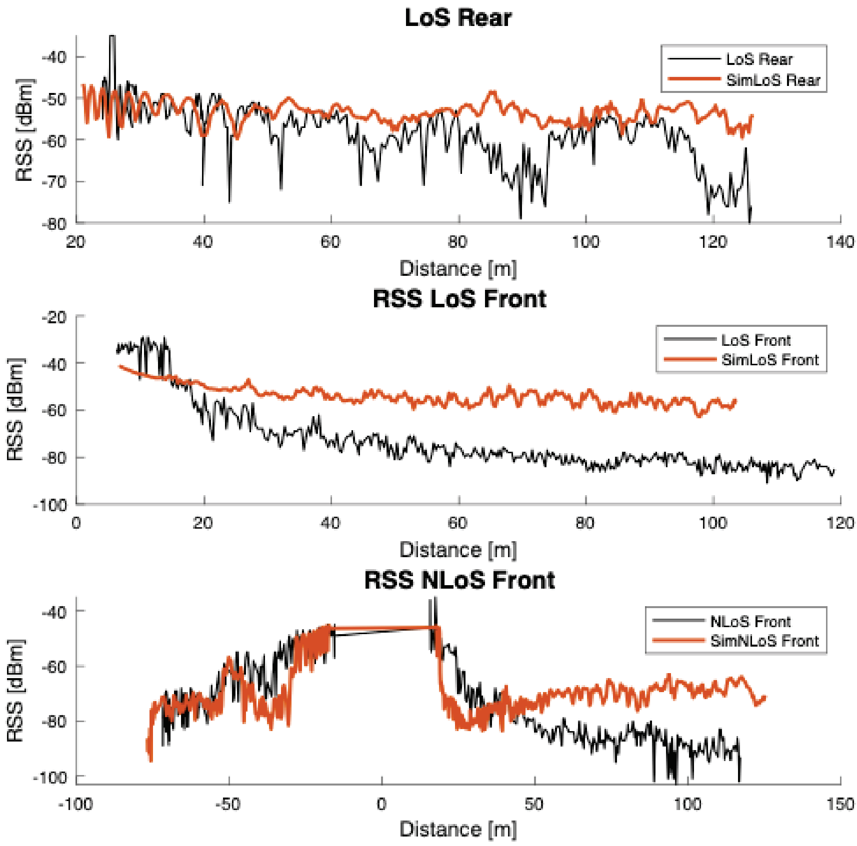


Figure 4-20, Comparison of the field tests and SIVERT2 simulation results: Top – LOS rear-mounted antenna; Middle – LOS front mounted antenna; Bottom – NLOS front-mounted antenna model should be extracted (via simulations or measurements) installed on the vehicle body structure, where body effects are included in the antenna diagram.

The Vasa field test validation demonstrates that SIVERT2's performance is highly dependent on antenna parameters. The simulation framework shows excellent agreement with real-world measurements when antenna patterns are available. However, discrepancies are expected when antenna data is only an approximation of the antenna installed on the vehicle. This makes the antenna data obtained through simulations and/or measurement essential for proper V2X propagation modelling and for accurate system evaluation.

4.2.3.6 Bi-direction API between Unity3D and ns-3

The communication protocol between Unity3D and ns-3 follows a carefully designed message structure optimized for real-time performance and ease of use:

Initialization Phase:

```
// Unity3D sends simulation parameters
UnityFixedUpd = receiveFromUnity();
SimStart = receiveFromUnity();
NumNodes = receiveFromUnity();
UseGSCM = receiveFromUnity();
IsEMIdisabled = receiveFromUnity();
```

Runtime Phase: - Channel matrix updates at configurable intervals - EMI spectrum data injection - Position and mobility updates - Performance metric feedback

FlatBuffers Serialization Architecture

FlatBuffers provides efficient serialization with zero-copy deserialization, crucial for real-time performance. The SIVERT framework employs two primary FlatBuffer schemas that define the complete data exchange protocol between Unity3D and ns-3 LENA.

Position and Spectrum Data Schema (positionSchema_EMI_vectorised.fbs)

The primary communication schema handles position updates, GSCM channel data, EMI spectrum information, and various simulation control parameters:

Core Data Structures:

```
// 3D position vector with node identification
struct Vec3API {
  x: float;
  y: float;
  z: float;
  id: int;
}

// GSCM channel information per transmitter-receiver pair
struct GscmInfo {
  Tx: int;
  Rx: int;
  rss: double;  // Received Signal Strength
}

// Spectrum channel data for EMI and channel modeling
table SpectrumValue {
  ChannelID: int;
  TxID: int;
  RxID: int;
  IsEMIChannel: bool = false;
```

```
  PSDGainCoefficient: [double];  // Vector of PSD Gain Coefficients
  CoefInd: int;
}
```

Complete Message Structure:

The main position update message (PosAPI) encapsulates all simulation data in a single, efficiently serialized structure:

```
table PosAPI {
  GSCM: GSCMstruct;                  // Global GSCM configuration
  GSCMvector: [GscmInfo];            // Per-link GSCM channel data
  CITS: [EEBL];                      // Cooperative ITS applications
  pos: [Vec3API];                    // Vehicle position array
  Suppl: [VehInfo];                  // Supplementary vehicle information
  terminateNS3: bool = false;        // Simulation control flag
  GSCMSpectruChannels: [SpectrumValue]; // Spectrum channel matrices
  NumberOfFrequnciesPerChannel: int;    // Frequency domain resolution
  V2Xstack: string;                  // Protocol stack identifier
}
```

Vectorized Data Transmission: The schema supports vectorized transmission of multiple channel links simultaneously, enabling efficient handling of multi-vehicle scenarios with complex interference patterns.

EMI Integration: The SpectrumValue structure specifically supports EMI modelling through the IsEMIChannel flag and PSDGainCoefficient vector, allowing injection of laboratory-measured interference spectra alongside computed channel data.

Frequency Domain Representation: The NumberOfFrequnciesPerChannel parameter enables precise control over frequency domain resolution, supporting both narrowband and wideband 5G NR channel modelling.

The bidirectional communication framework includes a dedicated schema for handling received message feedback from ns-3 to Unity3D:

```
// Packet transmission information
struct PacketInfo {
  senderID: uint;
  receiverID: uint;
  timeReceived: long;
  sent: bool = false;
}

// Complete message reception data
table MsgRecAPI {
  pos: Vec3Rx;              // Receiver position
  PackContent: PacketInfo;  // Packet metadata
  MsgContent: string;       // Message payload
}
```

This schema enables Unity3D to track packet reception success rates, timing information, and content delivery for realistic application-layer modelling.

Vector data structures leverage FlatBuffers' internal compression mechanisms to minimize network bandwidth usage during high-frequency updates.

Real-Time Data Flow Implementation

Synchronous Channel Updates: The primary data flow operates through the PosAPI schema, delivering synchronized position, channel, and EMI data:

```
// Unity3D transmission (C# side pseudocode)
var builder = new FlatBufferBuilder(1024);
var posAPI = PosAPI.CreatePosAPI(builder, gscmData, gscmVector,
    citsArray, positionArray, supplArray, false,
    spectrumArray, freqCount, v2xStackString);
socket.SendMore(builder.DataBuffer.ToSizedArray());

// ns-3 reception (C++ side pseudocode)
std::string receivedData = s_recv(subscriber_socket);
auto posUpdate = GetPosAPI(receivedData.c_str());

// Extract spectrum channel data
auto channels = posUpdate->GSCMSpectruChannels();
for (size_t i = 0; i < channels->size(); ++i) {
    auto channel = channels->Get(i);
    int txId = channel->TxID();
    int rxId = channel->RxID();
    auto psdCoeffs = channel->PSDGainCoefficient();

    // Inject into SIVERT spectrum model
    SetComplexChannelFromUnity3D(txId, rxId, psdCoeffs);
}
```

Schema Evolution and Extensibility

The FlatBuffer scheme design supports future extensions while maintaining backward compatibility:

Optional Fields: Default values and optional flags enable schema evolution without breaking existing implementations. Versioning Support: String fields like V2Xstack provide protocol version identification. Modular Structure: Separate schemas for different data types enable independent evolution of communication protocols

This comprehensive serialization architecture ensures that the SIVERT framework can handle complex, high-frequency data exchange between Unity3D and ns-3 while maintaining the real-time performance requirements essential for advanced 5G network simulation and hardware-in-the-loop testing.

4.2.4 GSCM integration to ns-3 LENA module: modifications and features supported.

Second core design decision of SIVERT2 lies in its replacement of the traditional 3GPP TR 38.901 channel model implementation with the SIVERT2 GSCM within ns-3 LENA. This modification addresses fundamental limitations in current simulation approaches and enables a new paradigm for realistic 5G network simulation.

Traditional 3GPP channel models, while standardized and widely accepted, present several technical limitations when applied to complex vehicular scenarios:

Statistical Approximation Limitations: The 3GPP TR 38.901 model relies on statistical distributions derived from measurement campaigns. While these provide good average behavior in an averaged certain environment, they cannot capture the specific propagation environment of a particular scenario. For instance, the model may predict average path loss for a generalized urban environment but cannot account for the specific building layout, material properties, or dynamic obstacles present in a real scenario.

Spatial Correlation Inaccuracy: MIMO systems critically depend on spatial correlation properties of the channel. Standard models use simplified correlation models that may not accurately represent the complex spatial relationships present in realistic environments, particularly in vehicular scenarios where the propagation environment changes rapidly.

Limited Environmental Adaptation: Traditional models use predefined scenarios (Urban Macro, Urban Micro, etc.) with fixed parameters. They cannot dynamically adapt to specific environmental features such as unique building geometries, and vehicle movement.

4.2.4.1 Approach to GSCM introduction to 5G-Lena.

Our solution replaces the channel matrix generation process within the SivertThreeGppSpectrumPropagationLossModel class, implementing a special injection mechanism that receives realistic channel matrices from Unity3D's ray-tracing engine.

The modification occurs at the spectrum propagation loss model level, specifically targeting the standardized for spectrum propagation loss models interface: DoCalcRxPowerSpectralDensity method. Instead of computing channel matrices using 3GPP equations, our system:

Intercepts Channel Computation: When ns-3 LENA requests a channel matrix for a specific transmitter-receiver pair, our modified model checks for Unity3D-computed data.

Injects Realistic Data: Unity3D-computed channel matrices, based on actual ray-tracing based GSCM links of the environment simulated, are injected into the 5G-lena simulation at each simulation step. These channel matrices are comprehensive in that they already incorporate all propagation effects including transmit and receive antenna influences, path attenuation, scattering effects, reflection characteristics, and diffraction phenomena. The Unity3D ray-tracing engine computes the complete propagation effects between transmitter and receiver, accounting for the full 3D antenna patterns, material properties of the environment, and all multi-path propagation effects, delivering a fully-formed channel matrix that represents the complete electromagnetic link.

Preserves LENA Signal Processing: All subsequent MIMO processing algorithms proceed normally using the realistic channel data, including **precoding matrix calculations**, **Channel Quality Indicator** (CQI) reporting**, Rank Indicator** (RI) feedback, reference signal processing, and **link adaptation mechanisms**. Note that while LENA's sophisticated signal processing algorithms operate on realistic channel conditions, the actual beam patterns remain static as pre-configured in the antenna port definitions rather than being dynamically adapted through beamforming algorithms.

This approach provides several technical advantages:

Physical Accuracy: Ray-tracing based GSCM closely simulates the wireless propagation physical phenomena in the 3D digital environment, providing physically accurate results.

Environmental Specificity: Each simulation reflects the exact propagation environment being studied, defined by the environment and UE/UEs mobility and mutual UE/gNB positions and dynamics.

Dynamic Adaptation: As objects move or the environment changes, the channel matrices automatically reflect these changes.

Multi-scale Modeling: The approach captures both large-scale path loss effects and small-scale fading.

Enhanced MIMO Realism: By using physically accurate channel matrices, our approach enables: - spatial correlation modelling for advanced MIMO techniques - Accurate representation of rank-deficient channels in constrained environments - Realistic modelling of channel reciprocity for TDD systems - Comprehensive evaluation of complex UE antenna systems, particularly vehicular UE installations where antenna patterns are significantly affected by surrounding materials, ECU placement, space restrictions, and vehicle body geometry

Vehicular Antenna System Evaluation: The SIVERT framework enables detailed analysis of complex vehicular UE antenna systems, which typically exhibit highly irregular radiation patterns due to:

- **Space Constraints**: Limited mounting space within vehicle structures forcing non-optimal antenna placement
- **Material Interactions**: Electromagnetic coupling with metallic vehicle body components, glass elements, and interior materials through the antenna patterns for full vehicle installation.
- **ECU Interference**: Nearby electronic control units and wiring harnesses that create EMI emissions.
- **Dynamic Environment**: Constantly changing vehicle position due to vehicle movement

Using FFI SIVERT, researchers can evaluate antenna designs at various development stages - from individual antenna characterization through full vehicle-level integration testing. This capability supports:

- **Antenna Design Comparison**: Quantitative evaluation of different antenna configurations under identical channel conditions
- **Virtual Prototyping**: Early-stage performance assessment before physical prototype construction
- **System-Level Integration:** Understanding antenna performance within complete vehicular systems
- **Development Process Acceleration**: Virtual testing reduces dependency on expensive prototype vehicles and measurement campaigns
- **Advanced Interference Injection**: study the potential influence of the internal vehicle (or other UE - surrounding) complex interference measured and synthesized pattern on the communication system system-level performance.

One important note here is that Unity3D and ns-3 use different time pace paradigm: Unity3D – step based (with physics calculation fixed step and rendering floating step), while ns-3 – operates as event-driven system with main scheduler concept. To ensure proper synchronization between Unity3D and ns-3 simulation pace one can use the two following approaches:

- Use RealTimeImplementation in ns-3 to align the passage of events execution in ns-3 with external clocks.
- Use blocking mechanism in ns-3 that is controlled by the external process (Unity in our case) to synchronise the data/status between ns-3 and Unity at the same step, defined by the Unity3D pace.

In our implementation we rely on the later approach which demonstrates better robustness and simplified process of the time synchronisation.

4.2.5 Antenna simulation and antenna modelling in SIVERT2 framework

Simulation was implemented at the beginning phase of the project development. Based on CST studio, a CAE (Computer Aided Engineering) tool, a digital representation of the antenna on vehicle was built. The antenna as well as the vehicle are mockups of the real installation. With correct settings such as frequency and excitation of the port, this simulation software could provide antenna parameters like reflection coefficient, antenna gain etc. as the results. These results were used as initial inputs for the further steps of WP1.

To have a good balance between simulation cost and reliability, some simplification is made in the model. The vehicle geometry complexity is reduced by removing physical details on reasonable level. The methodology of this geometry simplification process was created in SDIVA [*13*], a former research project. Apart from that, the mesh setting in the simulation software was also tuned to decrease the mesh cell amount into feasible level for execution on cluster. In addition, the hybrid solver approach implemented in CST studio was evaluated with respect to both computation accuracy and efficiency, and compared against the conventional single-solver method [*14*]. This hybrid solver approach partitions the simulation domain into the source regions (i.e. antennas) and the platform region (e.g. vehicles). This separation enables the use of distinct solvers and meshing strategies optimized for the respective scales, while the coupling between solvers is achieved through general field interfaces The evaluation results indicate that the hybrid solver produces results closely matching those obtained with the single-solver method, while achieving a substantial reduction in computation time. A comparison of the simulation and measurement was conducted for verification need. A prototype antenna was located under the roof of a Volvo car in this case.

The antenna gain was checked by means of CDF (Cumulative Distribution Function) as well as the averaged value over 5 degrees of azimuth angle. Take the horizontal plane (theta=90 degree) as the example, the following plots indicate a relatively good correlation of the simulated and measured results.

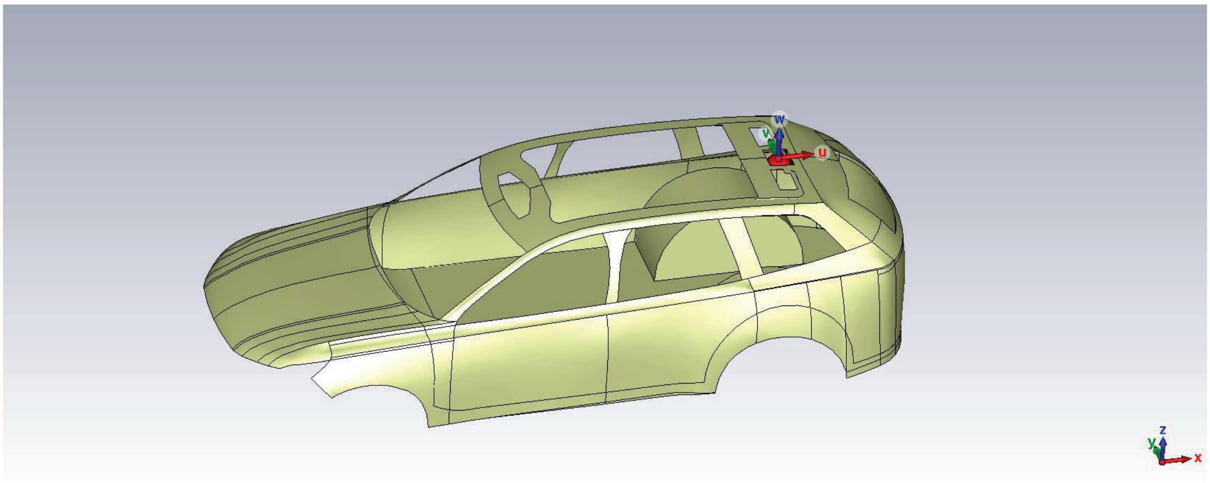


Figure 4-21, Vehicle CAD model view in CST

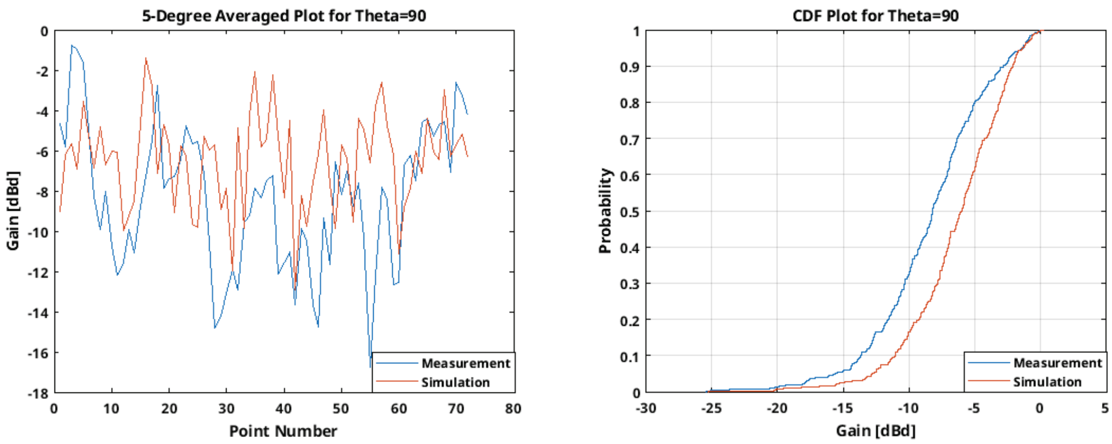


Figure 4-22, Left: Prototype antenna gain plot over phi plane, Right: CDF comparison results for the prototype antenna measurements and simulation

There still exist some shortcomings in the simulation procedure used. For example, the results are not as well-correlated as those within the main lobe (from theta=60 degree to theta=90 degree). But the trend keeps therefore the simulation is still a reasonable indicator of antenna performance.

Some improvement attempts were also made. To reduce the fluctuation of the data, a smoothing function with sliding window was utilized. Unfortunately, the standard deviation decreased but not significantly.

4.2.5.1 UE antenna radiation pattern sources in simulation framework

In general, SIVERT2 simulation framework can work with any radiation pattern sources: simulated, measured or analytical.

To achieve consistency in the antenna diagrams across different simulated antenna resolutions as well as measurement resolution (in the antenna labs or using the RanLOS measurement system), we implemented the helpers that can convert the theta/phi spherical antenna gain measurements into the Effective Aperture Distributed Function (EADF) format. The EADF transformation maps the spatial domain pattern into a Fourier domain thus, allowing to upsample/downsample antenna pattern data to a consistent format irrespective of the antenna diagram source. Inside Unity3D we utilise the highly optimised NativeParallelHashMap representation which we are obtaining at the Start() method of which simulation scenario form the EADF antenna files attached to each antenna objects: each EADF is recreating the 3D antenna diagram, which in it's turn sampled into a highly computationally efficient NativeParallelHashMap structure that is used for weighing each propagation path.

Overall, in scope of SIVERT we trialed antenna patterns from:

- CST simulation models developed in WP1A (see Chapter 3.1).
- RanLOS measurement system from WP2C (see Chapter 3.2).
- Antenna measurement labs – antenna diagrams measured on the complete vehicle.
- Antenna component measured in the lab.
- Analytical simulated models for gNB antenna ports.

Thanks to EADF and NativeParallelHashMap approach neither of the diagram sources cause any issues for the simulation framework.

4.2.5.2 Vehicle UE antenna diagrams and antenna ports diagrams for gNB

For the gNB (base station) side, our Unity3D implementation incorporates antenna port modelling that reflects real-world deployment scenarios:

Pre-configured Antenna Port Implementation: Rather than modelling individual antenna elements dynamically, our implementation uses pre-configured antenna ports that represent static beam patterns throughout the simulation duration:

gNB Port Configuration: Each antenna port consists of multiple antenna elements pre-configured into specific beam patterns that account for beam angle, gain, and directivity

Static Beam Patterns: Port configurations remain fixed during simulation, with beam characteristics captured in static port pattern diagrams

gNB Port Limitations: Particularly on the gNB side, we implement pre-configured beamforming where

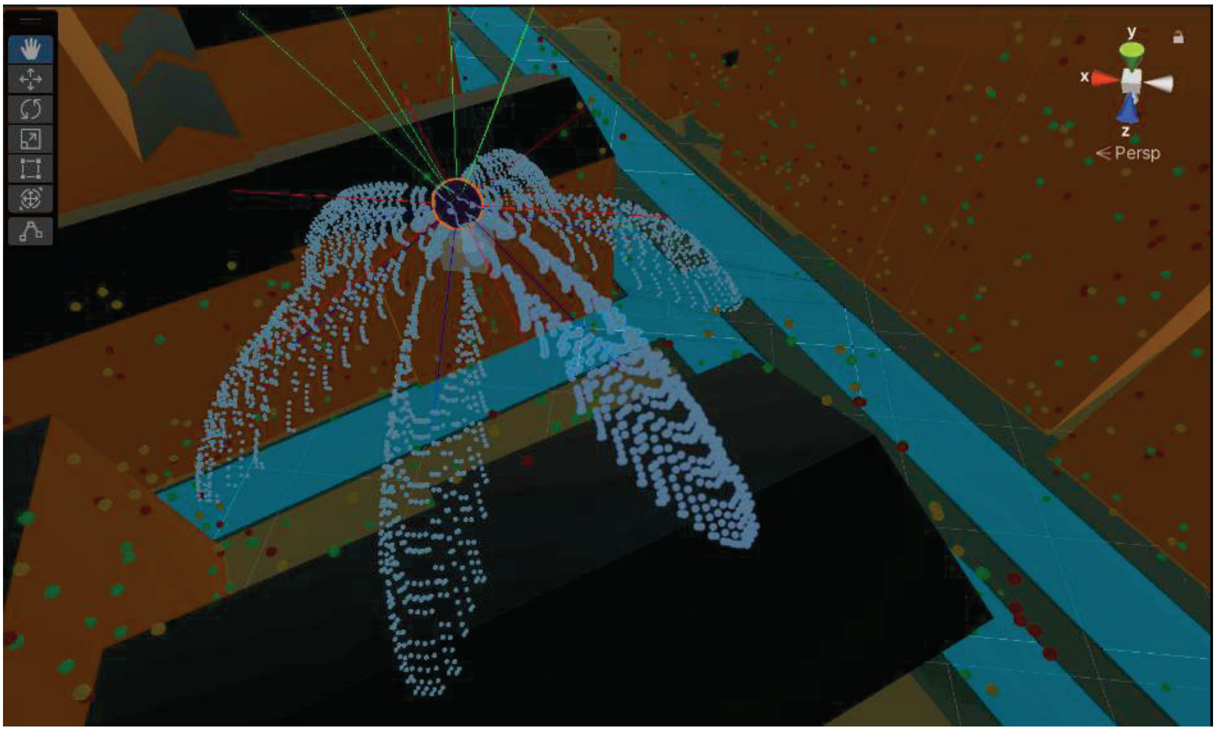


Figure 4-23, gNB static ports pattern example for 3-sectors (2 ports per sector)

ports represent predetermined beam patterns rather than individually controllable antenna elements.

Pattern Integration: While individual elements are not dynamically controlled, the GSCM ray-tracing accurately accounts for the overall antenna pattern effects through precise electromagnetic modelling

UE Antenna Patterns: Vehicle UE use actual antenna patterns that are simulated or measured using RanLOS measurement system or in other antenna labs.

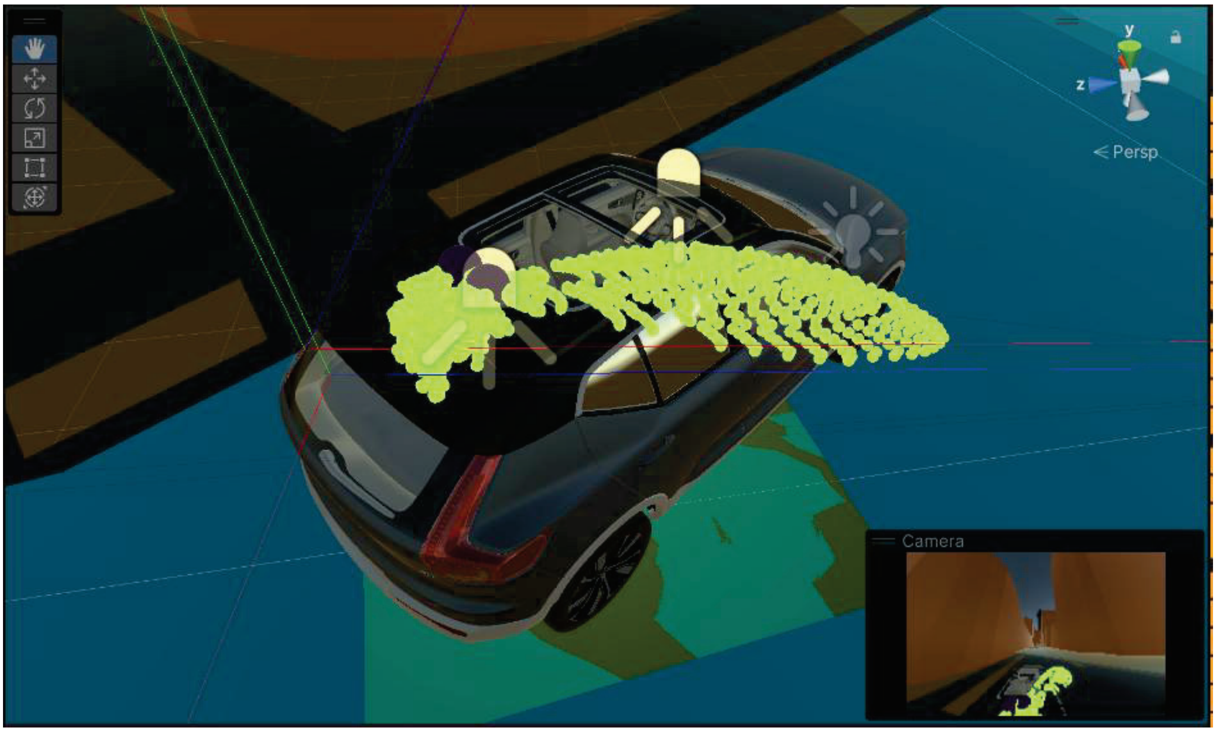


Figure 4-24, UE analytical and lab measured antennas examples

Implementation Rationale: This approach reflects practical limitations in current 5G implementations where:

- UE devices typically use traditional 2-4 antennas in the current telematic units
- Complex beamforming algorithms in commercial systems are proprietary and vary significantly between vendors
- Static beam patterns provide computational efficiency while maintaining accuracy through Unity3D ray-tracing
- As of August 2025 Lena 5G module doesn't support neither intra-cell nor inter-cell HO. For the single gNB we decided to model 3-sector with several ports spaced equally around the gNB and use same Physical Cell ID (PCI) and no RRC/RLC extra signalling due to the ns-3 current limitations, while keeping all the rest MIMO computations intact.

GSCM Integration Benefits: Despite the static nature of beam configurations, the Unity3D GSCM implementation provides accuracy by: - Computing precise interactions between pre-configured antenna patterns and the environment - Accounting for all propagation effects (reflection, diffraction, scattering) that interact with the antenna patterns - Modelling the complete propagation environment including geometric relationships. The integration maintains and enhances all advanced MIMO capabilities of ns-3 LENA through sophisticated algorithm preservation:

- LENA's spatial multiplexing algorithms operate on Unity3D-provided channel matrices to perform rank adaptation and layer allocation based on realistic propagation conditions. While the antenna beam patterns remain static as pre-configured, the Unity3D channel matrices provide physically accurate spatial correlation and rank characteristics that enable LENA to make realistic decisions about optimal layer allocation.
- LENA's Adaptive Coding and Modulation (AMC) algorithms select modulation and coding schemes based on Signal-to-Interference-and-Noise (SINR) measurements computed from Unity3D channel

data. This ensures that modulation decisions reflect actual propagation conditions including realistic interference patterns and spatial filtering effects.

- The AMC link adaptation provides accurate throughput predictions under realistic channel conditions. The hybrid ARQ procedures operate with channel quality feedback computed from Unity3D channel matrices, ensuring that retransmission decisions reflect actual electromagnetic propagation conditions rather than statistical approximations.

Ray-Tracing Based Pattern Generation: Unlike traditional simulations that use analytical antenna patterns, our approach computes antenna responses through ray-tracing: - Individual rays interact with each antenna element based on its physical geometry - Element patterns are computed considering the actual propagation environment - Scattering and coupling effects from nearby structures are automatically included - Frequency-dependent behaviour is naturally captured through the ray-tracing process.

This preservation of LENA's sophisticated algorithms while operating on realistic Unity3D channel data provides high simulation accuracy. Traditional simulations using statistical channel models cannot capture the complex wireless signal propagation interactions that significantly impact MIMO performance in real environments. By maintaining LENA's advanced signal processing while providing realistic channel conditions, SIVERT enables researchers to study the true performance of 5G systems under realistic conditions, leading to more accurate network planning, antenna design validation, and system optimization.

This comprehensive approach ensures that our simulations capture both the realistic electromagnetic environment through Unity3D ray-tracing and the sophisticated 5G protocol behaviour through ns-3 LENA, providing an advanced level of simulation fidelity for advanced MIMO system research.

4.2.6 Electromagnetic Interference (EMI) Modelling

V2X simulations are mainly performed to explore and predict the behavior and performance of the network under non ideal circumstances. There are a number of factors that can degrade communication performance from the theoretical maximum for the technology used. Some of the factors can be seen as controllable, like receiver sensitivity and antenna gain. Other factors are more of an uncontrollable nature, like propagation environment (reflecting, blocking and scattering objects) in the surrounding environment or ambient electromagnetic fields. In a modern vehicle there are several radio technologies used for entertainment and to enhance safe driving. At lower frequencies AM, FM and Digital broadcasting radio reception is normally interference limited meaning that the signal to interference and noise ratio, SINR, is more limited by the high electromagnetic interference level than the receiver system noise level. During vehicle development significant effort and cost are spent on reducing the electromagnetic emissions from the vehicles electric system to a level to achieve acceptable range and reception performance. The technology development today is toward higher data rates in communication, faster control loops all giving rise to electromagnetic emissions at higher frequencies, up to several GHz.

In high end cars with today's technology the electromagnetic emissions around 6 GHz is normally at an acceptable level but will increase with new technologies.

A typical measured spectrum can look like as in Figure 4-25 below, where the dotted green and pink line are the recommended CISPR25 limits for average and peak detector respectively.

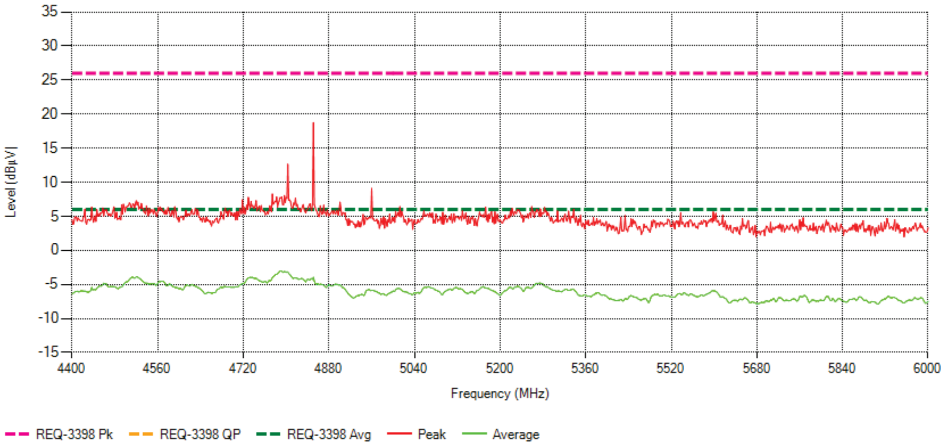


Figure 4-25, Volvo Car EMI measurement example following CISPR25 process

As seen in Figure 4-25 there are still emissions that can appear up in this frequency band up to 6 GHz but the levels are often at an acceptable level.

If, during the development of a vehicle, electromagnetic emissions from a component are measured to be higher than originally aimed for the question arises whether the component shall be redesigned or if it can be accepted.

If the electromagnetic interference levels were considered in the VANET simulations those simulation models could be used to judge the significance of the interference and degradation of the communication could be assessed.

In this work package we investigate a number of questions in this context:

- Can we find V2X simulation efforts from other groups where electromagnetic interference has been considered?
- Can we find other related information in the literature that can support us how to add electromagnetic interference into the simulation models?
- Can measured and simulated electromagnetic interferences be considered in the simulation framework?
- How shall measurements of the interference be performed when it comes to measurement bandwidth, measurement time and other factors to fit in the simulation?

4.2.6.1 Intentional and unintentional interference

Electro-magnetic interference, which EMI stands, can be categorized based on different aspects, the source, the duration or the bandwidth of the interference. In this document, we categorize EMI as Intentional EMI (IEMI) and Unintentional EMI (UEMI).

IEMI, by its widely accepted definition out of the 1999 EMC Symposium, is 'intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting confusing or damaging these systems for terrorist or criminal purposes' [*15*].

IEMI can be implemented in different ways, radio frequency (RF) jamming and HPM (High power Microwave) attacks are commonly named [*16*]- [*17*]. As the society's functionalities rely more on the wireless communication and services, a lot of research or engineering work have been devoted to analyze the risk and develop the anti-interference solutions. For example, RF jamming, which is one major form of IEMI, has been widely investigated concerning various wireless networks. In [*18*] a comprehensive jamming experiment was carried out. Authors came up with both continuous and reactive radio jammers setups to attack 5.9 GHz 802.11p based V2X communications. It has been demonstrated that even reactive jammer can severely compromise wireless communications. In the presence of the continuous jamming signal CSMA/CA based V2X stations defer from communication and do not transmit messages. At the same time, continuous jamming is very easy to detect. Reactive jamming, however, can implement strategies when jammer triggers interfering signal only upon overhearing of the Orthogonal Frequency Division Multiplexing (OFDM) preamble and emits signal only when the payload is transmitted, which leads to dropped message at Rx end, while keeping a jamming transmission practically indistinguishable from legitimate V2X exchange. Authors demonstrated that even in the pass by scenario, when jammer is placed on the side of the road, it can cause complete outage in V2X communication in a few hundred meters radius (which will cause several seconds communication block out for passing vehicles), outcome can become even more severe if jammer is travelling along the vehicles.

The study in [*19*] provides a comprehensive survey on jamming attacks and anti-jamming strategies covering WSNs, WLANs, cellular networks, GPS systems, vehicular networks and more. The paper states that the anti-jamming strategies can only be thwarted at the physical (PHY) layer but not at the medium access control (MAC) layer or network layer, and most of the current wireless networks can be easily paralyzed by jamming attacks. Which agrees with conclusions done in [*18*] that reactive jammer cannot be detected at the PHY layer.

As comparison, the EMI due to natural sources, like lightning, or coming from the electrical/electronic components that are massively deployed in our daily lives nowadays, can be defined as unintentional EMI. The electronics have been taking up a bigger share in the cost of a whole vehicle. The electronics made up only about 10% of a total car cost in 1980, and increased to 35% in 2010, and it is projected that this share will be around 50% in 2030 [*20*], mainly driven by the major development trends towards connectivity, electrification and automation. The radiated and conducted EM emission from all the electrical/electronic components on-board (installed in vehicles) are becoming higher in strength levels and wider and wider in frequency band. Such disturbances inevitably exist in every vehicle and might interfere with vehicular wireless communications. In the SIVERT2 project we keep the focus on how such unintentional EMI from vehicles is estimated when estimating the EMI impact on V2X wireless communications and how to introduce it to our simulation framework to be able to assess its influence on the performance of the wireless connectivity on the system level.

4.2.6.2 Relevant EMI industrial standards

There are several legal requirements all over the world to regulate both the EM emissions and immunity of the whole vehicle as well as the individual electrical or electronic equipment on board. For example, the United Nations Economic for Europe (UNECE) Regulation No. 10 [*21*] states every vehicle and every electronic sub-assembly (ESA) that is sold in any of the UNECE member countries should be compliant with the UNECE R10 requirements regarding the electromagnetic compatibility for the automotive industry. Other regions and countries have their own requirements but many of them are well harmonized with UN ECE Regulation No. 10 like for example the Chinese GB 34660 requirement. On top of these legal regulations, there are further international standards for any electrical or electronic component intended for use in vehicles. In the aspect of controlling unintentional EM emissions, the international standard CISPR25 containing limits and procedures for the measurement of EM emission the frequency range of 150 kHz to 5925 MHz [*22*]. The legal limit defined by R10 for vehicle-level type approval focuses on the EMI from the vehicle under the test to the environment/surroundings with the aim to protect radio reception in society. The more stringent limits defined by CISPR25 are intended to provide protection of receivers installed on-board the vehicle. Chapter 5 in CISPR25 describes the requirement and method to measure the emissions received by the antennas installed on the same vehicle, and also gives the example limits for these disturbance emissions considering typical radio receivers as the table in Figure 4-26 shows. The table is from CISPR25:2021 revision. It could be noted that this 2021 revision expand the limit from 2500MHz to nearly 6000MHz as compared to its previous 2016 revision, mainly for covering two new applications 5GHz Wi-Fi and 5.9GHz V2X.

5.5 Examples of limits for vehicle radiated disturbances

It is recommended for acceptable radio reception in a vehicle using typical radio receivers, that the disturbance voltage at the end of the antenna cable should not exceed the values shown in Table 4 and Table 5. Where different receivers are used or different coupling models for the propagation of disturbances are valid, the limits can be changed and detailed in the vehicle manufacturer's own specification.

Table 4 – Example for limits of disturbance – Complete vehicle – General

Service / Band[a]	Frequency MHz	Limit of disturbance voltage at antenna terminal of receiver in dB (µV)			RBW
		Peak	Quasi-Peak	Average	
Analogue broadcast services					
LW[b]	0,15 to 0,3	26	13	6	
MW[b]	0,53 to 1,8	20	7	0	9 kHz
SW[b]	5,9 to 6,2	20	7	0	
FM[b]	76 to 108	26	13	0	
TV Band I[c]	41 to 88	16	-	6	120 kHz
TV Band III[c]	174 to 230	16	-	6	
TV Band IV[c]	470 to 944	16	-	6	
Digital broadcast services					
DAB III	171 to 245	26	-	16	
TV Band III[c]	174 to 230	26	-	16	
DTTV	470 to 770	32[d]	-	22[d]	1 MHz
DAB L Band	1 447 to 1 494	32	-	22	
SDARS	2 320 to 2 345	32	-	22	
Mobile services					
CB[b]	26 to 28	20	7	0	9 kHz
VHF[b]	30 to 54	20	7	0	
VHF[b]	68 to 87	20	7	0	
VHF[b]	142 to 175	20	7	0	
Analogue UHF[b]	380 to 512	20	7	0	120 kHz
RKE & TPMS 1[e]	300 to 330	20	-	6	
RKE & TPMS 2[e]	420 to 450	20	-	6	
Analogue UHF[b]	820 to 960	20	7	0	
GPS L5[f]	1 156,45 to 1 196,45	-	-	10	
BDS, B1I[g]	1 553,098 to 1 569,098	-	-	-4,5	9 kHz
GPS L1[h]	1 567,42 to 1 583,42	-	-	0	
GLONASS L1[i]	1 590,781 to 1 616,594	-	-	0	
Wi-Fi / Bluetooth	2 402 to 2 494	26	-	6	
Wi-Fi	5 150 to 5 350	26	-	6	1 MHz
Wi-Fi	5 470 to 5 725	26	-	6	
V2X (Wi-Fi)	5 850 to 5 925	50	-	30	

Figure 4-26, Snapshot of part of Chapter 5.5 in CISPR 25:2021 [23] showing the example limits of the disturbance voltage at the end of the antenna cable for acceptable radio reception in a vehicle using typical radio receivers.

4.2.6.3 Known measurement campaigns and research projects

In [24] authors propose a method to simulate sinusoidal CW (continuous wave) based interference, taking into account the path loss between the Tx jammer/interferer and the Rx V2X node. The approach is based on the Friis propagation between Tx and Rx and takes into account the pathloss variation form the previous V2X field measurements. Analytical approach towards CW EMI introduction into simulations also accounts for phase shift and doppler for dynamic scenario, when vehicle passes along the jammer. Authors in [*24*] also propose to use the RC (Reverberation Chamber) to measure the influence of the EMI on V2X communications.

In [*25*] the results of the EMI measurement experimental setup are presented. Authors targeted the interference at 2.4 GHz. The source of the interference originated from the vehicle systems, when the engine was turned on (ICE Land Rover was used). Measurement concludes that there could be quite a few EMI impulses coming from vehicle system, some of which could be up to -50 dBm in power. However, in this particular measurement, even though the average number of EMI impulses observed was ~100 per second, the duration of the majority of them is below 150 nanoseconds.

The Swedish FFI financed project EMCCOM developed new EMC test methods for vehicle electronic units and simulation models. Both are to be used to protect the performance (both reliability and capacity) of wireless digital communication services and by that ensure high availability of implemented safety and transport efficiency functions. The output from this project was part of the input to the 2021 revision of IEC CISPR25 standard. Systems that were studied were W-CDMA, LTE, GNSS (GPS), WLAN (802.11g), C-ITS (802.11p) [*26*]. Within this project there were investigations done, both simulations and measurements, on jamming and interference vulnerability in terms of bit or packer error probability for different interference type signals, CW, AM, FM, PULM. In [*27*] the authors have analyzed interference signal approximations for system performance predictions and the impact on the IEEE 802.11p system in terms of bit and packet error probability and packet delays. Necessary conditions for when a Gaussian approximation can be used accurately for impulsive interference, in a DSSS system using convolutional coding is derived in [*28*]. Susceptibility to the different interference type signals have been measured on IEEE 802.11p communication link [*29*] and on a LTE communication link [*30*].

4.2.6.4 EMI modelling considerations

There are two main approaches/levels to model the wireless propagation environment in wireless simulations:

- Link level simulators. Link level simulations are focusing primarily on the PHY layer with a great level of details to be able to capture majority of the propagation artefacts into account, desirably on the modulation symbol level. It normally covers channel model (path loss and fading, doppler, etc.), MCS (modulation, effective code rate, codewords segmentation), Tx/Rx modes (SISO/MIMO in various Tx modes), etc. Also calibrated on real measurement for state-of-the-art chipsets. The most known link-level simulator for LTE is [*31*] - Vienna 5G Link Level Simulator. These tools are also quite restrictive in licenses.
- System level simulators. Ideally, they should capture the same effect with some abstractions to details to reduce the complexity of the model and computational costs. The general approach is to find a model/function/conversion function from bit/symbol level to packet/sub-channel level. The generic approach is to collect data using a link-level simulations and use it as input to system-level models.

The state-of-the-art system level network simulators on PHY layer are enabled via SpectrumChannel abstraction. In spectrum channel the entire BW of the channel is spliced into chunks (sub-bands) of spectrum of the equal size, e.g., a 180kHz OFDM Resource Block (RB) (12 sub-carriers) or other smaller frequency unit (100 kHz by default in ns-3 spectrum channel). Each sub-band is modelled as PSD (power spectral density) flat level, see graphical representation on Fig.1, i.e. the channel is assumed to be flat in each of those sub-bands. To obtain the BLER or PER the SINR is first calculated over sub-bands in spectrum channel and then using the matching between SINR eff. and BLER curve is used to get the BLER and "flip the coin", see below.

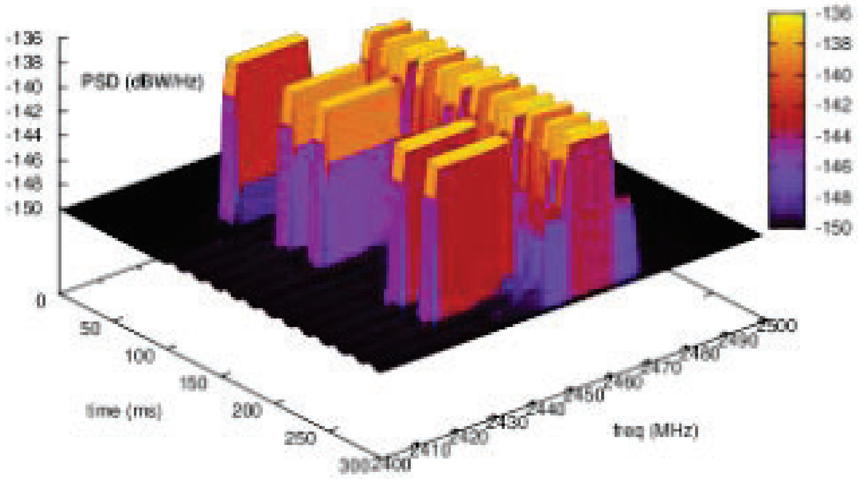


*Figure 4-27, Spectrum channel visualisation [*33*]*

Surely, on the top level, the path-loss, fading/shadowing, interference from other legitimate transmissions is calculated in the simulation as an input to spectrum model. How precise the frequency-dependent effects are taken into account can vary depending on the specific models used. In our case, due to the level of details GSCM provides, the path loss and fading are frequency and spatially dependent on the raster of OFDM sub-carrier. Antenna patterns are also included in GSCM with all the details. Most commonly used fading models are frequency dependent, but do not account for the spatial propagation of the signal, which is instead "captured" by statistical properties of the distribution used in the model. The generic match between System level and Link level are shown on Figure 4-28 below.

From Link level simulators over extensive modelling one could extract the match between SINR and BER for the specific Tx/Rx mode, MCS, etc. The task is then to match (or rather aggregate) these detailed SINR levels with a very high resolution to the RB or packet level without loosing the frequency selective properties using non-linear averaging techniques.

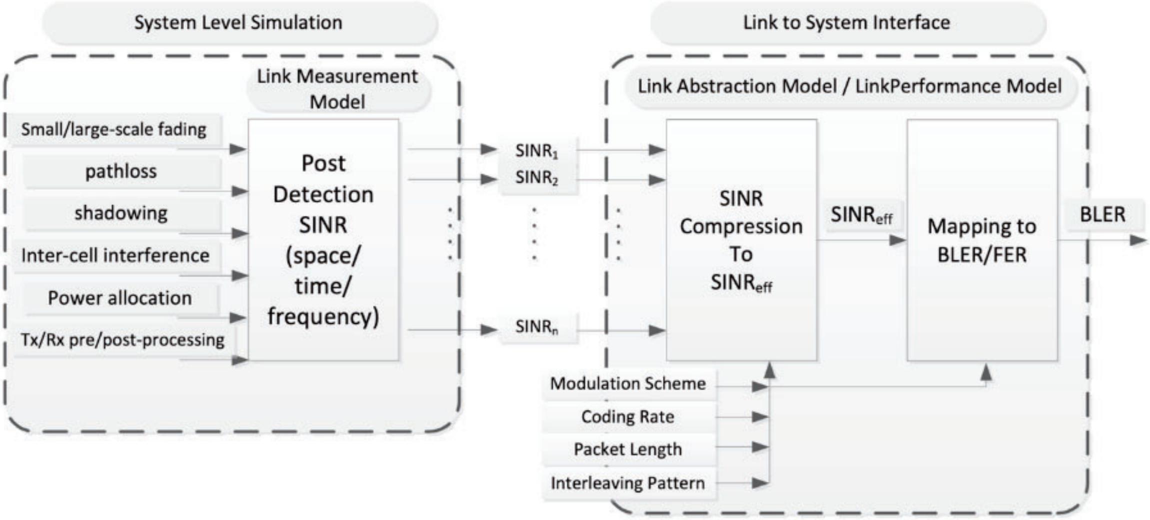


Figure 4-28, Frequency selective fading [34]

In broadband multi-carrier system under dynamic environment, OFDM in particular, two links with the same linear average SINR may still experience greatly different environment, due to large variability of the instantaneous channel states. Accordingly, linear average SINR is no longer sufficient to estimate instantaneous link performance. However, the effective SINR mapping approach can be utilized and summarized in two main steps as depicted in Figure 4-29 below.

Firstly, the most challenging task is to obtain a compressed SINR value of the current instantaneous channel states, such as the instantaneous SINR for each subcarrier in OFDM within a given Transmission Time Interval (TTI) period or other time span by using a non-linear average approaches, thus the effective value should be very representative with high accuracy measure. Secondly, the effective value, as a scalar, yields an estimated Block Error Probability (BLEP) or BER, which is obtained by the simulation of additive white Gaussian noise (AWGN) channel as a Look-up table LUT and is equivalent to other channel models.

At the end BLEP/BER approximated for effective SINR under AWGN assumption should match the instantaneous channel conditions SINR BLEP/BER observed in the channel.

To achieve this, several state-of-the-art approaches are available, which are used not only in system-level simulations but also in real-world cellular systems - for example, for mapping channel measurements at the UE to Channel Quality Indicators (CQI), which have a limited resolution due to their constrained size.

Two most common are:

- Exponential Effective SINR Mapping (EESM), [*32*]
- Mutual Information Effective SINR Mapping (MIESM), [*32*]

Both of the mapping metrics are used quite interchangeably in the literature. There are also other similar metrics that has been proposed in the literature in the earlier times (e.g., Capacity Effective SINR Mapping (CESM), Logarithmic Effective SINR Mapping (LESM)), but they proved to be inferior in precision to EESM and MIESM [*33*].

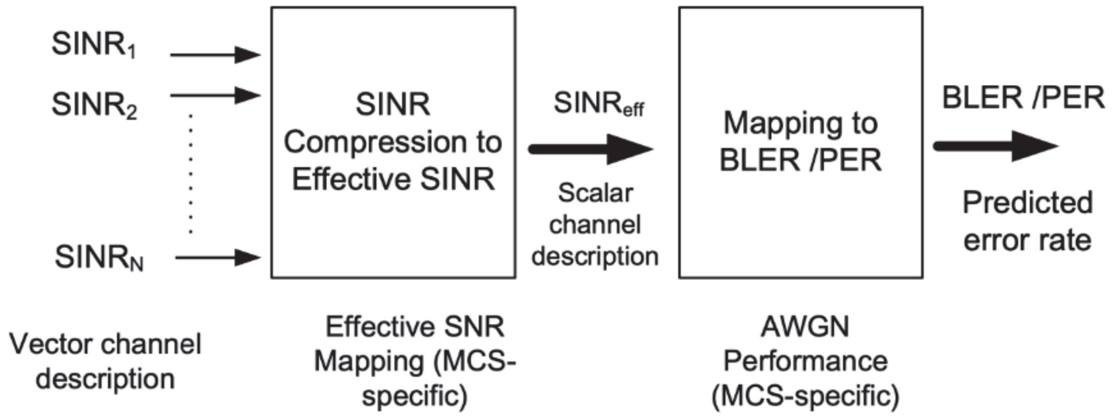


Figure 4-29, effective SINR mapping [34]

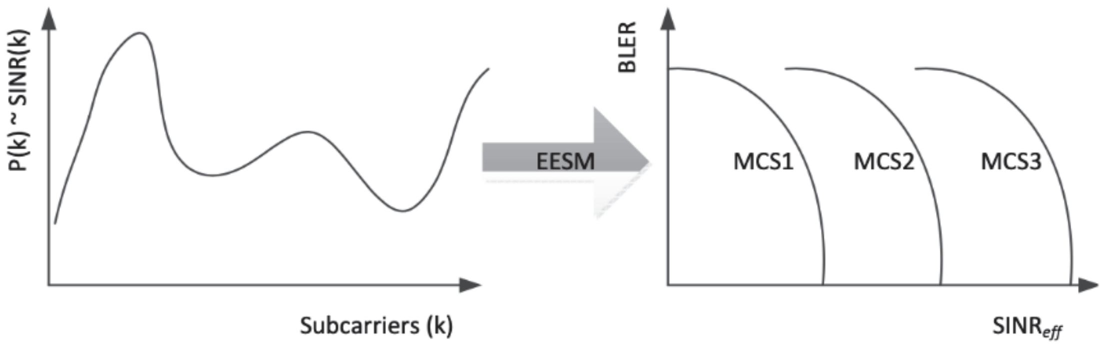


Figure 4-30, SINR to SINR eff (EESM) and ESM to BLER conversion principle [34]

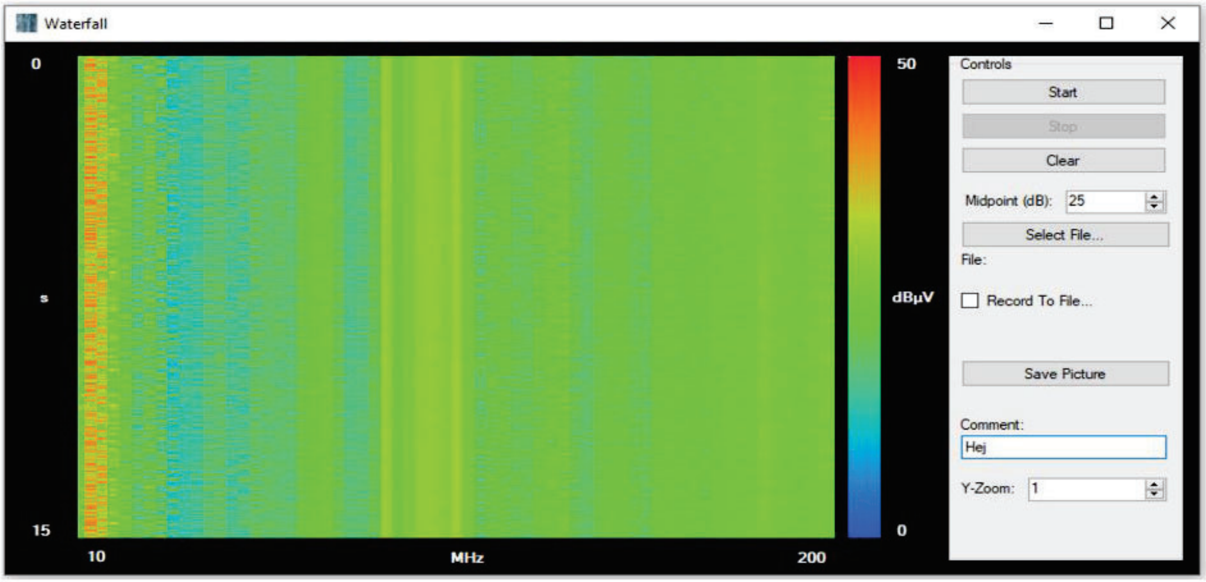
At the end of the day the SINR eff is calculated over the channel and pre-calculated LuT are used to match BLER/BER (BLEP) to SINR for particular MCS (modulation, effective code rate and code block sizes), Figure 4-30. In other words, System level simulator calculates the SINR for the spectrum channel sub-band and uses it to get corresponding BLER/BLEP to understand if block is successful or lost. The assumption is that SINR_eff preserves the narrow band effects of SINR at sub-carriers/symbols level when the proper EES function (EESM or MIESM) is used. Thus, resulting in the approach when one can have single SINR_eff value over, let say RB, and it still allows to capture quite precisely the narrow band effects.

4.2.6.5 EMI introduction into system level

Thus, the preliminary plan would be to re-utilise the existing PHY layers implementation, where the ESM to BLER mapping is already done, calibrated and verified for us. In 5G LENA ns-3 there's a [*35*] available and is used by default in simulations to match the SINR in sub-band to BLER. By introducing the additional interference level into the SINR calculation, calibrated on power level for the BW (to eliminate power difference between measured and simulated BW) would enable EMI account for us.

With this in mind we would like to focus on the development of the tool for the future needs, that will allow us to study the influence of various EMI levels on the wireless communication system performance. We did a (Power over Coax?) PoC EMI generation in the Volvo Cars EMC lab using the signal generator, being able to generate a narrow and wide band interference, while utilising dynamic waterfall spectrum analyser capabilities to be able to record dynamic measurements over time. The approach and data was used for the initial EMI implementation in SIVERT2 framework.

4.2.6.6 Sample EMI data sets collection in Volvo Cars EMC lab



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	New meas	Comment	Sweep tim	Points:401	Start freq	Stop freq	Start time: 2023-02-06 15:40:20							
2	10	10,475	10,95	11,425	11,9	12,375	12,85	13,325	13,8	14,275	14,75	15,225	15,7	16,175
3	18,99345	19,81403	24,65276	29,13232	33,81718	39,26685	36,64094	38,7997	37,77742	36,02228	36,23104	46,15736	41,41586	45,36355
4	19,91128	23,69798	25,64078	29,59622	31,47583	34,4203	31,38264	48,95143	50,83625	36,42303	35,00339	30,05606	29,24686	25,19424
5	21,26588	22,26749	23,41059	28,10915	44,59997	48,47243	42,13219	33,80305	30,75568	28,77215	28,03806	37,04226	30,54058	24,38474
6	20,78292	20,58728	26,63834	31,75443	35,62671	38,76892	43,10394	42,89204	47,29965	46,94123	50,92258	32,56155	26,7783	24,47945

Figure 4-31, Waterfall EMI data sample collection in the lab - graphical example

Our EMI characterization encompasses multiple wireless communication bands, providing a comprehensive database of interference characteristics across the spectrum used by modern vehicular communication systems. The measurement campaigns were conducted using FFT-mode spectrum analysis to capture the temporal dynamics and spectral characteristics of EMI sources.

Data Format and Structure:

- All EMI measurements follow a standardized data format optimized for subsequent simulation integration:
- Receiver Configuration: FFT mode operation capturing receiver antenna port voltage in dBµV as a function of time
- Temporal Resolution: Measurements repeated at defined intervals to capture EMI temporal variations

Data Structure:

- Row 1: Time-domain measurement sequences
- Row 2: Sub-band centre frequencies in MHz
- Row 3-N: Measured voltage levels in dBµV for each frequency bin with defined measurement bandwidth

Each measurement dataset is processed and formatted for direct integration into the SIVERT simulation environment, with automatic interpolation and spectral alignment algorithms ensuring compatibility with ns-3 LENA's internal spectrum representation. The comprehensive multi-band characterization enables researchers to study interference effects across the selected spectrum used by modern vehicular communication systems, from legacy ITS-G5 through advanced 5G NR implementations.

4.2.6.7 EMI integration approach into simulation framework

The most sophisticated aspect of our EMI implementation is the integration with ns-3's spectrum power spectral density (PSD) model through callback mechanisms. This integration operates at the fundamental level of spectrum processing, ensuring that EMI effects are incorporated into every spectrum-related calculation performed by the simulation.

The EMI processor is registered with the spectrum channel model to ensure it processes every spectrum calculation.

Real-Time Spectrum Modification: Every time ns-3 calculates SINR for link adaptation, the calculation includes actual measured interference characteristics rather than simplified models.

Frequency-Selective EMI: Unlike broadband noise models, our implementation captures the frequency-selective nature of real EMI sources, where interference power varies significantly across the 5G NR bandwidth.

Protocol-Level Impact: Because EMI is injected at the spectrum level, it automatically affects all higher-layer protocol decisions including: - Link adaptation algorithms (modulation and coding scheme selection) - Hybrid ARQ retransmission decisions - Handover triggering based on signal quality - Power control mechanisms

In the future one can use the SIVERT2 simulation framework to estimate the influence of the EMI in the following way:

- In the lab, emission patterns are measured using the spectrum analyser in waterfall mode to capture evolving spectral power.
- The traces are replayed into the simulator, where they are automatically mapped onto the per-resource-block noise spectral density during every downlink transmission.
- The influence of elevated or fluctuating EMI on wireless system performance including adaptation is tested virtually and more data-driven decision on severity of EMI levels and their influence on communication performance can be take.

4.2.7 SIVERT2 simulation framework - performance evaluation examples

In this section we make a brief comparison of two antenna systems in 2x2 MIMO scenario. We drive the vehicle UE along the route marked with red line on the Figure 4-32 with a single-cell 5G base station. Carrier: 3.5 GHz, TDMA, bandwidth 20 MHz, numerology 0 (15 kHz SCS, 106 RB usable). Traffic: Downlink saturated UDP (1000-byte packets, 40 µs inter-packet interval – 200 Mb/s max throughput) to force continuous load and expose adaptation dynamics. gNB Antenna: 2 logical TX ports. UE Antennas: 2 physical receive antennas on each of the antenna systems, see Figure 4-33, Performance evaluation of 2 different dummy antenna systems Figure 4-33.

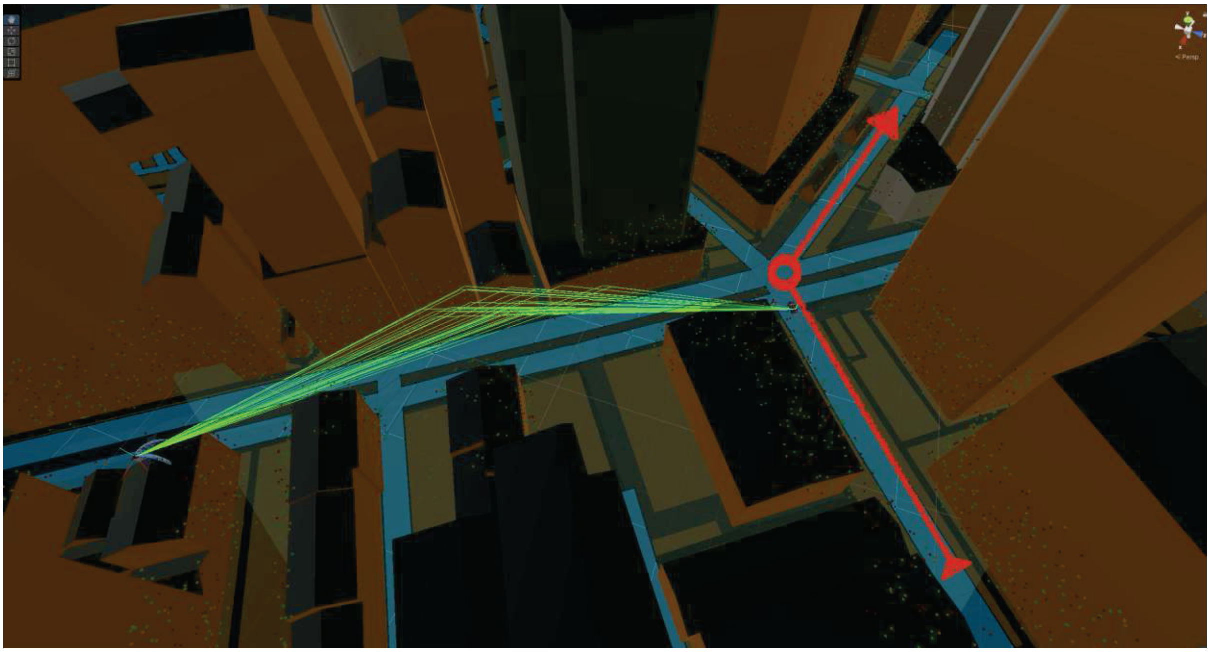


Figure 4-32, 5G Urban Dense drive scenario simulated

The scenario we run is closed-loop follow CQI 2x2 MIMO. We model the DL performance to compare 2 different UE antenna systems solutions. Below on Antenna System 1 delivers a consistent 5–8 dB SINR advantage during the critical strong multipath section of the drive, translating into longer residence at top CQI (14–15) and sustained maximum MCS, as well as better SINR at the beginning of the route due to a more balanced antenna diagrams, which translated in higher throughput, Figure 4-34. Rank-2 MIMO operation was both longer and more stable in System 1; System 2 more frequently fell back to rank 1 as its per-layer SINR dipped below the high-rate BLER target thresholds. In Figure 4-36 we're presenting results based on the logs we are collecting for each of the antenna systems simulation run. The UE is driving in the heavy NLOS propagation environment with no LoS component during the entire simulation run.

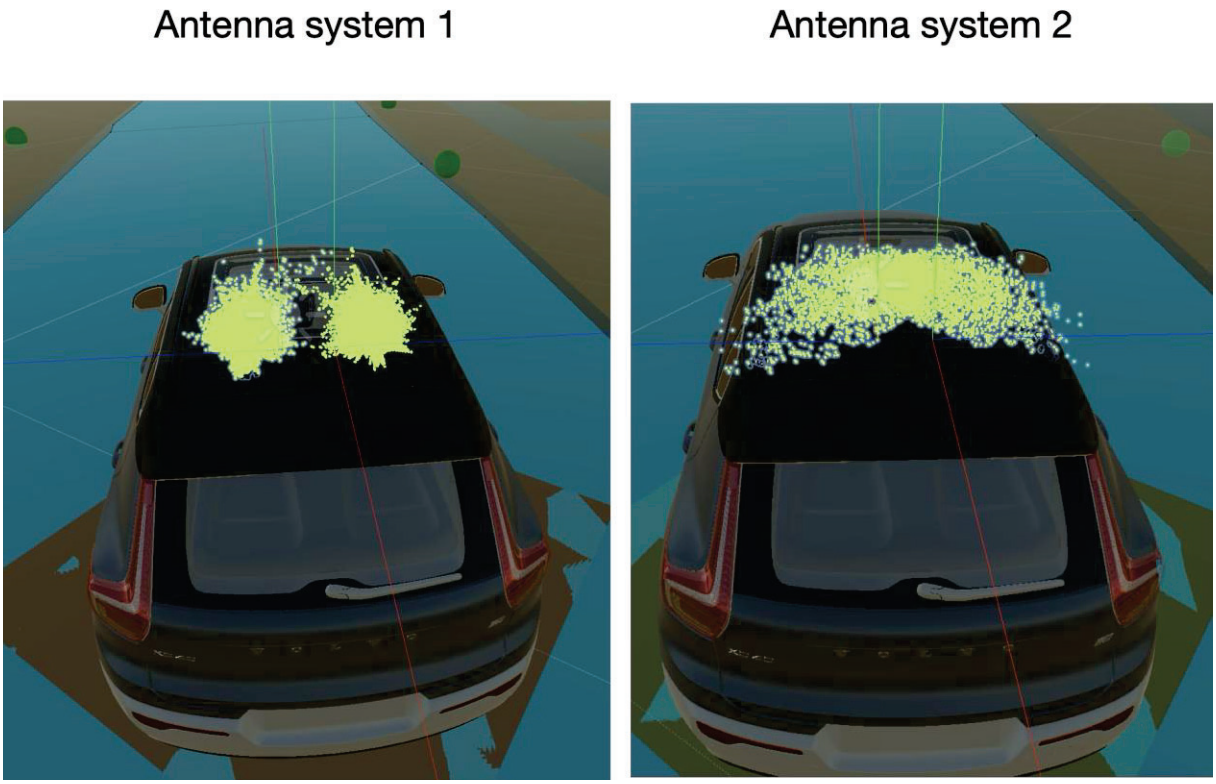


Figure 4-33, Performance evaluation of 2 different dummy antenna systems

Figure 4-33 shows SINR/CQI/MCS comparison for two antenna systems. SINR is closely follow the propagation geometry with higher rise around the middle of the scenario when vehicle reaches the intersection marked with the circle. Antenna system 1 demonstrates more consistent SINR (and power) due to a better balanced radiation pattern comparing with more directed antenna system 2 elements. That gives better balanced coverage during the whole NLoS drive and supports more stable adaptation of the ACM to a channel conditions. CQI closely tracks SINR. System 1 hits and sustains the table's top CQIs (≈14–15) earlier and longer; System 2 oscillates below the top for more intervals, causing frequent MCS back-offs. As expected, Rank-2 operation is favoured in the 5.5–9 seconds high SINR window. System 1 reaches maximum MCS soon after the SINR surge and holds it through most of the high-SINR plateau. System 2's MCS curve climbs more slowly, saturates later, and yields earlier - consistent with being just inside/outside BLER target thresholds of the ACM, Figure 4-33.

Antenna System 1 delivers a consistent 5–8 dB SINR advantage during the critical strong multipath section of the drive, translating into longer residence at top CQI (14–15) and sustained maximum MCS, as well as better SINR at the beginning of the route due to a more balanced antenna diagrams, which translated in higher throughput, Figure 4-36. Rank-2 MIMO operation was both longer and more stable in System 1; System 2 more frequently fell back to rank 1 as its per-layer SINR dipped below the high-rate BLER target thresholds.

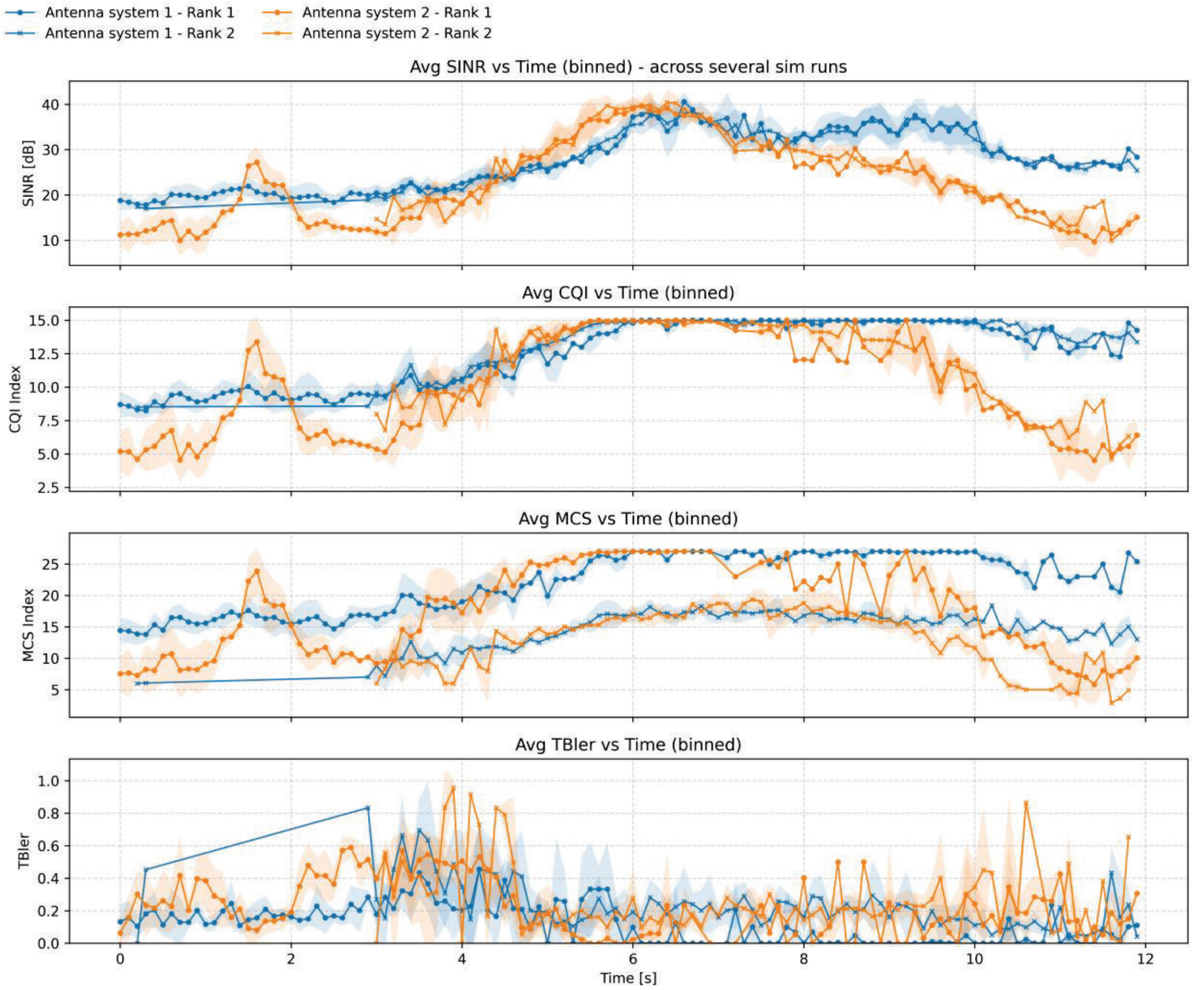


Figure 4-34, Simulation outputs: SINR, CQI, MCS. Comparison between antenna systems

As an additional experiment, we also introduced the dummy/synthetic EMI levels that we have measured in EMC lab to the simulation scenario with Antenna System 1. We executed the same UE drive route simulations, while replaying the recorded EMI levels dynamically during the run. We can observe how elevated EMI levels stressing the link adaptation of the Antenna system 1. Broadband EMI elevates the noise floor without boosting signal power, shifting System 1's SINR distribution down by approximately 3-4 dB, Figure 4-35. This truncates the high-CQI/high-MCS plateau and reduces stable rank-2 usage, yielding about 20-25% throughput loss (Figure 4-36), but also higher early-interval TBler volatility. After AMC re-converges at lower MCS, TBler returns near the target but sustained efficiency is lower. The effect is purely SINR-margin driven: same signal PSD, higher denominator. Early TBler spikes reflect transient rate overshoot before adaptation compensates. Such simulations can allow designers and researchers to estimate how the elevated EMI levels from a complex environment can affect different parts of the wireless communication system and make estimation of the degradation level, compare various placements and packaging fully virtually before the design freeze.

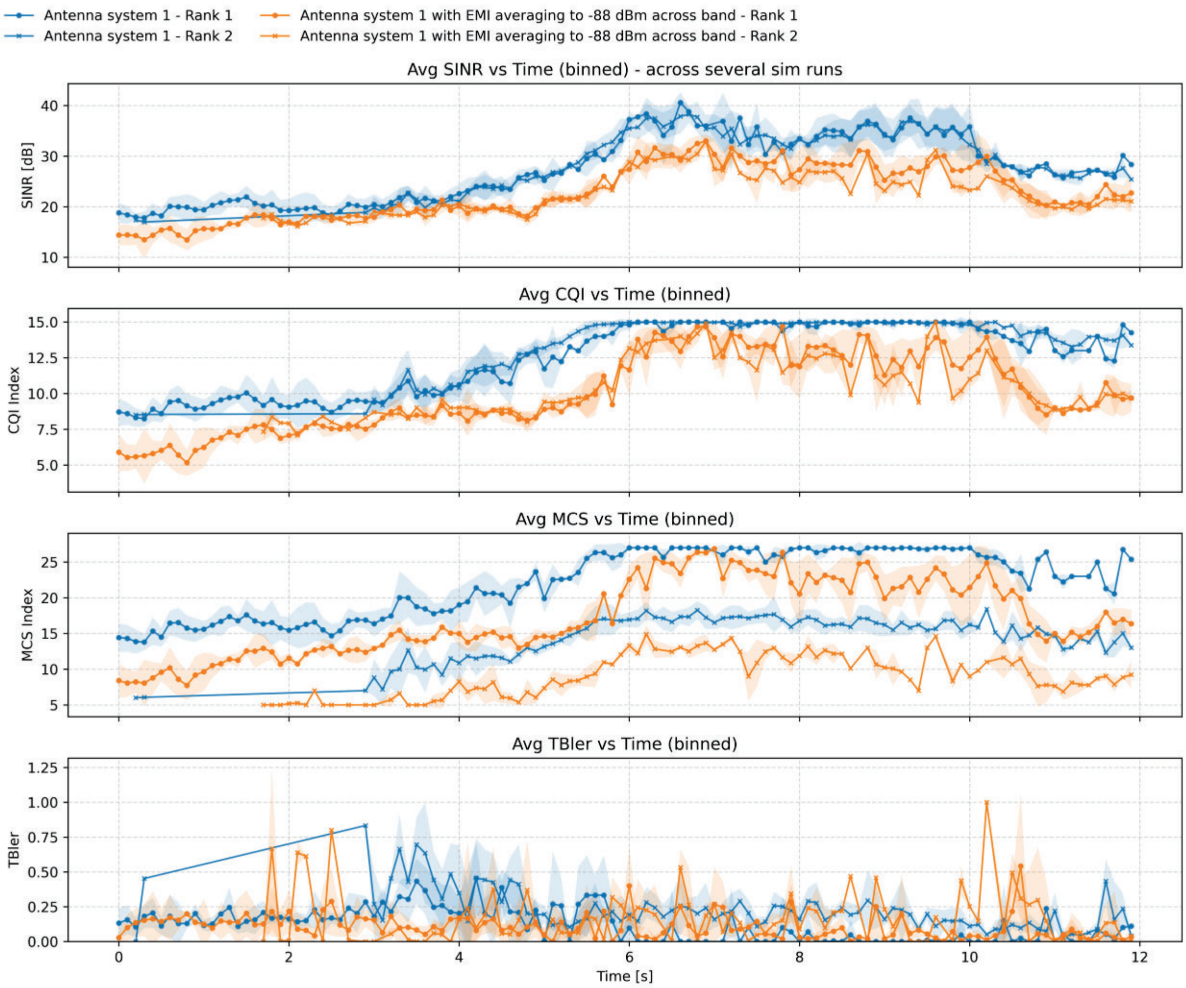


Figure 4-35, Comparison between antenna system 1 with and without injected EMI levels

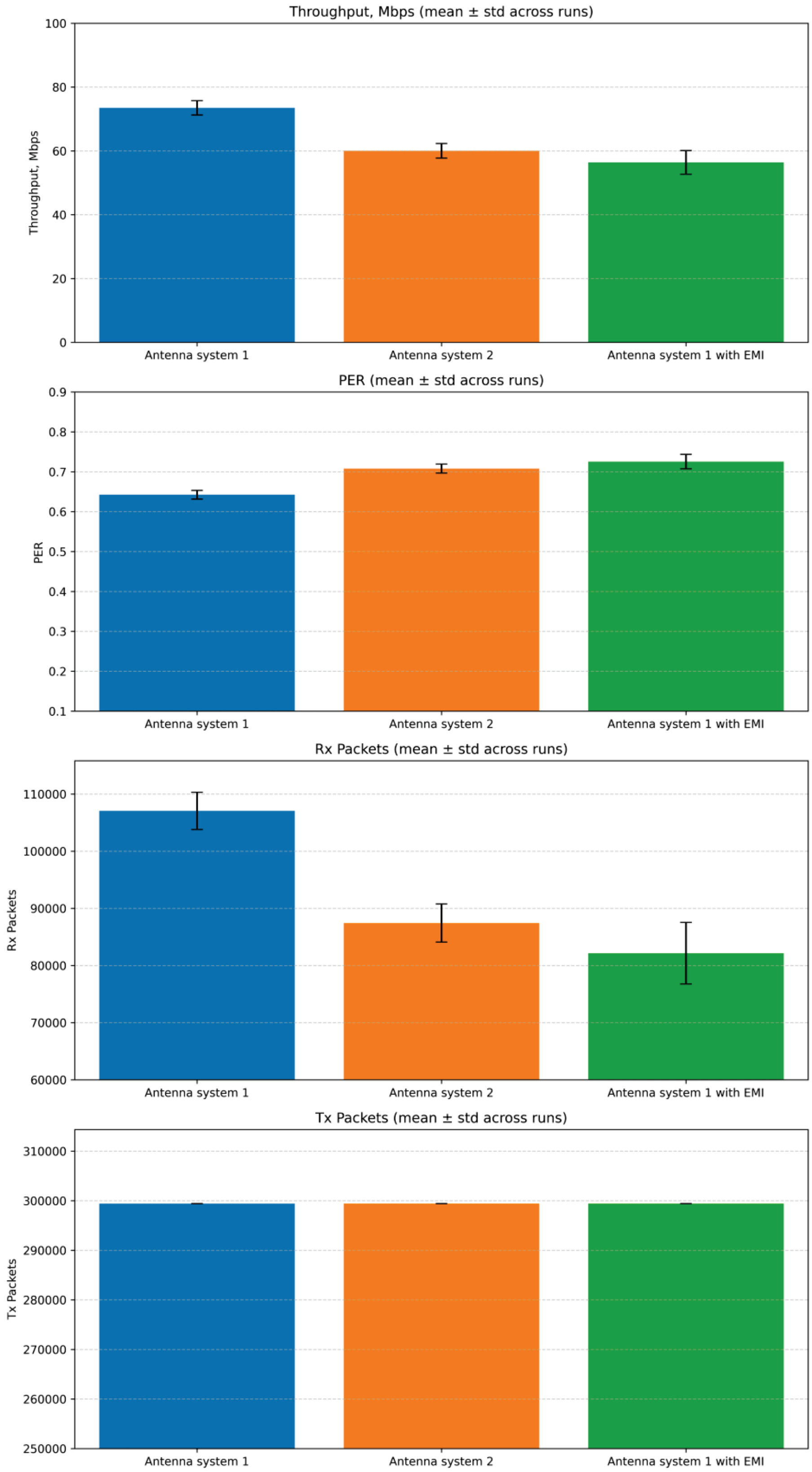


Figure 4-36, System simulation output: DL aggregated statistics, comparison between antenna systems

Overall, SIVERT 2 framework provides a rich capabilities for:

- Comparison and benchmarking different antenna system solutions
- Which can be done in virtually infinite amount of typical LoS/NLoS scenarios
- Study and compare how well antenna system can support

  - link adaptation,
  - coverage,
  - throughput,
  - and stability and various propagation scenarios.
- Estimate the influence of the elevated EMI levels on all of the mentioned above KPIs.

4.2.8 Work Package 1 – Conclusions

Modern connected and automated vehicles depend on reliable wireless links – for infotainment, safety, and over-the-air software updates. Yet real vehicles operate with integrated antennas in complex urban and rural, and increasingly "noisy" environments. In this work package we developed a unified simulation platform for future vehicle connectivity. Our goal in the project was to make verification of vehicle-to-everything communications more realistic, more repeatable, and directly comparable to measured wireless environments.

We implemented three pillars:

- realistic vehicle antenna behaviour
- geometry-based radio channel derived from a 3D real world
- dynamic electromagnetic interference - EMI

Vehicle installations never have a single, perfectly placed omni antenna. Instead, there are multiple, each with its own radiation pattern and polarization characteristics. This has a strong influence on the experienced performance. In Unity3D, we implemented the exact orientation and geometric context; our extended channel model consumed those and applied realistic gain per direction for every path. Antenna system strategy directly affects wireless system performance from coverage to how well a multiple simultaneous data streams can be supported. Evaluating the impact of antenna system design at the early stage is valuable guidance for future vehicle hardware design and early-stage performance evaluation.

Crucially, we extended Geometry-Based Stochastic Channel Models into a Vehicle-to-Everything ray-tracing implementation within Unity3D. This approach represents an optimal balance between computational efficiency and modeling accuracy, addressing the fundamental limitations of both traditional statistical channel models and deterministic ray-tracing methods.

Unlike purely statistical approaches (e.g., Nakagami-m, 3GPP, Quadriga, etc) that lack scenariowide spatial correlation accuracy required for advanced MIMO systems, our implementation provides spatially consistent channel realizations by incorporating actual 3D environment geometry, where line-of-sight, reflection, scattering, and blockage effects are consistent with the geometry. Simultaneously, it overcomes the computational prohibitive costs and material parameter requirements of full electromagnetic ray-tracing by compensating for unknown environmental details through stochastic scatterer distributions derived from extensive channel sounding experiments.

The SIVERT 2 implementation in Unity3D utilizes volumetric scatterer distribution around 3D objects, where activated scatterers enable propagation paths and contribute to the total channel response through ray-casting procedures. This digital twin approach integrates building 3D geometries extracted from OpenStreetMap data, detailed elevation models, and realistic infrastructure layouts. The system extends beyond vehicle-to-vehicle scenarios to support vehicle-to-network communications by implementing 3D angular spread concepts aligned with 3GPP 38.901 parameters (Azimuthal and Zenith Angular Spread of Arrival/Departure).

The resulting outputs of the channel modelling part of SIVERT2, frequency and time domain channel realizations, are streamed in real-time to Network Simulator 3, enabling comprehensive modelling of the 5G protocol stack, physical layer adaptations including modulation and coding schemes, rank adaptation, and ultimately throughput and delay performance. Validation against field measurements in both line-of-sight and non-line-of-sight scenarios demonstrated close agreement, building confidence that the simulated link behaviour accurately mirrors practical V2X deployments.

The last critical addition is “EMI”. Vehicles host high-speed digital buses, DC-DC converters, and switching electronics- each a potential broadband or narrowband emission source. Instead of treating interference as a static noise floor, we introduced a dynamic, time and frequency-resolved EMI layer. In the lab, emission patterns were synthesized and radiated; a spectrum analyser in waterfall mode captured evolving spectral power. Those traces were replayed into the simulator, where we mapped them onto the per-resource-block noise spectral density during every downlink transmission. Now influence of elevated or fluctuating EMI on wireless system performance including adaptation can be tested virtually.

Bringing these elements together, the SIVERT2 simulation framework can now quantify trade-offs among antenna system solutions, interference hardness, and adaptive radio algorithms - bridging RF design and higher-layer performance. We delivered a unified, measurement-informed, geometry-aware 5G-V2X simulation environment with real antenna patterns, wireless propagation and dynamic EMI, which shortens iteration loops between hardware concept and system performance. This advances fidelity, helps de-risk future deployments, and supports safer, more reliable connected mobility

4.3 Work Package 2: Component and System Verification

The purpose of WP2 is to further develop the component and complete vehicle test methods from the previous research project SIVERT1, making them suitable for verification of 5G and Vehicle-to-Vehicle (V2V) technologies in next-generation vehicles. During the project new requirements were addressed such as higher throughput and wider system bandwidth. This also involved evaluation of systems with more antennas, distributed antenna setups, and more detailed channel emulation of radio channels for specific traffic or V2V scenarios.

In SIVERT1, it was concluded that multiple Over-The-Air (OTA) test methods are needed to achieve reliable validation results. In this project, efforts are focused on developing and analysing the Reverberation Chamber (RC), the wireless cable, and the RanLOS measurement system to address the identified challenges. The RC allows for precise and efficient OTA characterization at high system bandwidths and throughputs but operates in an isotropic environment and has limited capability for detailed channel emulation (see WP2B). The wireless cable method offers more realistic emulation of real-world conditions and was used in the project to simulate scenarios for both functional and non-functional testing, including V2V and Vehicle-to-Infrastructure (V2I), as well as integration of wireless communication in Virtual-Drive-Test (VDT), see WP2C. The RanLOS measurement system proved to be an efficient and promising method for measuring antenna patterns in key elevation planes relevant to V2V/V2I, and for active V2V/V2I tests (see also WP2C).

This WP also covers the development of OTA test methodologies to implicitly address requirements on Quality of Service (QoS) from the customers through non-functional performance metrics such as throughput, receiver sensitivity, and block error rates. Input for these QoS metrics came from WP3, where they were broken down into testable Non-Functional Requirements (NFRs) for the lower layers of the Open Systems Interconnection (OSI) model. However, results from WP3 showed that it is not straightforward to isolate a single parameter to determine a functional “breaking point.” The use cases tested in WP3 revealed significant interdependencies between different parameters, making it challenging to evaluate them in isolation and thus break them down to NFRs.

4.3.1 Verification Framework Vision

The overall vision of the verification framework for long-range and short-range V2X communication is depicted in Figure 4-37 below. The main idea behind this is to move testing earlier in the vehicle development projects, i.e. “shift left”. If no lab measurement or simulation resources are available, field tests late in the vehicle projects are the only options to understand the system performance of long-range and short-range V2X communication. This is cumbersome and also jeopardize the quality, as issues found late in the vehicle projects may be difficult to mitigate. The earlier this verification can be done, the better.

The first step in the verification framework is to perform simulations utilizing known or approximated system parameters of the V2V/I communication system. This step is appropriate once requirements and/or target performance levels of the system is known. For example, if target antenna gain levels are stated (or simulated) the overall system performance can be approximated by utilizing the simulation tool with realistic channel models etc. This will give a first indication if the antenna performance is good enough.

The second step in the verification framework is when hardware starts to become available, i.e. antennas and transceivers are delivered by suppliers. In this stage measurements utilizing the actual hardware (and software) can be performed. However, this testing might need to be done using standalone hardware, i.e. not installed in a vehicle, since a test vehicle might not be available at this stage. Once a test vehicle is available, the measurements should be done with the actual installation positions, to replicate the final scenario as close as possible.

As a final verification, a limited number of field tests can also be performed.

In order for these different validation steps to make sense, it is of outmost importance that the results from the different evaluation steps correlate. In other words, a device evaluated as “good” during simulations should also be evaluated as “good” during the final field test.

This vision is guiding the verification methods development in this project.

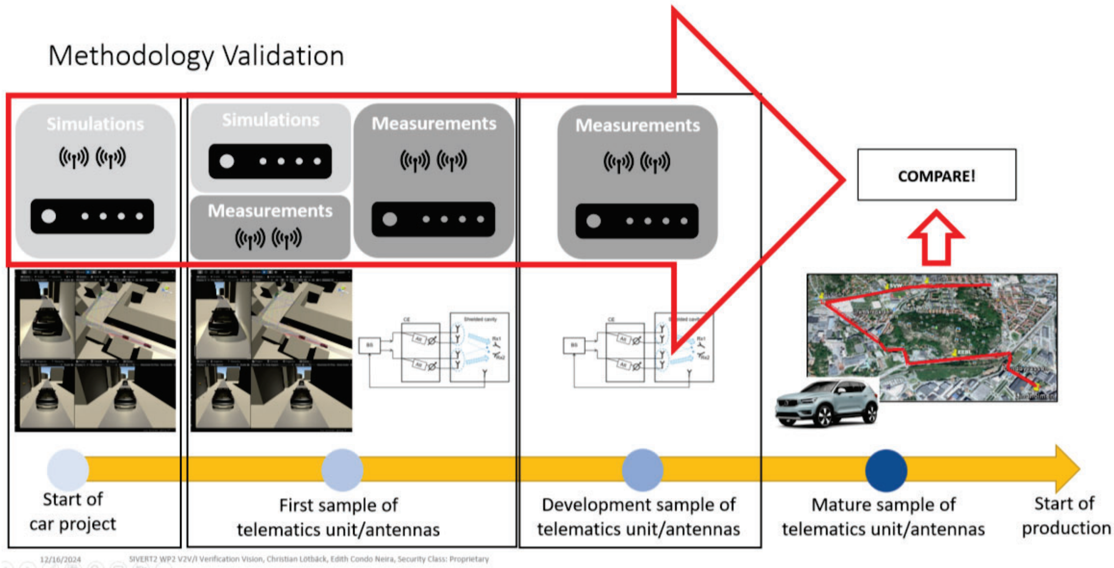


Figure 4-37,Vision of Verification Framework.

4.3.2 WP2A: Wideband Channel Emulation

This sub-WP has addressed its objectives of investigating the state-of-the-art in wideband channel emulation and extending existing test setups from the SIVERT1 project to support the bandwidths and frequencies relevant to 5G and V2V/V2I systems. Two project internal reports have been produced providing a comprehensive review of current research, standardization efforts, and practical test methodologies, forming the foundation for defining and implementing OTA test systems in subsequent project work packages (WP2B and WP2C). A summary of the review is presented below.

4.3.2.1 State-of-the-Art Analysis

A detailed state-of-the-art review was conducted covering:

- 5G NR OTA testing for both small devices and large vehicular systems.
- Standardization progress from 3GPP, CTIA, ETSI, and 5GAA.
- Recent research on dynamic channel models, MIMO testing, and virtual drive testing.

Based on the state-of-the-art, critical parameters for modelling in vehicular contexts include delay spread, Doppler shift, correlation, and antenna patterns.

4.3.2.2 OTA Test Methodologies

The project internal reports evaluate and compare several OTA test setups as given below:

- **Reverberation Chamber (RC) without channel emulator:** Enables testing of large bandwidths without channel emulator limitations. Suitable for higher-order MIMO, throughput testing, sensitivity testing, and dynamic channel modelling using hardware like step attenuators.

- **Reverberation Chamber (RC) with channel emulator:** Supports rich channel models (e.g., UMi) with up to 40 MHz bandwidth (in the present hardware setup). Useful for emulating more specific scenarios.
- **Radiated Two-Stage (RTS) and wireless cable:** Particularly relevant for V2V and V2I testing, as well as V2N for cell edge scenarios, where angular channel properties and radiation patterns are critical. This setup is suitable for 2x2 MIMO. Can be extended to higher-order MIMO with careful calibration. It is not ideal for adaptive Devices Under Test (DUT) due to static antenna pattern assumptions.
- **Multi-Probe Anechoic Chamber (MPAC):** Effective for small devices, but limited scalability for large vehicles due to cost and complexity. 3GPP defines MPAC for up to 4x4 MIMO in FR1 and 2x2 MIMO in FR2.

4.3.2.3 Channel Emulation Insights

The project's current channel emulator (Spirent Vertex) supports 40 MHz bandwidth and 4x4 MIMO, sufficient for emulating key scenarios such as cell-edge conditions with limited signalling bandwidth. As coverage-critical cell-edge scenarios were prioritized, no immediate need for more advanced wideband emulator hardware was identified. However, future work may consider investing in upgraded emulation hardware.

The state-of-the-art review also highlighted the importance of dynamic channel models. In particular, the use of Clustered Delay Line (CDL) models and Variable Reference Channels (VRC) was emphasized to better simulate real-world conditions, as link adaptation and dynamic spatial variation are critical for realistic testing.

4.3.2.4 WP2A summary

Based on the findings in the state-of-the-art report, the project concludes that two different OTA test methods are sufficient for evaluating 4G, 5G, and ITS-G5 communication. Specifically, the RC OTA method is selected for Vehicle-to-Network (V2N) testing, while the two-stage methods are chosen for V2V and V2I testing.

4.3.3 WP2B: V2N

The WP2B aim is to extend the SIVERT1 OTA test setups to support 5G V2N communication, focusing on Frequency Range 1 (FR1) frequency bands and both Standalone (SA) and Non-Standalone (NSA) modes. This work builds on insights from WP2A and focuses on below:

- Enhancing RC OTA testing for 5G.
- Supporting higher-order MIMO, antenna integration, throughput, Block Error Rate (BLER), sensitivity, and bandwidth variation.
- Conducting field tests for verification and comparison with lab results.
- Enabling scenario-based virtual-drive-test.

4.3.3.1 Integration and Characterization of Amarisoft Advanced

The Amarisoft Base Station (BS) simulator, model Advanced [*36*], was selected as the 5G BS simulator for the project due to its flexibility and cost-efficiency. The setup and operation involve configuring the system using text-based configuration files, terminal commands, and a web GUI. A detailed (project internal) manual was created to guide users through connection, configuration, and testing procedures.

To handle the Amarisoft BS, configuration files were tailored for 4G, 5G SA and 5G NSA. Parameters such as Modulation Coding Scheme (MCS), rank indicator, resource block allocation, and power settings were adjusted to align with 3GPP TR 37.977 eNodeB (4G) emulator settings for downlink test.

A key difference between classical Radio Frequency (RF) instrument manufacturers and the Amarisoft Advanced system is how output power is handled. To perform repeatable and calibrated OTA tests with Amarisoft, calibration is essential due to its lack of absolute power traceability. In the project, a method was developed to convert Amarisoft's *tx_gain* parameter to EPRE (Energy Per Resource Element) using a spectrum analyser. Furthermore, several observations were made regarding output power during testing:

- Output power of the SDRs scales with bandwidth: $\Delta P = -10log_{10}(BW_{new}/BW_{ref})$, where BW_{ref} is the reference bandwidth during calibration and BW_{new} is the bandwidth during a test.
- Modulation type (64QAM vs. 256QAM) does not affect output power.
- Filling resource blocks with sufficient data is critical to maintain stable output power.
- Rank Indicator (RI) must be forced to ensure consistent throughput and BLER calculations and align with the to align with 3GPP TR 37.977 eNodeB (4G) emulator settings for downlink test.

4.3.3.2 Reverberation Chamber OTA Test Setup

Based on the state-of-the-art, a straightforward setup with the BS directly connected to the RC was chosen as the main test setup for V2N, see Figure 4-38. This approach avoids the hardware limitations of the channel emulator, such as limited bandwidth and the keyhole effect [*37*] during test of higher-order MIMO systems.

The main drawback is the limited ability to emulate channels as it only emulates the so called NIST model [*38*] (Rayleigh distribution). However, the state-of-the-art concluded that challenging scenarios - such as cell-edge cases - are better evaluated using the V2V/V2I setup, which does include the channel emulator.

Another challenge is the large RC needed when testing full sized cars and trucks. As a rule of thumb for RCs, the DUT shall not occupy more than 1/8 of the total RC volume. These large dimensions cause a high Q-value, which in turn causes high delays spread of the transmitted signal.

In Figure 4-39 the Amarisoft BS is shown when placed outside the RC tent. The Downlink (DL) and Uplink (UL) RF signal cables are connected to the antennas inside the RC tent. In that figure the DL antennas inside the RC are shown as well. These are placed behind a conductive screen to avoid any direct coupling with the Vehicle Under Test (VUT).

Figure 4-40 shows a truck and a car placed in the RC respectively. Here cardboard boxes filled with RF absorbing material are also shown (to control RMS delay spread), as well as the conductive screen placed in front of the DL antennas.

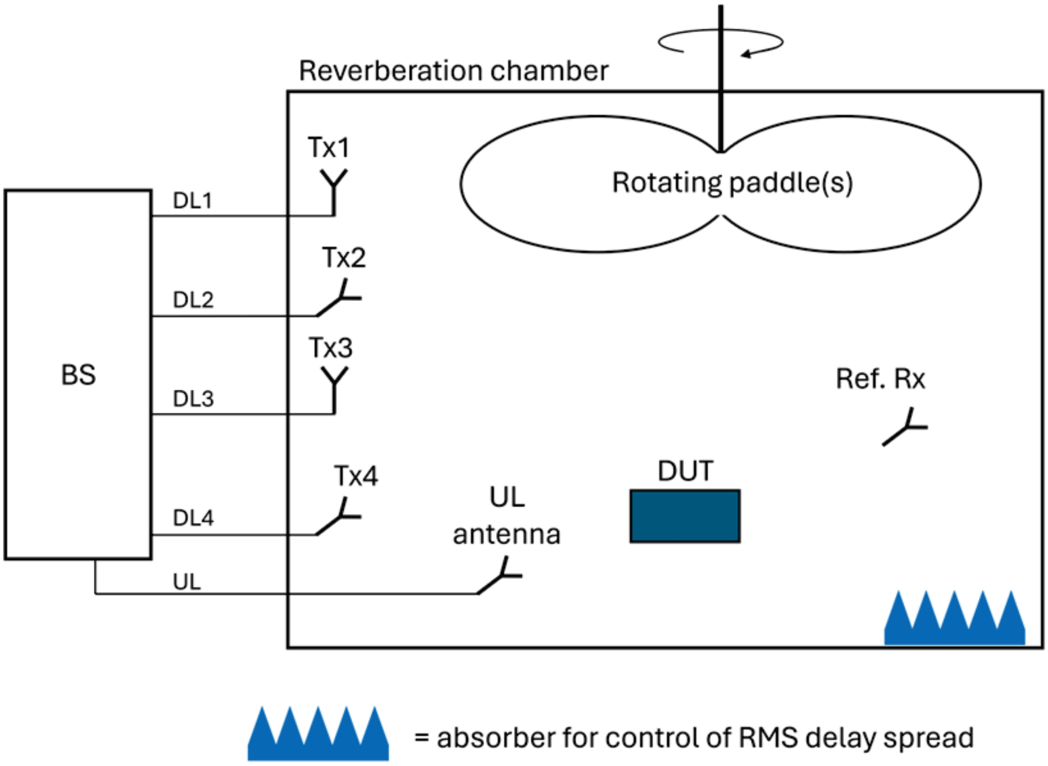
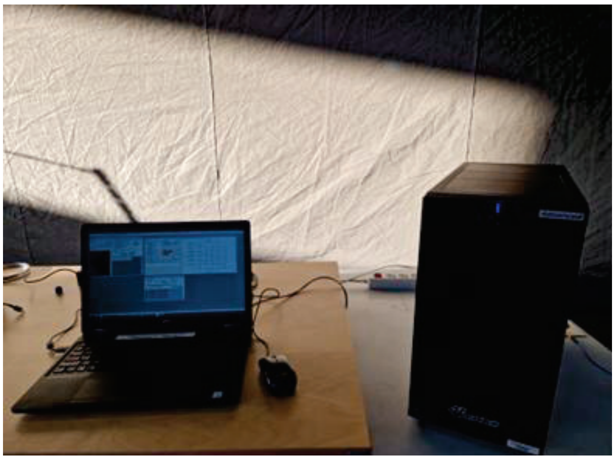


Figure 4-38, OTA test setup using RC. The BS DL are connected to Tx antennas in the RC.

OTA testing, data capture, and BS control are carried out using the RISE OTA test software (Figure 4-41), which was partially developed during the project. The software includes several GUI windows designed to manage different aspects of the test. For example, there are dedicated windows for controlling the Amarisoft BS, managing iPerf traffic generation, and running tests while collecting key data such as throughput.



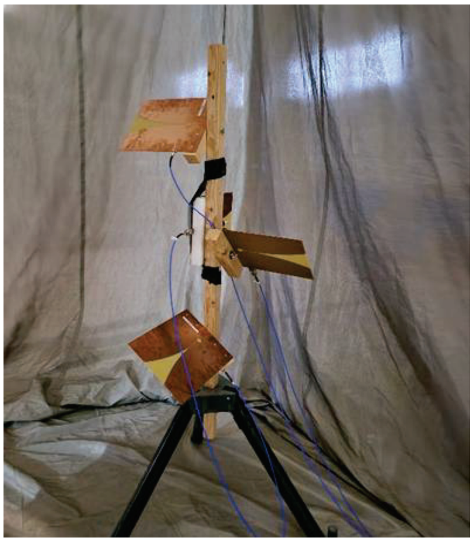


Figure 4-39, Left: Test setup outside the RC. Amarisoft callbox Advanced and a control computer. Right: Inside the RC. 4 DL antennas connected to the Amarisoft call box present outside the RC.

Figure 4-40, Test setup in RC with car (left) and truck (right). Cardboard boxes contain RF absorbing material for RMS delay spread tuning. UL antenna can be seen to the right in the left picture. Reference antenna can be seen to the right in the right picture.

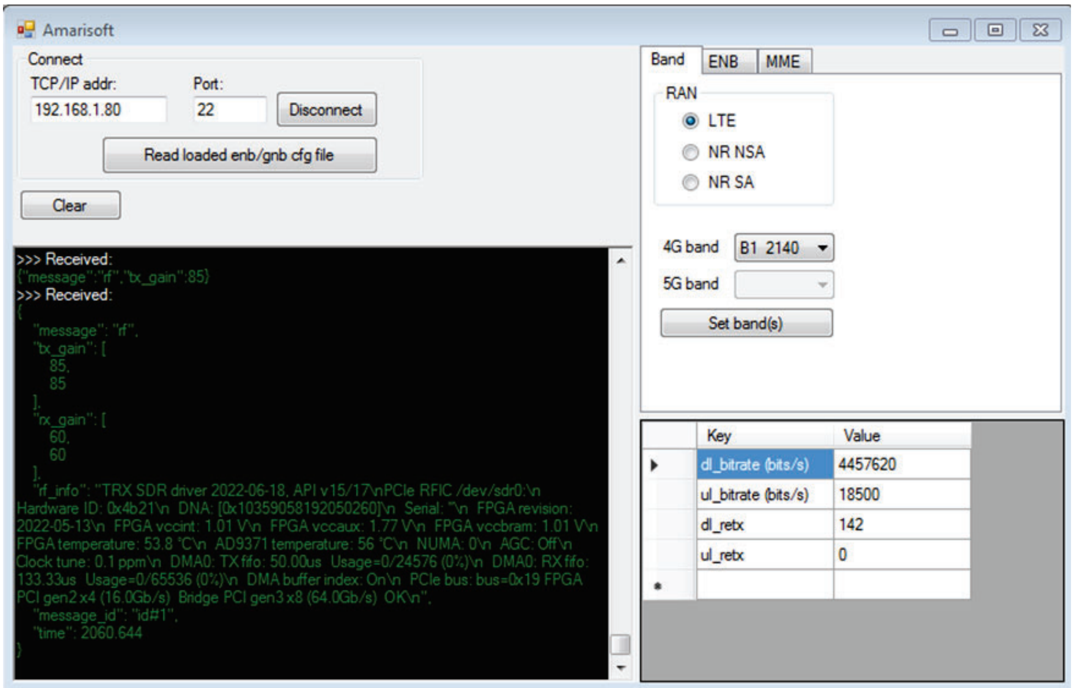


Figure 4-41, RISE OTA test software. Amarisoft communication window.

4.3.3.3 Good / Nominal / Bad: Component Test

The method has been validated with a good / nominal / bad test in an RC on component level. This test was performed for 5G SA, 2x2 MIMO. The good / nominal / bad User Equipment (UE), see Figure 4-42, was created by adding 3 dB and 6 dB attenuators to the antenna ports of an off-the-shelf radio modem according to:

- Good: no extra attenuators mounted.
- Nominal: a 6 dB RF attenuator mounted of UE RF port #2.
- Bad: a 3 dB attenuator mounted on UE RF port #1, and 6 dB on port #2.

- Port #3 and #4 were terminated with 50 Ohm terminations.

Figure 4-42, The UE (from Teltonika, TRB500). The RF attenuators for shifting between good/nominal/bad are placed between the modem and its external antennas.

Between tests, but not between each test, the following were changed:

- Day of the week
- Amarisoft power on/off
- UE placement
- RF attenuators detach/attach between UE and its antennas
- UE external antennas detach/attach
- Operator

Results can be seen in Figure 4-43 below and Table 4-2. The standard deviation per good / nominal / bad configuration gives an estimate of the repeatability of the method (0.24 dB on average).

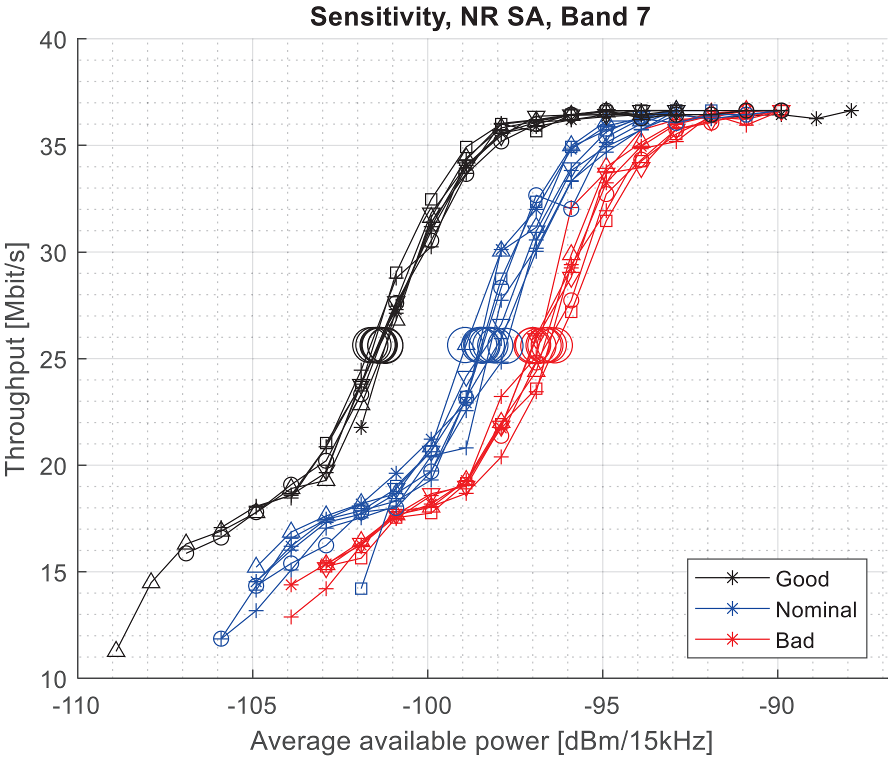


Figure 4-43, Comparison and repeatability, good / nominal / bad.

Table 4-2, Good / nominal / bad measurement results.

Configuration	RF attenuation Port #		Average power	Diff. compared to good configuration	RF attenuation average	Standard deviation
-	#1 [dB]	#2 [dB]	[dB/15kHz]	[dB]	[dB]	[dB]
Good	0	0	-70.5	0	0	0.15
Nominal	0	6	-67.4	3.1	3	0.34
Bad	3	6	-65.8	4.7	4.5	0.24

4.3.3.4 Good / Nominal / Bad, Full Vehicle Test

The method was also validated with a full vehicle, a truck tractor. The test was done for 5G SA band n78 (3500 MHz) TDD with 80MHz bandwidth, 2x2 MIMO. The UE was once again an off-the-shelf modem (Teltonika, RUTX50 [*39*]) connected to two magnetic foot antennas (general purpose lab antennas) mounted on the cabin exterior, see Figure 4-44. The antennas used were of type Planar Inverted Cone Antenna (PICA) – which is a broadband monopole antenna, see Figure 4-45.

In addition, for each antenna installation, a good / nominal / bad UE was created by adding 3 dB and 6 dB RF attenuators to the antenna ports #1 and #2 of the UE as described below:

- Good: no extra attenuators mounted
- Nominal: 3 dB RF attenuator mounted to each UE RF port
- Bad: 6 dB attenuator mounted on each UE RF port
- #3 and #4 terminated with 50 Ohm

Figure 4-44, Truck tractor under test in RC tent with patch antennas, Left: Vertical mount, and Right: horizontal mount.

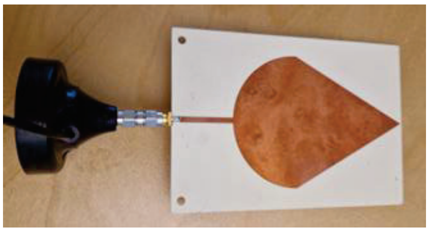


Figure 4-45, PICA antenna.

Test results are presented in Figure 4-46. The throughput curve shifts by about 3 dB to the right when moving from a good to a nominal UE, and another 3 dB from a nominal to a bad UE, across both antenna installation setups. As expected, the results from the two installations are very similar, since the field distribution in the RC is statistically isotropic. The bad UE, configured with 6 dB attenuators, did not reach its maximum throughput in this setup because it requires a higher power level than what the Amarisoft callbox can provide.

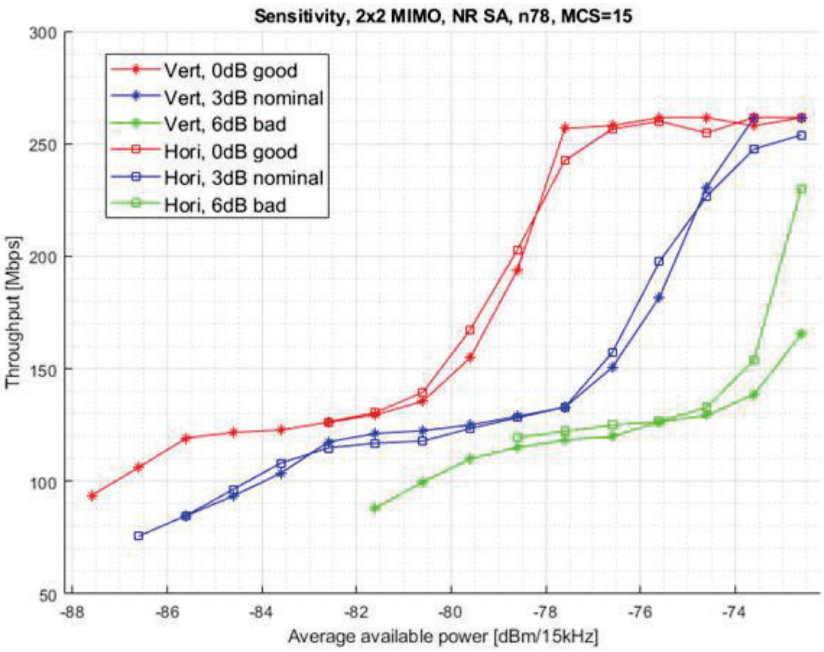


Figure 4-46, Comparison of good / nominal / bad UE on full vehicle, with vertically and horizontally installed antennas respectively.

4.3.3.5 Scenario tool (VDT Tool)

A scenario tool, or VDT tool, was developed to use the channel emulator for generating small-scale fading based on the operator's selected channel model (e.g., a UMi channel). In this approach, only large-scale fading, such as path loss from a field test or link budget calculation, is needed as input. This contrasts with the more detailed modelling in the WP1/2 collaboration, where all channel characteristics are generated by the WP1 ray-tracing software, allowing full 3D modelling within a consistent simulation environment.

The scenario tool is used in several steps. First, a large-scale fading profile is created using field tests, simple ray tracing, or path loss calculations. This data is added to a scenario file, which is then loaded into the channel emulator. The channel emulator adds small-scale fading using a selected channel model (e.g., UMi or UMa). For accurate results, the large-scale fading should not be affected by the

DUT's antenna pattern (idealized omni-directional antennas are preferred), though hard to replicate in field tests. Tuned dipoles can serve as a practical reference. Once the scenario file is ready, the UE's antenna patterns can be loaded into the channel emulator to preserve correlation and coupling. The setup supports multiple Radio Access Technologies (RATs), including 4G, 5G, ITS-G5, and V2X/V2N. An overview of the scenario tool can be seen in Figure 4-47.

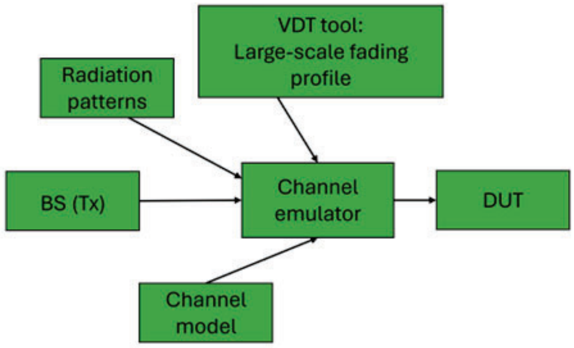


Figure 4-47, Scenario tool part 1, schematics.

In this project, we conducted a field test to collect data for analyzing the large-scale fading profile. The test was carried out on a dedicated track using a private 5G network operating in TDD band 78. Data was gathered using a truck equipped with two general-purpose wideband monopole antennas (PICA model, see above) mounted on the roof of the truck cabin. These monopoles served as reference antennas. Although several antenna configurations were tested, this report focuses only on the case where the antennas were mounted in a vertical orientation. To extract the large-scale fading profile, small-scale fading was removed by applying a smoothing process to the measured data (see Figure 4-48 below).

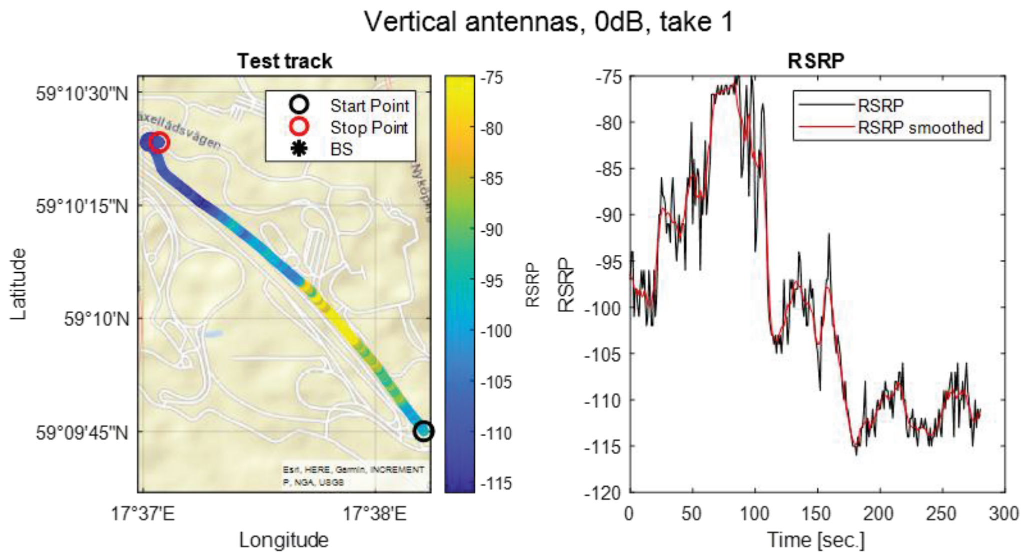


Figure 4-48, Left: Field test location; Right: recorded RSRP.

The test setup is shown in Figure 4-49. If necessary, either the BS or the UE can be placed in a shielded cavity. In the channel emulator, all radio links should be enabled. Any differences in power levels compared to the scenario will be adjusted at the channel emulator output ports.

The test scenario is provided to the RISE OTA test software via a text file, see below for a typical example. The format of the text file is designed to be flexible: any remote command defined in an instrument manual can be sent by specifying the instrument (e.g., “CE;”) followed by a command that the instrument can interpret. Figure 4-50 shows a screenshot of the scenario tool, which includes both the virtual drive test module and the channel emulator control module. The tool allows the scenario to be started, paused, or stopped as needed.

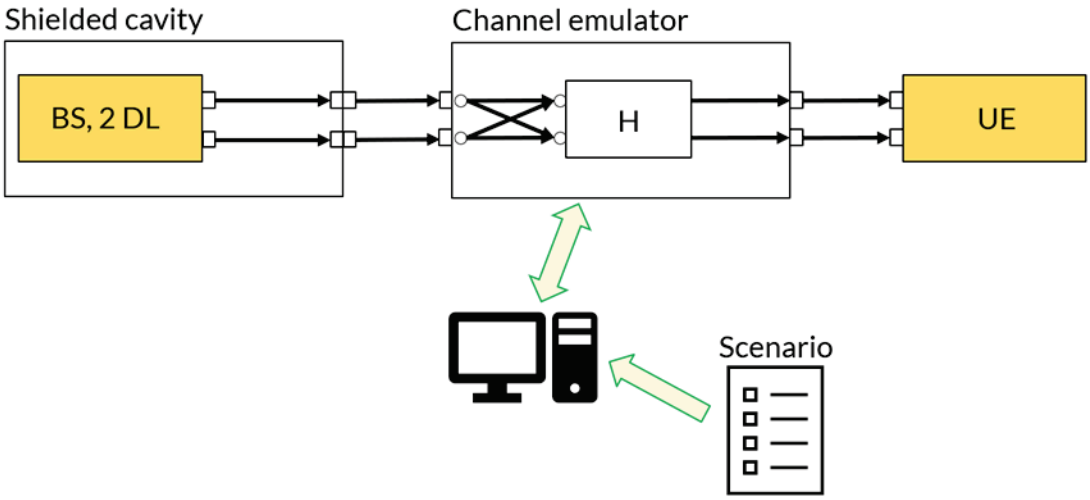


Figure 4-49, Scenario tool part 1 (5G) test setup.

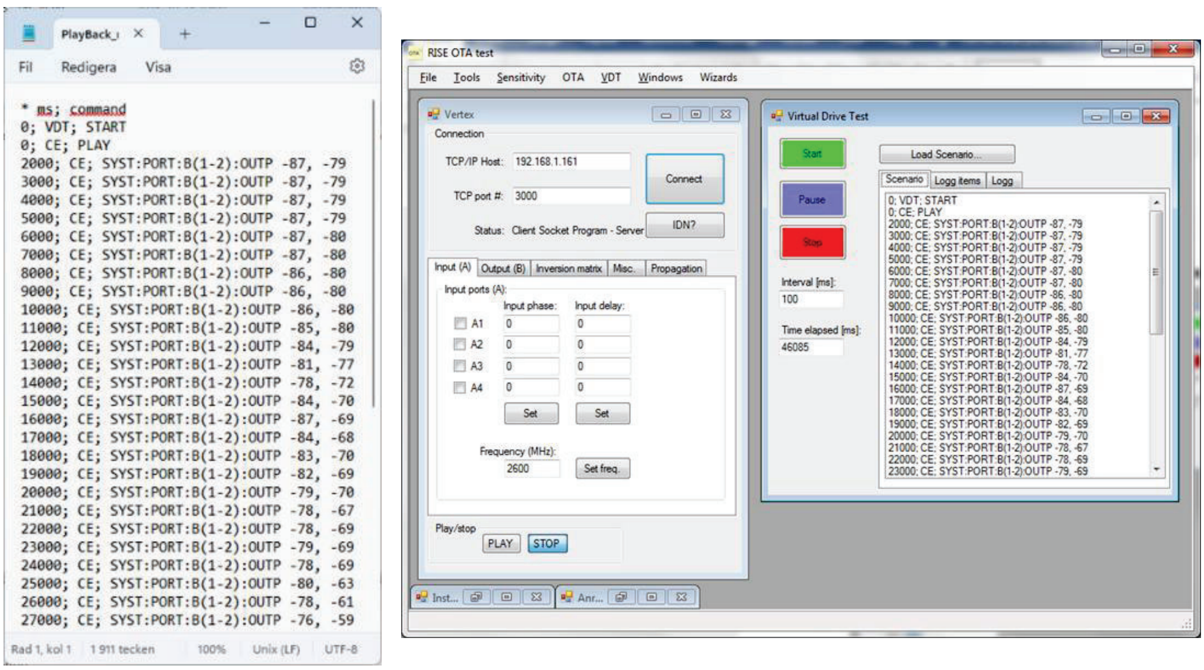


Figure 4-50, Left: A scenario file. Right: Scenario tool (5G) test software.

After the generation of a scenario file, a Conducted Two Stage (CTS) test was conducted to evaluate the performance of V2N communication for a truck. The test used an off-the-shelf modem from Teltonika as the UE. By using the CTS setup, a full truck was not required for testing. Instead, the influence of the truck on the radiation patterns was represented by the antenna simulated when mounted on the vehicle.

The radiation patterns were simulated in CST [*40*] for different configurations: vertical and horizontal mounting, and attenuation levels on the radiation patterns of 0 dB, 3 dB, and 6 dB. The purpose of the attenuation levels is to mimic good / nominal / bad antennas. The CAD model used for the simulations is shown in Figure 4-51, while the resulting radiation patterns are presented in Figure 4-52.

Further details about the electromagnetic simulation methodology can be found in the publication by Y. Feng (see Publications, Chapter 5.4), which was presented at EuCAP 2025.

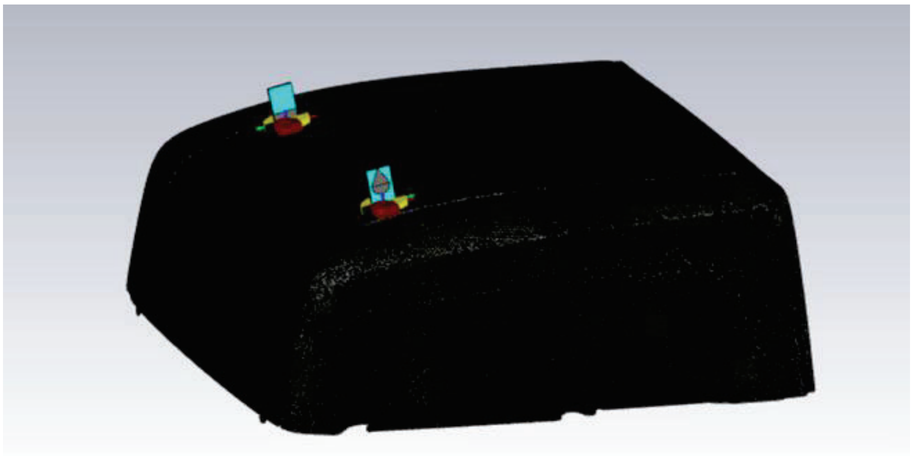


Figure 4-51, CAD model of the truck roof and vertically mounted antennas.

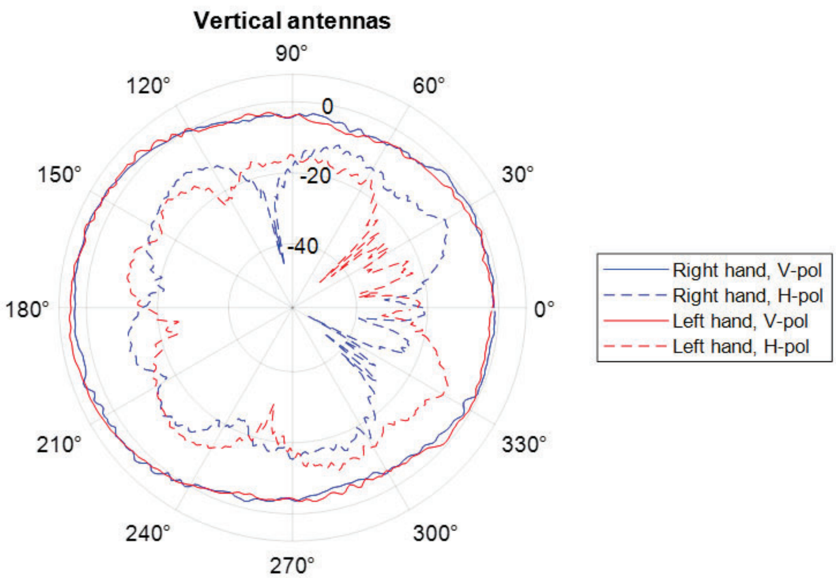


Figure 4-52, Radiation pattern of vertically mounted antennas.

Figure 4-53 shows a comparison between the field test and the CTS lab test for vertically mounted antennas with 0 dB attenuation. The average received power is -85.3 dBm for the field test and -84.3 dBm for the CTS test. These values are similar, as expected, since the CTS test was calibrated.

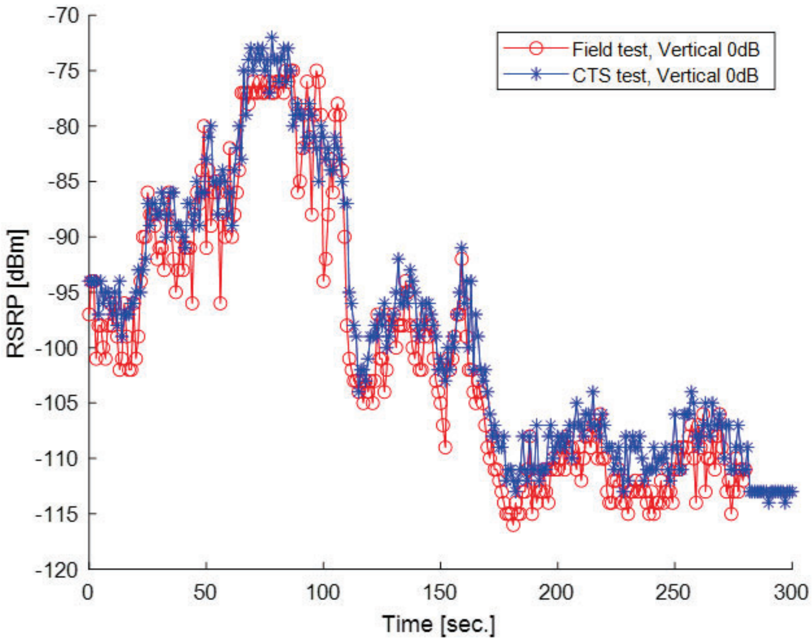


Figure 4-53, CTS test result compared to field test result. Both tests with vertical antennas and with 0 dB attenuation. Linear average power of CTS test is -84.3 dBm, and field test is -85.3 dBm.

In Figure 4-54, the vertical antennas are tested with different attenuation levels applied to their radiation patterns (0, 3, and 6 dB). Figure 4-55 presents the same test setup repeated for horizontally mounted antennas. The results are summarized in Table 4-3 and show good agreement with the expected effects of the selected attenuation levels.

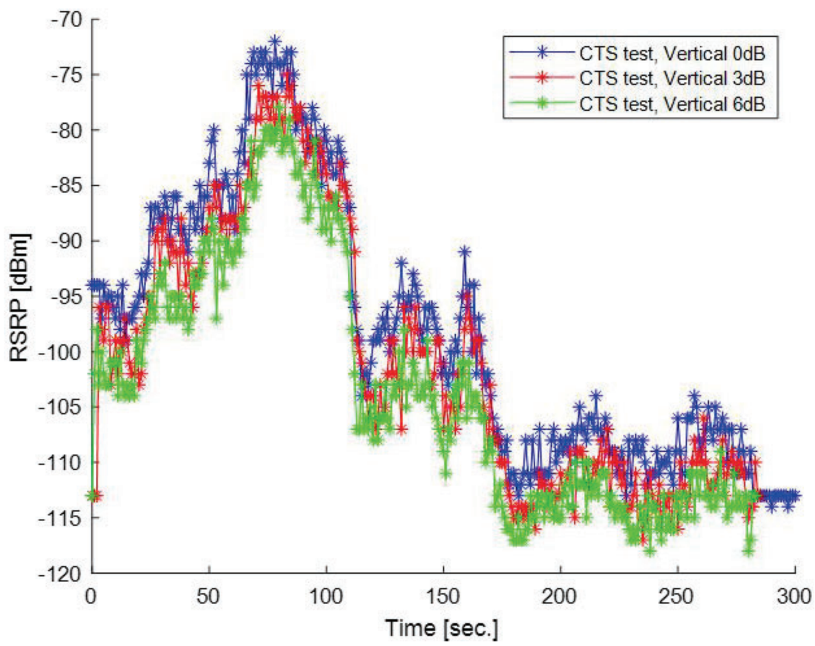


Figure 4-54, CTS test result of 0, 3, and 6 dB attenuators. All tests with vertical antennas. Linear average of 0 dB: -84.3 dBm, 3 dB: -87.5 dBm, 6 dB: -90.6 dBm, i.e., approximately 3 dB difference between each setting.

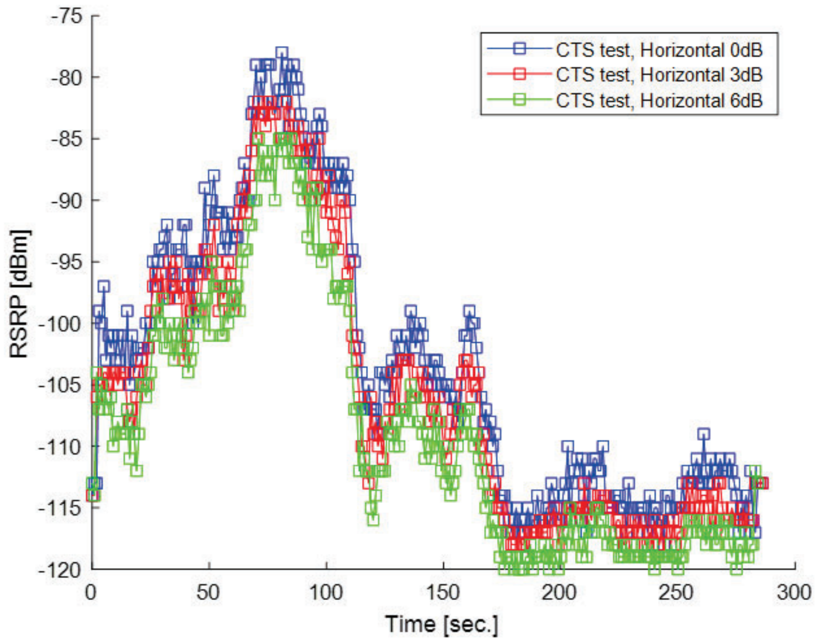


Figure 4-55, CTS test result of 0, 3, and 6 dB attenuators. All tests with horizontal antennas. Linear average of 0 dB: -90.2 dBm, 3 dB: -93.2 dBm, 6 dB: -96.5 dBm, i.e., approximately 3 dB difference between each setting.

Table 4-3, CTS test. Horizontal polarization was on average 5.9 dB lower than vertical polarization.

Pattern attenuation [dB]	Average RSSI [dBm]		∆ CTS test, normalized RSSI [dB]	
	Vertical	Horizontal	Vertical	Horizontal
0	-84.3	-90.2	0	0
3	-87.5	-93.2	-3.2	-3.0
6	-90.6	-96.5	-6.3	-6.3

Finally, we compare the RC OTA test with the field test. This comparison is not entirely straightforward; it is a bit like comparing apples and pears. In the RC test, the measured value is the power at 70% throughput during the OTA test, while in the field test, the measured value is the average power (RSRP) along a specific route.

In the RC test (described in earlier chapters), the good/nominal/bad conditions were created using RF attenuators: 0,0 dB for good, 0,3 dB for nominal, and 3,6 dB for bad. These attenuation values differ from those used in the field test, but this does not affect the conclusions. Data was normalized before plotting, using the following formula for each case (good, nominal, bad):

$$P^{70\%}_{good,norm} = P^{70\%}_{good} + \Delta P_{RC},$$

where:

$$\Delta P_{RC} = mean\left[P^{70\%}_{good}, \quad P^{70\%}_{nominal} + 1.5, \quad P^{70\%}_{bad} + 4.5\right]$$

In the field test, good/nominal/bad conditions were also created using RF attenuators: 0 dB for good, 3 dB for nominal, and 6 dB for bad. Normalization was performed as follows:

$$\Delta P_{Field,Vert,norm} = mean[P_{good,vert}, \quad P_{nom,vert} + 3, \quad P_{bad,vert} + 6]$$

And

$$\Delta P_{Field,Hor,norm} = mean[P_{good,hor}, \quad P_{nom,hor} + 3, \quad P_{bad,hor} + 6]$$

The results, shown in Figure 4-56 indicate consistent trends: good performs better than nominal, which in turn performs better than bad. The differences in dB are within the measurement uncertainty, except for the horizontal field test at 0 dB.

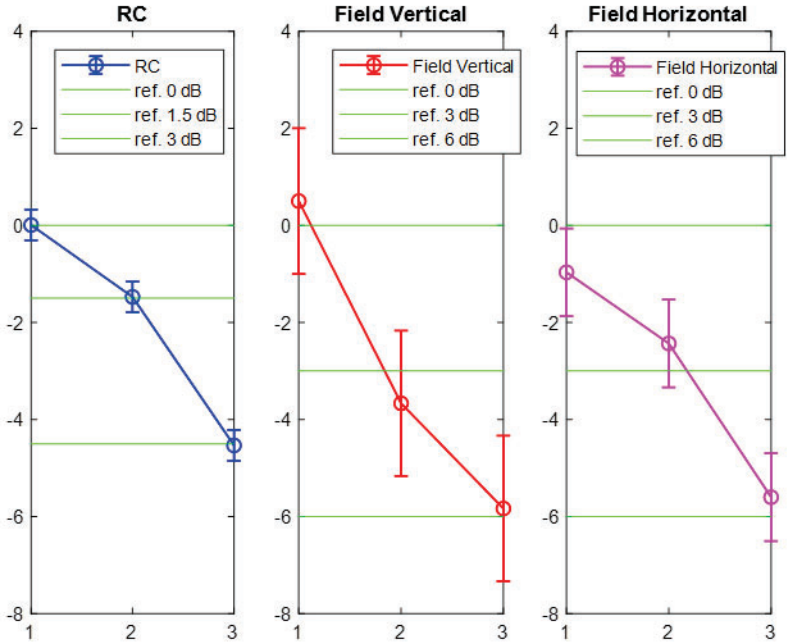


Figure 4-56, Measured good/nominal/bad in the RC as well as field test. Combined with one (k=1) standard deviation error bars.

4.3.4 WP2C: V2V/V2I

The WP2C work package aimed to extend the SIVERT1 OTA test setups to support V2V and V2I communication, focusing on the 5.9 GHz frequency band for side-link communication. Most efforts have been spent on V2V scenarios.

This work builds on insights from WP2A and focuses on:

- V2V/V2I channel models
- Test setup definition V2V/V2I: wireless cable method, conducted 2-stage method and a novel method called the Roof-top-box method
- Scenario tool including interaction with WP1
- RanLOS measurement system

This chapter discusses *two-stage* methods for testing. These methods generally involve determining the radiation pattern of the UE separately, either through measurement or simulation. During testing, the radiation pattern is combined with the channel model under evaluation. Two specific two-stage methods are highlighted:

- Conducted Two-Stage (CTS): This method uses RF connectors on the UE to establish a direct wired connection to the channel emulator during testing.
- Wireless cable: Similar to CTS but intended for UEs without RF connectors. A specialized setup is used to create a wireless link—referred to as a "wireless cable"—to enable testing.

4.3.4.1 Roof-top-box method

In the SIVERT1 project, the roof-top-box method was introduced as a specialized version of the wireless cable method. This project builds on that concept by integrating conductive textile into the setup [*41*]. The textile covers the entire vehicle, providing electromagnetic isolation from external radio signals and creating an enclosed test zone inside the vehicle. This enables controlled testing environments for tasks such as throughput or scenario testing.

To maintain communication with antennas located on or near the vehicle's exterior, roof-mounted boxes are placed over the antennas but under the conductive textile (see Figure 4-58). Each box contains a downlink antenna and, if required, an uplink antenna. The conductive textile thus replaces the need for a traditional shielded chamber, offering a more flexible and cost-effective testing solution.

This conductive textile-based roof-top-box method provides several advantages over conventional shielded chambers:

- High flexibility: Easily installed on a stationary vehicle, enabling testing in various locations.
- Compact footprint: Suitable for production lines and quick performance checks.
- Cost efficiency: Lower system complexity and reduced setup costs.

Compared to the rooftop box method from SIVERT1, this development introduces the capability to:

- Measure distributed antenna systems.
- Evaluate hidden or irregularly positioned antennas.

However, the method also has limitations:

- Limited shielding: Some interference from the surrounding electromagnetic environment may still occur.
- Static testing only: The VUT must remain stationary; internal electromagnetic interference (EMI) from a running vehicle is not captured.
- Influence on EMI paths: The conductive textile may alter propagation paths, affecting internal EMI representation.

After the rooftop boxes are mounted, a two-stage method is used for measurements. Depending on the Radio Access Technology (RAT) and the test objective, Key Performance Indicators (KPIs) may include Packet Error Rate (PER), Block Error Rate (BLER), Received Signal Strength Indicator (RSSI), Received Power Strength per Path (RPSP), or data age.

Tests may be categorized as either scenario or throughput tests:

- Scenario tests (e.g., using KPIs like data age): Use *H*-matrix data from WP1 (antenna patterns included in simulations).
- Throughput tests: Focused on overall data performance.

Figure 4-57 presents a schematic overview of the test setup. Figure 4-58 illustrates a vehicle fully wrapped in conductive textile, including the floor beneath it. The interface between the floor textile and the wrapping is sealed by folding the textile layers together to maintain RF shielding.

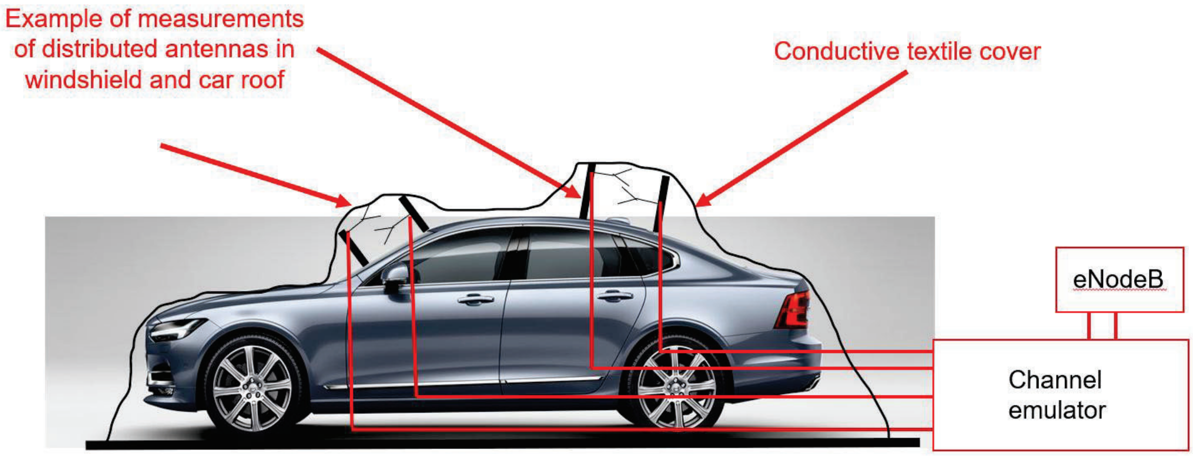


Figure 4-57, Schematic view of the roof-top-box test setup.

Figure 4-58, Vehicle wrapped in conductive textile. This includes also conductive textile on the floor.

4.3.4.2 Scenario tool including interaction with WP1

The simulation framework in WP1 can be used to simulate specific scenarios and how the vehicles react in such. Various antenna and radio solutions can be evaluated through these detailed simulations. In WP2, we aim to translate these simulations into a measurement setup that enables scenario-based testing of vehicles or their components. The goal is to develop a method for assessing the performance of radios, antennas, and vehicle functions. Depending on the laboratory setup, this scenario testing can be referred to as VDT or Hardware-In-the-Loop (HIL).

When using a simulation tool, there are several ways to extract results with varying levels of detail. In this approach, we will export the *H*-matrix from the simulations to a file, which will then be replayed in the lab. This method is open-loop, meaning there is no feedback from the lab setup to the simulator. The exported *H*-matrix includes comprehensive channel characteristics, such as the effects of buildings, objects, and velocities, as well as the VUT and BS antenna patterns, incorporating factors such as the vehicle body and vehicle dynamics in a scenario such as an intersection setup. This testing setup will allow us to evaluate radio performance within the simulated channel conditions.

During the project WP1 has simulated and transferred several scenarios to WP2. Four of these are presented here and for the two last scenarios (Torslanda and Vasastan) complementary field tests have been performed for comparison:

- *H-LOS*: A Line-Of-Sight scenario when two vehicles approaching each other in an intersection. All reflected, scattered, etc., rays except the ground reflection, are removed before compiling the *H*-matrix.
- *H-Vienna*: A simulated scenario on an urban street in Vienna. In this scenario two vehicles meet each other on a street [*12*].
- *H-Torslanda*: A real Line-Of-Sight scenario when two vehicles approaching and passing by each other on a rural road. Full *H*-matrix. This scenario is both measured during a field and simulated.
- *H-Vasastan*: A real Line-Of-Sight scenario with two vehicles in a tight intersection in an urban environment. Full *H*-matrix. This scenario is both measured during a field and simulated.

The transferred datasets consist of several rows and columns. There is a column for *Tx* position, *Rx* position, and after that the *H*-matrix of *Nf* columns (frequencies) for complex h-elements describing the channel response as function of frequency. The data is repeated over time for the entire scenario (*Ns* time snapshots).

The field test data logs consist of: Time stamp, packet number, Tx position, Rx position, RSSI1, and RSSI2.

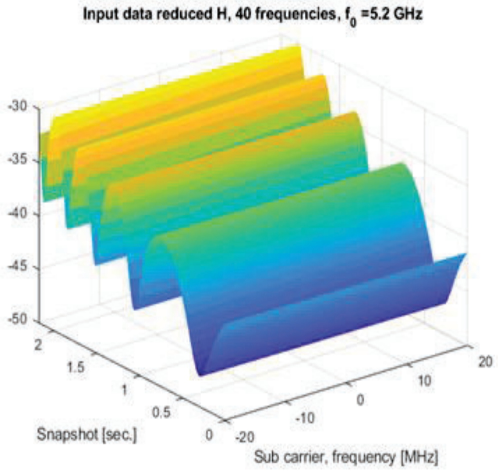
The channel emulator used is the Spirent Vertex. It is a modular instrument with variable RF inputs/outputs, bandwidths etc. This channel emulator have several different possibilities when it comes to channel emulation [*42*], and the most detailed way of replaying a channel is playing data in IQ mode, which allows you to disable the internally generated fading in Vertex and supply your own fading sample data. In IQ play, you can change the following parameters: Delay, I data, Q data.

The available Vertex is capable of 24 such sets of {Delay, IQ}, i.e., for a SISO case there are 24 paths available. However, for a diversity case with one Tx and two Rx there will only be 12 available paths per link. And so on.

In the scenario time domain, the Vertex limitations are less. For these simulations with normal vehicle speeds even neglectable as the data is rather up-sampled instead of down-sampled. The inherent sample rate of the Vertex is 10 000 samples per second.

The conversion from channel simulation data (*H*) to IQ-data is described in detail in a SIVERT2 conference paper by K. Karlsson *et al*. (see Publications in Chapter 5), which was presented at EuCAP 2025.

In the first scenario, the LOS scenario, the data sent from the simulator in WP1 to WP2 contains Nf=40 frequency points over a 40 MHz bandwidth centered at 5.2 GHz (see Figure 4-59).



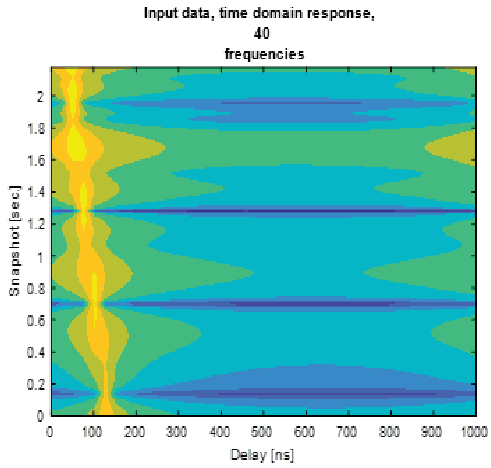


Figure 4-59, Left: Input data. Right: Inverse Fourier transform of the H-matrix.

The right part of Figure 4-59 shows the inverse Fourier transform of the *H*-matrix, performed row by row to convert the data from the frequency domain to the time domain. As described in the previous chapter, the IQ-file format supports a maximum of 24 paths. In this scenario, with one transmitter (Tx) and two receivers (Rx), this results in 12 paths per link. To convert the frequency-domain data into a time-domain representation suitable for such a limited number of paths, we use the inverse chirp transform instead of the general Fourier transform. To make the best use of the 12 available paths, several optimization steps are applied. First, we remove any signal components that occur before the arrival of the first physical path. This is done using a distance-based time adjustment. Knowing the positions of the Tx and Rx nodes and using the speed of light, we can calculate the earliest possible arrival time of the direct path. Any signal data before that point is not needed for emulation. This adjustment does not affect the receiving DUT, as V2V / V2I receivers do not begin demodulation until the first signal component is received.

To validate the processing, we ensure that energy is preserved by integrating power over the delay time axis for each time snapshot. Figure 4-60 shows the comparison between the original data and the distance-adjusted version, both prepared for input into the Vertex. In this Line-Of-Sight (LOS) scenario, the difference is small, but as will be shown in later examples, this adjustment becomes more important for more complex channels.

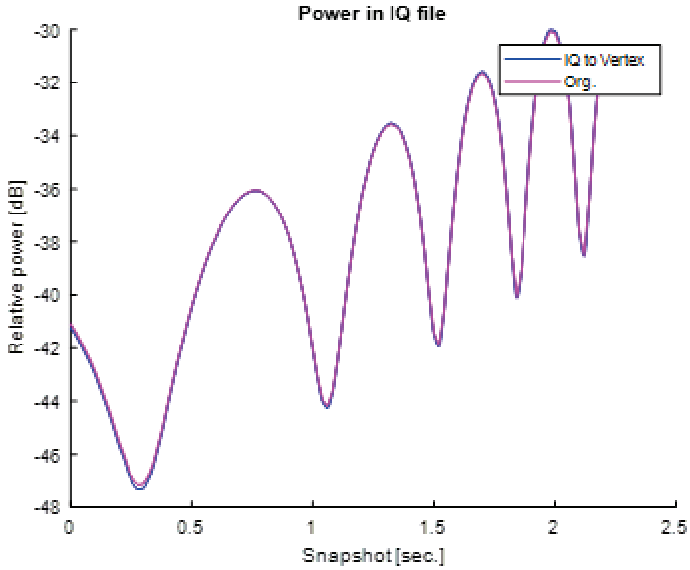


Figure 4-60, Power in IQ-file as function of snapshot time.

The data sent to the channel emulator is illustrated in and Figure 4-62. The former shows IQ data without distance correction, while the latter shows the corrected data with early signal components removed.

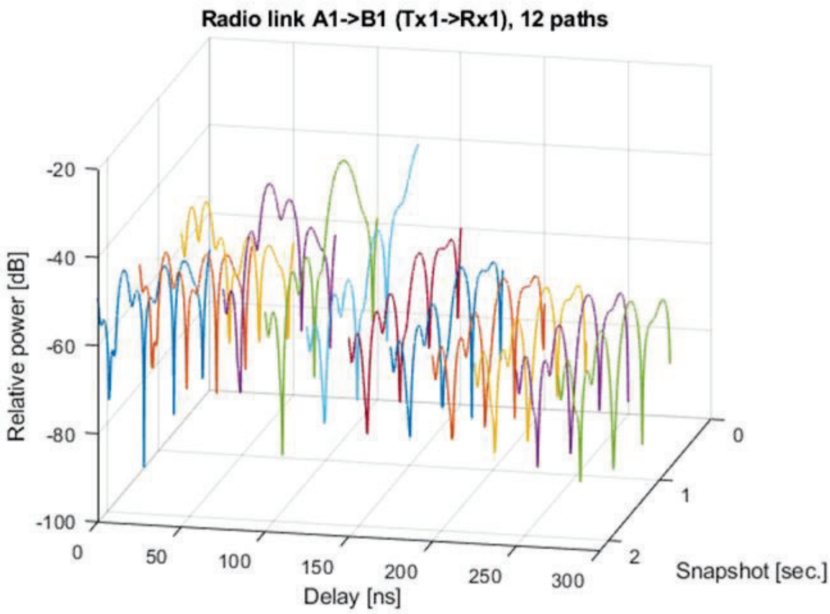


Figure 4-61, Radio links Tx to Rx1. No distance adjustment (as can be seen as a few week signals are present to the left, before the LOS arrives).

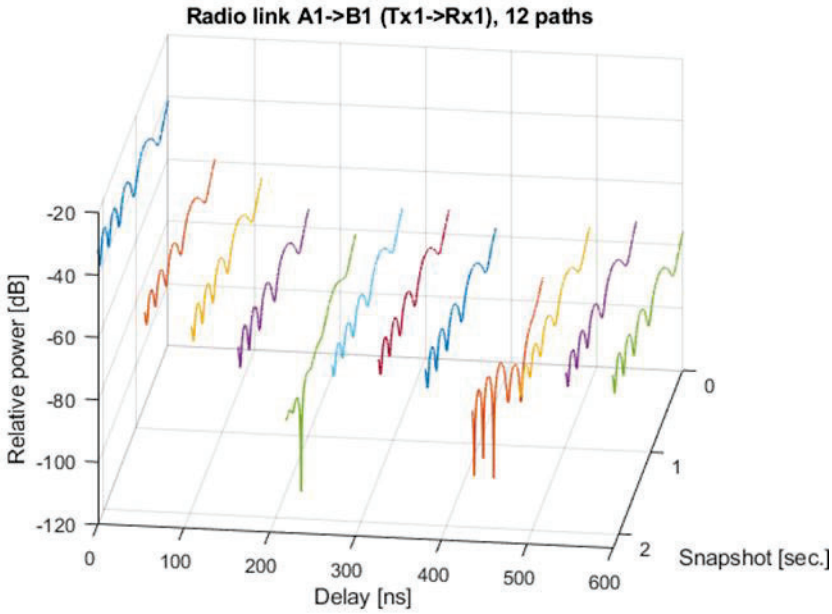


Figure 4-62, Radio links Tx to Rx1. With distance adjustment (as can be seen as the first path is the strongest in this LOS channel).

Finally, the IQ file is played back in the Vertex, and the resulting signal is measured through the scenario using a Vector Network Analyzer (VNA), as shown in figure below. Additional validation is presented in Figure 4-64, confirming that the channel delays are preserved and that delay shifts occur smoothly over time.

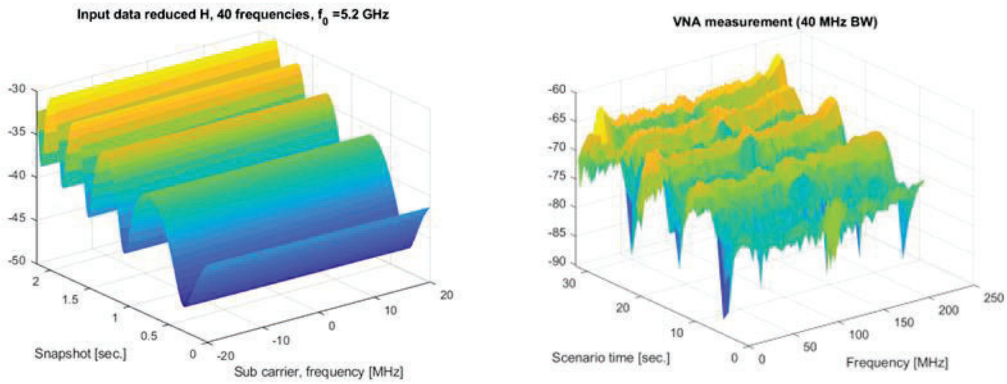


Figure 4-63, Simulated input data (left) and measured data (right).

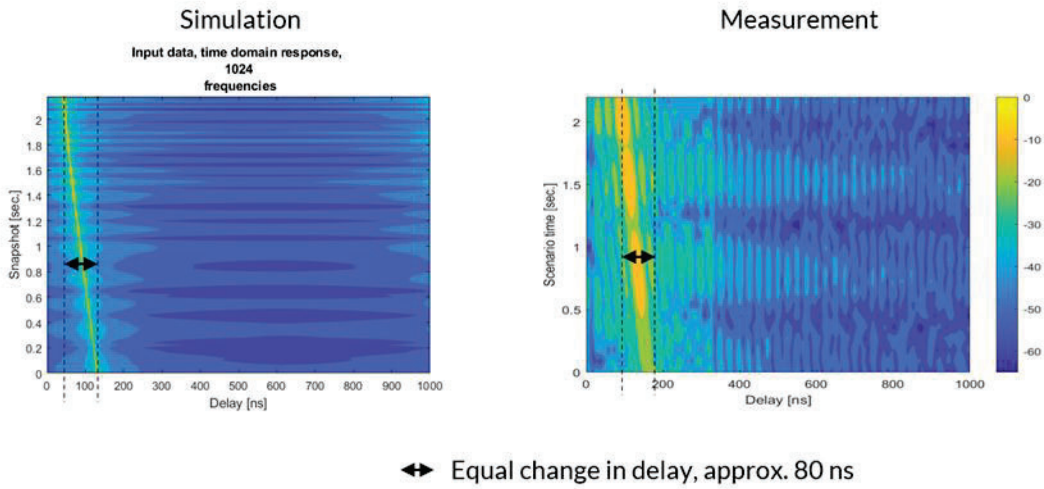


Figure 4-64, Time-domain of simulated input data (left) and measured data (right). (This is without removal of time before first LOS component).

Next scenario is the so called Vienna scenario, which is based on the geometry from [*12*], where two cars meeting and passing by each other on a street in Vienna, Austria. See Figure 4-65. Input from WP1 simulations is shown in Figure 4-66. This figure also illustrates the process of removing part of the signal arriving before the first LOS component. And how this effects energy preservation is shown in Figure 4-67.

Figure 4-68 shows a comparison between simulated *H*-matrix and the *H*-matrix that was measured with a VNA after the steps performed above.

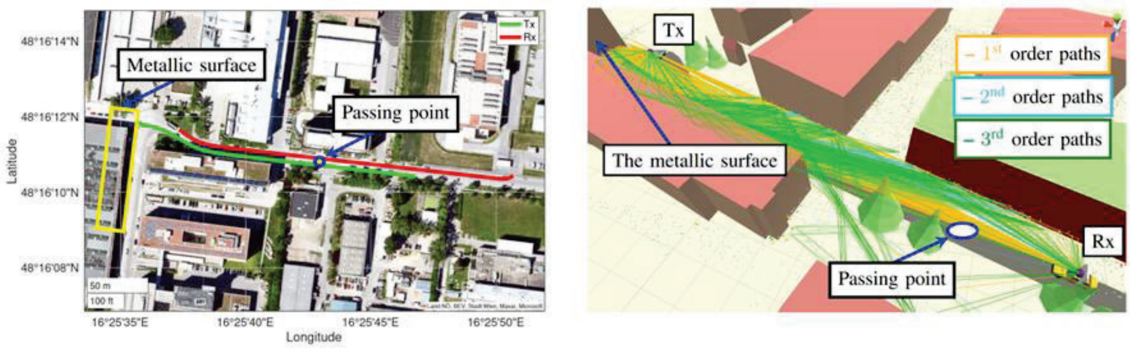


Figure 4-65, Left: the Vienna scenario from [12] , Right: Visualisation of a GSCM-RT simulation run in Unity near the passing point.

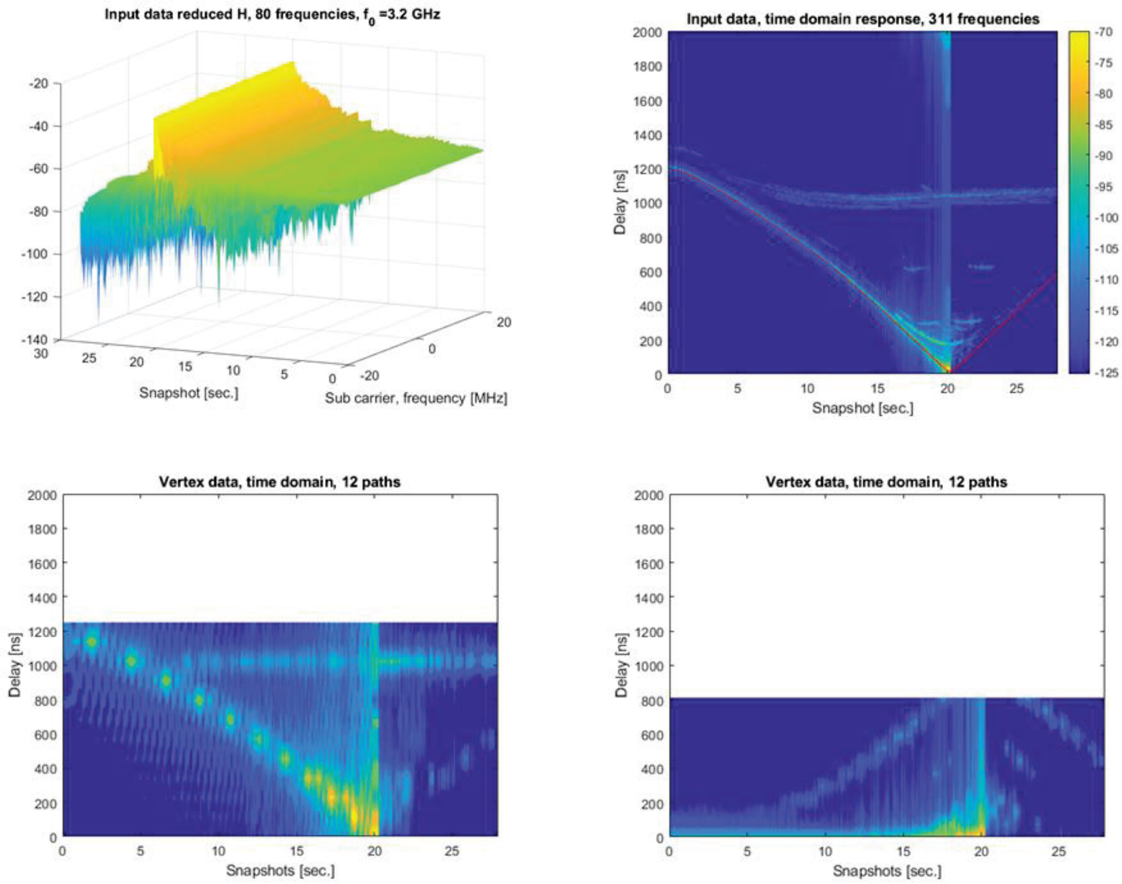


Figure 4-66, Upper left: Input data. 40 MHz frequency band. Upper right: Inverse Fourier transform of the H-matrix. The full dataset transformed. Lower left: Inverse Chirp transform of the H-matrix. 40MHz dataset transformed to 12 paths. Lower right: Inverse Chirp transform of the H-matrix. 40MHz dataset transformed to 12 paths and distance adjustment.

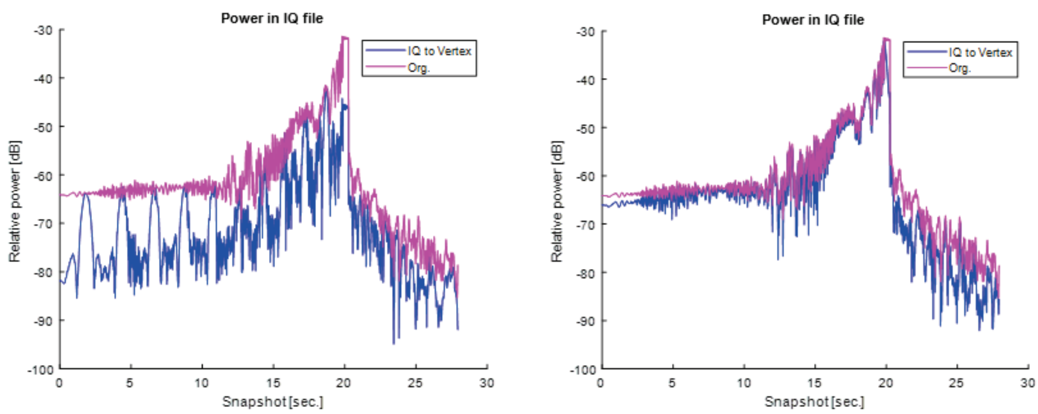


Figure 4-67, Power in IQ-file as function of snapshot time. No distance adjustment to the left and with distance adjustment to the right.

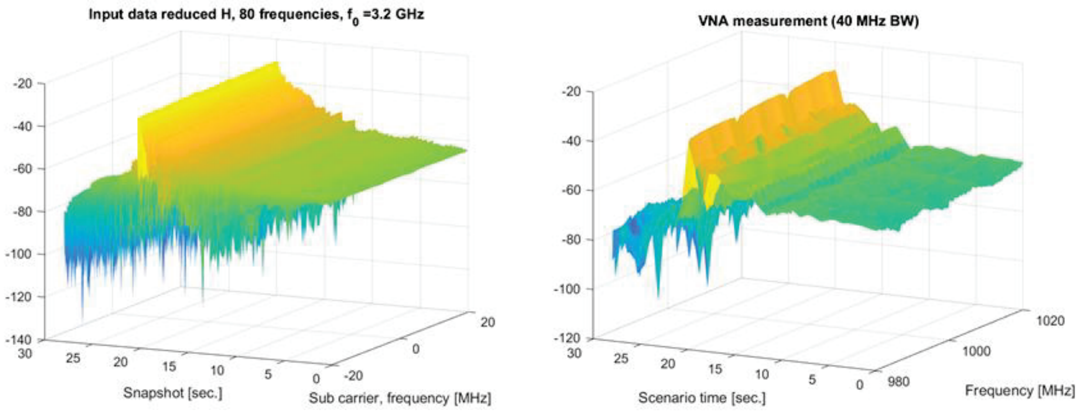


Figure 4-68, Simulated input data (left) and measured data (right).

For evaluation, one can study how a single frequency varies over scenario time. Compared to the integrated power, a single frequency power will vary faster due to the super positioned multipaths. As can be seen in Figure 4-69 below we don't emulate the exact channel response, however, the emulated response has similar dynamics, variations etc.

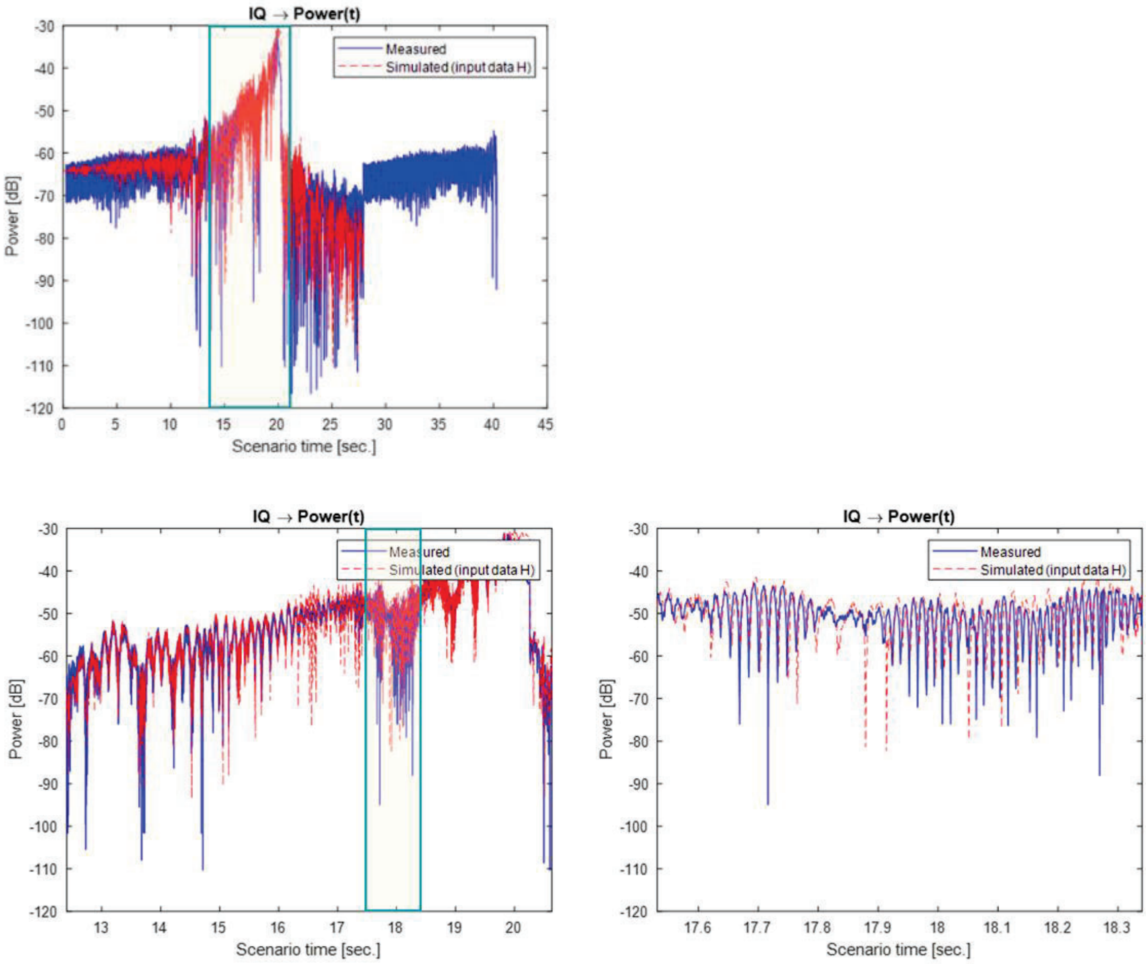


Figure 4-69, Upper: Simulated input data and emulated measured data at single frequency. Scenario repeats at approximately 27 sec. Lower: Zoom in on above.

In a final validation we look at the Doppler profile of the original data and compare with measured emulated data. The measurement is performed by transmitting a CW signal and sample it with a spectrum analyser in IQ mode. Results after transformation into Doppler domain is shown in Figure 4-70 below. As can be seen the Doppler profile of the scenario is preserved.

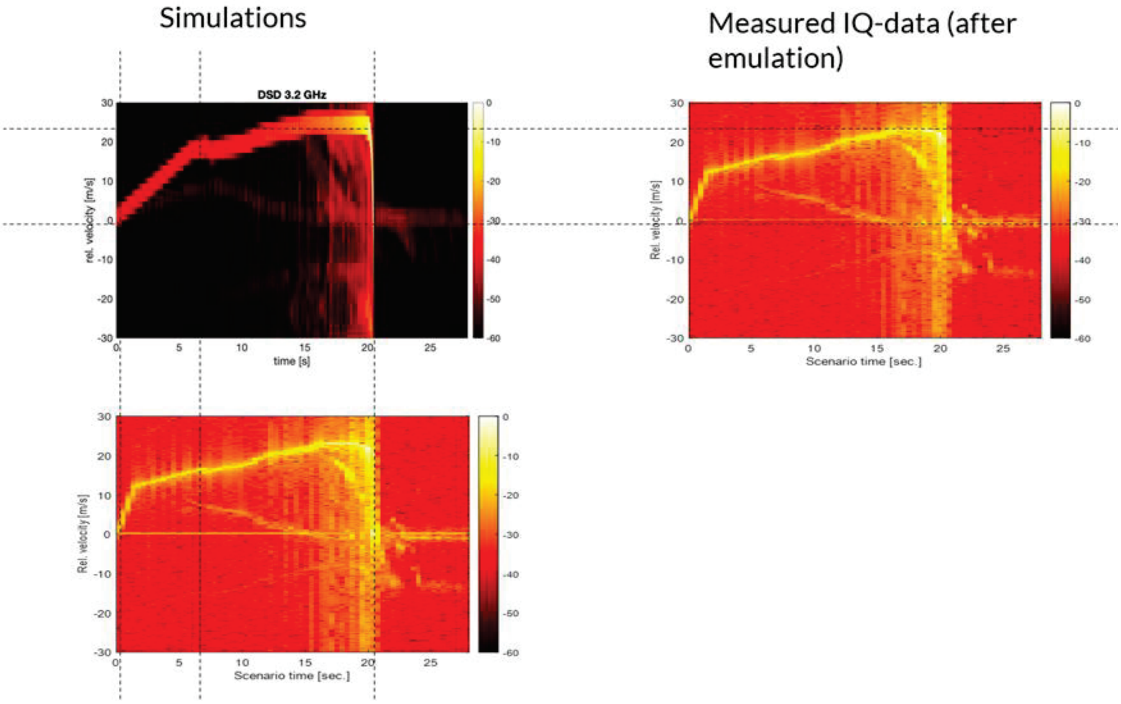


Figure 4-70, Doppler profile of simulated input data (upper left), compared to Doppler profile of emulated and measured data (upper right and lower left).

The Vienna scenario was also used in a real OTA test. As shown in the test setup (Figure 4-71), the Tx node was placed inside a shielded cavity. This was necessary because, although the radios use antennas, a small fraction of the transmitted signal can leak directly from the PCB. The same occurs on the receiving side if some of the received signal is picked up directly by the PCB, not only through the antenna. While these fractions are very small, they can interfere with tests aiming to detect very low power signals by attenuating the main signal path inside the channel emulator. To avoid unintended direct PCB-to-PCB paths, the Tx node was shielded. Additionally, 30 dB attenuators were added on the channel emulator RF outputs to allow for low enough transmission levels, as the channel emulator has limitations in output power.

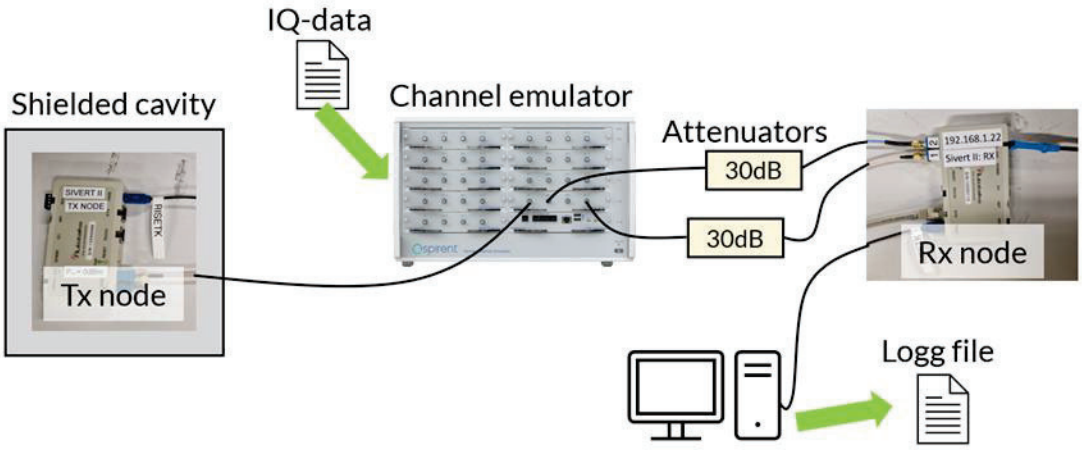


Figure 4-71, OTA test setup for replaying WP1 IQ-data. The Tx node is placed inside a shielded cavity to avoid signalling directly from the PCB (left). IQ-data file is loaded by the channel emulator. The channel emulator plays the IQ-file. 30 dB RF attenuators are added to enable low enough signals. Rx node with two RF ports. Computer connected to the Rx node for logging of result.

In this test setup, the antenna patterns were not loaded into the channel emulator. Their effect is already accounted for in the WP1 simulations and included in the IQ data file used for replay. The tests were conducted using IEEE 802.11p nodes from Autotalks [*43*] on both Tx and Rx sides. One Tx RF port and two Rx RF ports were used. Results are shown in Figure 4-72.

Selecting the correct average power level is crucial before testing. If the simulation is based on field test data, the OTA test power can be adjusted to match the field test. If no field test exists and only simulations are available, careful consideration must be given to Tx node output power, *H*-matrix loss, test system losses, and similar factors.

Data age, also referred to as age of information, shown in the same figure, increases when consecutive packets are lost.

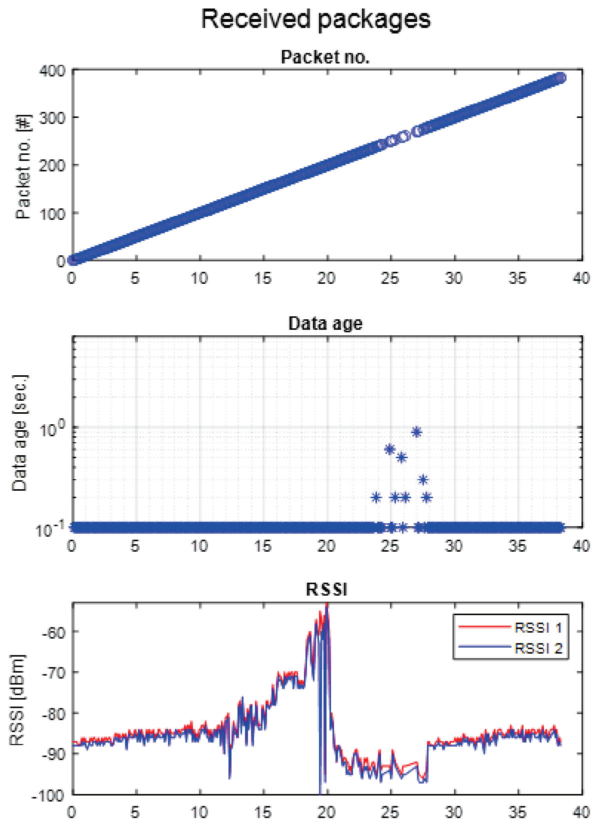


Figure 4-72, Results. Received packet number (upper), data age (middle), and received RSSI (lower).

Two additional scenarios—Torslanda and Vasastan—are presented in this final report. For both, field tests were conducted for comparison. This evaluation bridges field testing with OTA testing based on simulated scenarios and assesses multiple aspects of the SIVERT2 project. It verifies the WP1 simulations, which serve as inputs for the OTA tests, and evaluates the test methods developed in WP2 by comparing OTA results to real-world data. It also validates the process of converting WP1 simulation data into IQ files for channel emulator replay.

The test setup used two vehicles: a Tx car (Volvo XC90 with a metal roof) equipped with a transmitting ITS-G5 node, and an Rx car (also a Volvo XC90 with a metal roof and a small glass cut-out) with a receiving ITS-G5 node. The Tx vehicle used a single roof-mounted monopole antenna, consistent across all test cases. The Rx vehicle used two receiving antennas for diversity. Although several antennas were tested, only results from the monopole configuration are reported here—specifically, two monopoles mounted at the front and rear of the roof.

Field tests were conducted at two locations: a rural road in Torslanda and a dense intersection in Vasastan (see Figure 4-73 and Figure 4-74). These scenarios were also used in the OTA tests, with the test setup shown in Figure 4-71. In this setup, the Tx modem is connected to the channel emulator input via an RF cable, and channel emulator outputs are routed to downlink antennas (RF cables not yet connected in the photo). These antennas are placed close to and above the VUT (vehicle under test) receiving antennas. The Rx modem was installed inside the VUT. As before, antenna patterns were not loaded into the channel emulator, as their influence is already captured in the WP1 simulations.

The “XC90” and “EC40” tests refer to cases where the radio is mounted in different car models. However, any difference in performance due to vehicle design comes from the antenna radiation patterns included in the simulation. The physical car only affects the result if it causes interference to the receiver.

Finally, a complete evaluation of the test chain is performed using both the Torslanda and Vasastan scenarios. In each case, OTA test results—based on IQ data generated from WP1's ray-tracing GSCM simulation—are compared directly to field test results from the same scenario. This validates the full process from simulation to OTA testing.

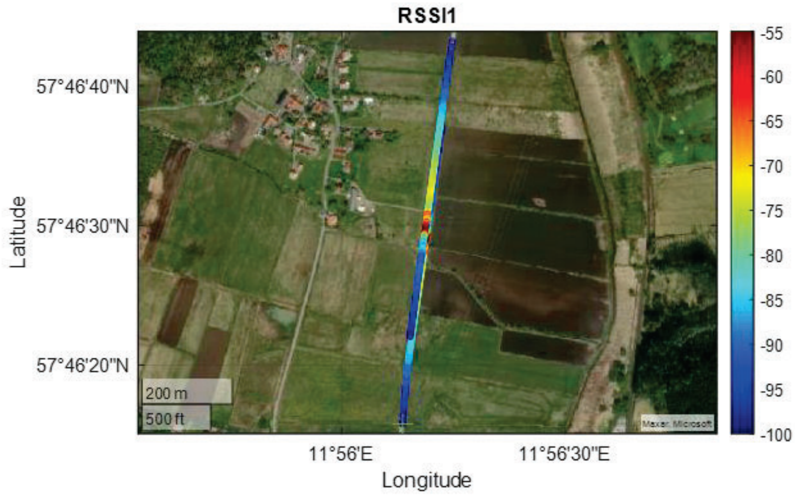


Figure 4-73, Rural road in Torslanda, Gothenburg.

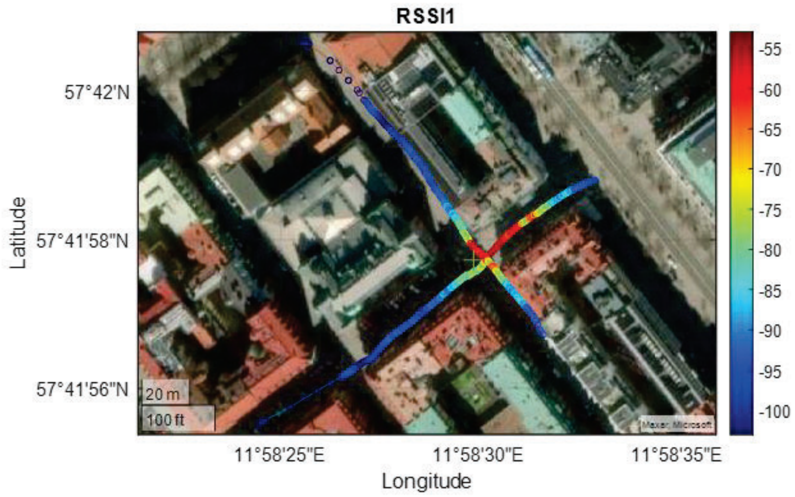


Figure 4-74, Tight intersection, urban road in Vasastan, Gothenburg.

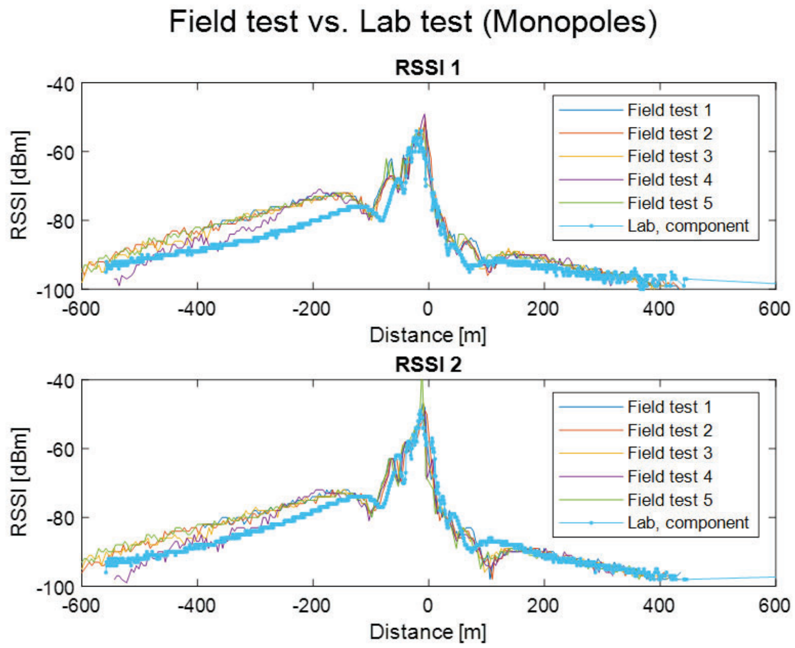


Figure 4-75, Comparison monopole antennas. Torslanda rural scenario: Five repeated field tests vs. component lab test.

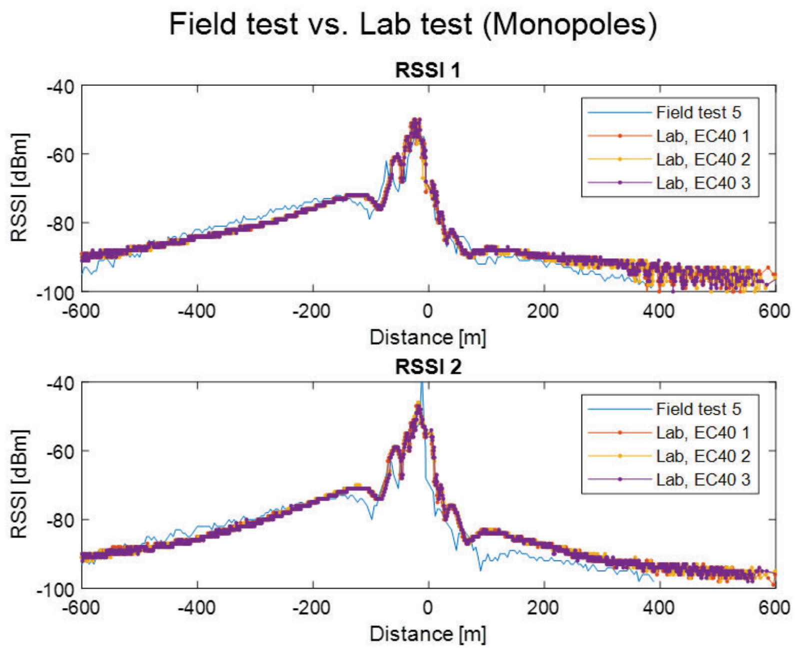


Figure 4-76, Comparison monopole antennas. Torslanda rural scenario: Single field test vs. Three EC40 lab tests.

4.3.4.3 The RanLOS measurement system

The work on the RanLOS measurement system, BeamForce 42, is a continuation of the work done in SIVERT1. In SIVERT2 the BeamForce 42 system was upgraded with a lift and tilt-device, BeamTilt (see Figure 4-77), to perform semi-3D antenna radiation pattern measurements for a complete vehicle. This upgrade also included an update of the software to support the control of the BeamTilt, as well as 3D plotting capabilities. An upgrade in frequency was also performed to support the V2V bands. The upgrade in frequency was covered by updating the system with a new feed array covering 3-6 GHz. The measurement system is based on the idea of random line-of-sight, which was first introduced in [*44*].

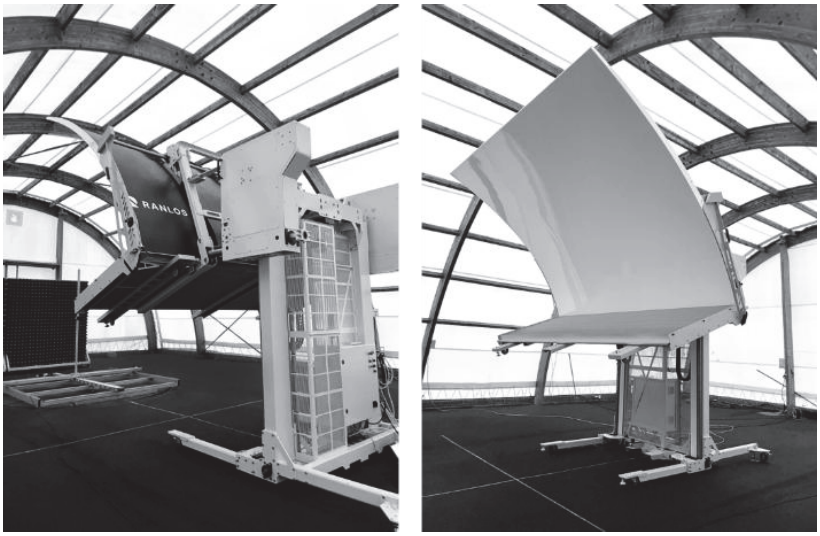


Figure 4-77, RanLOS BeamForce 42 with BeamTilt, shown from the backside (left) and frontside (right).

RanLOS BeamForce 42 is a dual-polarized passive cylindrical reflector antenna that generates a plane wave at a short distance from the antenna, see Figure 4-78. With the plane wave the system simulates the signal from, e.g., a base station to the vehicle or another device under test. The system including its lift and tilt-device, the BeamTilt, can simulate signals at elevation angles of $0° - 20°$, and by placing the device on a turntable it is possible to measure the device performance for $0° - 360°$ in azimuth. Together these angles cover many of the relevant vehicle scenarios. Depending on the use case, BeamForce 42 can be used as a standalone system (for 2D measurements) or together with BeamTilt (for semi-3D measurements).

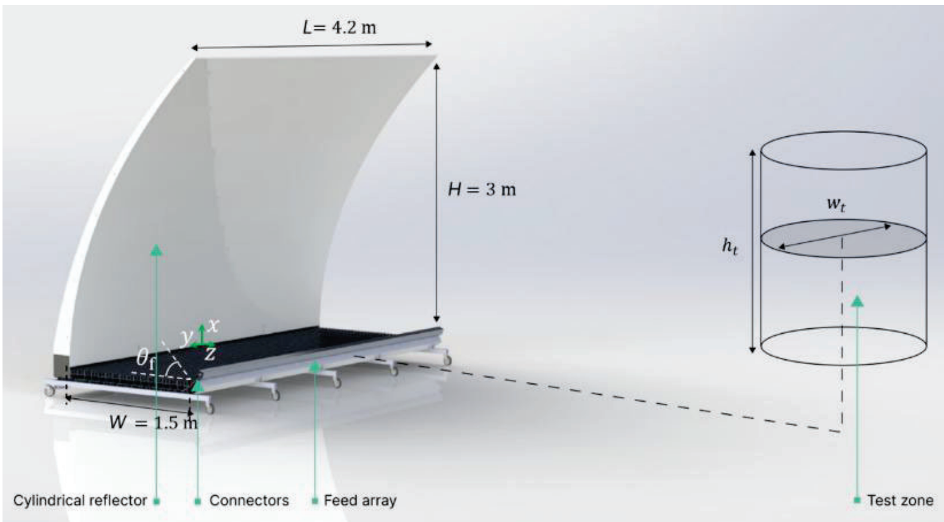


Figure 4-78, Drawing of the RanLOS BeamForce 42 reflector antenna and its dimensions.

The system consists of two parts, the hardware and a control and measurement software. The RanLOS measurement software, RanLOS BeamLab, controls the BeamTilt, instruments and peripheral equipment needed for performing a measurement, such as a turntable, see Figure 4-79. To perform a measurement, five steps are followed; Select a setup (passive, active, 2D or 3D), Select a measurement instrument (typically vector network analyzer or communication tester), Select a positioner (type of turntable, 2D or 3D), Perform measurement, Plot the results.

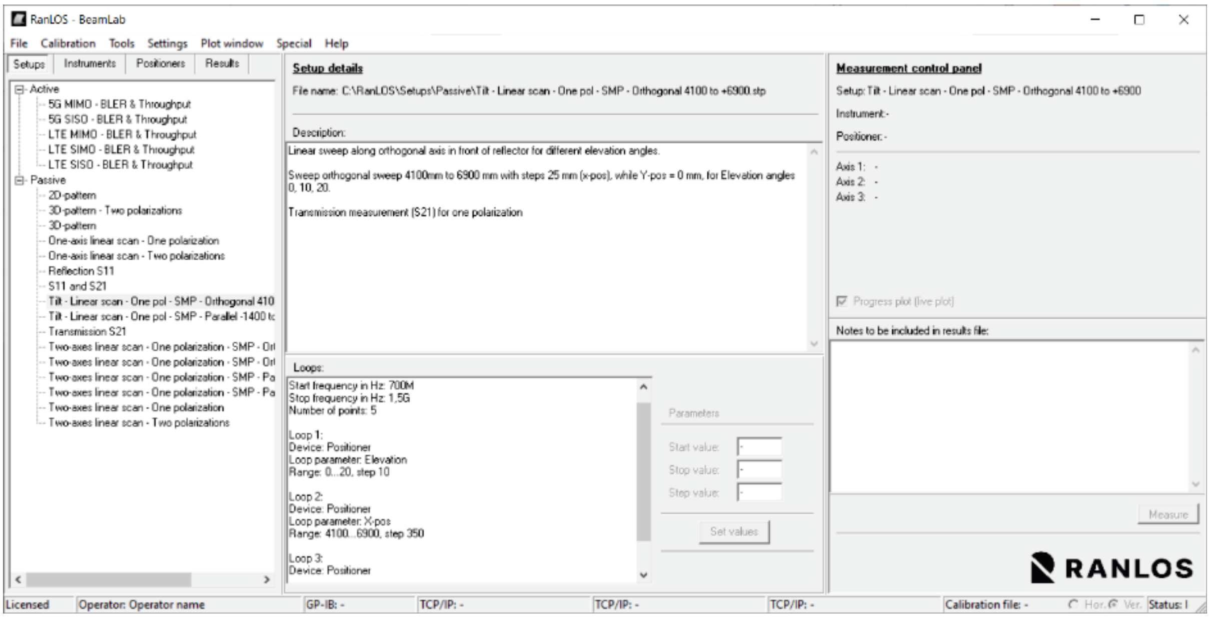


Figure 4-79, RanLOS BeamLab measurement software.

The RanLOS BeamForce 42 system can be configured for two different types of measurements, passive and active. For passive measurement, radiation pattern for an antenna mounted on a vehicle is obtained by the use of a vector network analyzer. Throughput, or any other relevant parameter, for a complete wireless system is measured using the active setup. In this case, typically a communication tester is used.

It should be pointed out that BeamForce 42 should ideally be used in a semi-anechoic chamber where reflections from the surroundings are negligible and interference from external sources will not affect the measurements. In this project the measurements were performed in an outdoor tent, which is not ideal, but care has been taken to reduce the influence of these external sources as far as possible.

Hardware upgrade of the RanLOS measurement system

The RanLOS BeamTilt, see Figure 4-77 and Figure 4-80**,** was developed during SIVERT2 to be able to upgrade the BeamForce 42 system to cover semi-3D measurements and not just 2D measurements. The BeamTilt will both lift, tilt and slide the BeamForce 42 reflector, such that the same focal point can be kept for all the elevation angles. Since BeamForce 42 was a large and heavy reflector antenna it needed to be upgraded from a heavy fiberglass material in the reflector to a lighter carbon fiber reflector such that it could be lifted and tilted up to heights of 2.5 m to cover the desired elevation range.

Figure 4-80, RanLOS BeamForce 42 together with BeamTilt in a semi-3D vehicle measurement setup.

The development of BeamTilt, done in SIVERT2, included all the mechanical design, the manufacturing and the control of the lifting and tilting through the RanLOS BeamLab software. The BeamTilt consists of a fork that goes under the base of BeamForce 42 and lifts it up using server motors. To make sure that the desired elevation angles were achieved and the focal point was fixed, numerous alignment measurements were performed using lasers.

The hardware realization that has been used in the project is designed to cover the frequency range 700 MHz to 6 GHz, thus covering most of the wireless frequency bands used today. The system covers this frequency range by using three different feed arrays. In SIVERT1 the focus was on the frequency range 1.5 GHz-3 GHz, which was covered by a 32-element feed array. However, in SIVERT2 the focus was on the higher part of the frequency range, namely 3 GHz-6 GHz, and particularly the V2V bands around 5.9 GHz. That meant that a new feed array had to be developed and manufactured. The new amplitude tapered linear feed array used for the 3 GHz-6 GHz band consists of 64 dual-polarized Bowtie antennas, plus 4 additional dummy elements, see the insert in Figure 4-81.

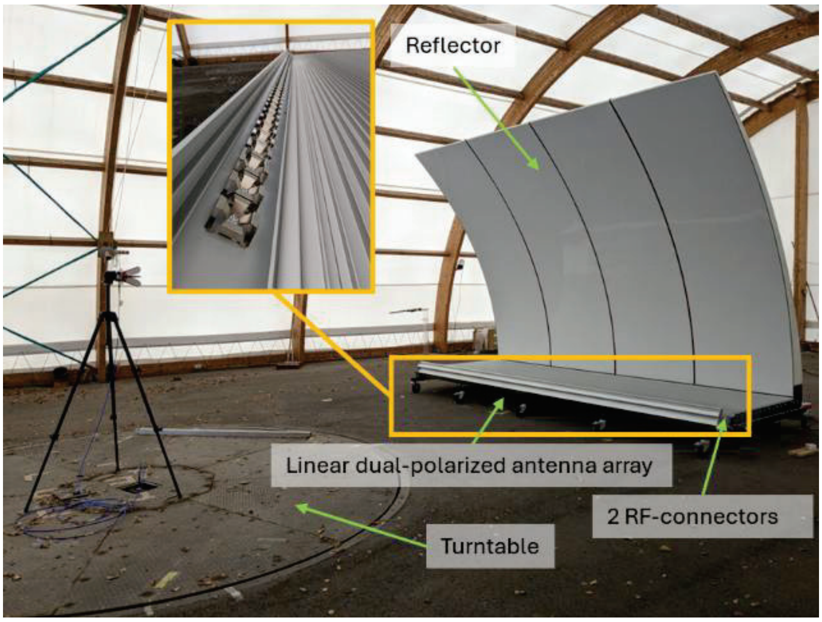


Figure 4-81, BeamForce 42 in a stand-alone antenna 2D radiation pattern setup. The insert shows the linear bowtie antenna array for the frequencies 3 GHz-6 GHz.

Verification of BeamForce 42 at 3 GHz-6 GHz

Extensive field measurements in front of the measurement system have been performed, to fully characterize the system and verify the performance compared to numerical physical optics simulations. A full description of the physical optics code is given in [*45*]. The field strength has been sampled in the test zone in front of BeamForce 42 along two lines, one in *y*- and one in *z*-direction, see coordinates in Figure 4-82. The line along *y* went from -1.4 m to +1.4 m and the line along z went from 4.1 m to 6.9 m. The two lines crossed each other at the coordinates y = 0 and z = 5.5 m. The spacing between the measurement points along these two lines was 2.5 cm, corresponding to half a wavelength at the highest frequency. These crosslines were measured for different heights above the ground, from 1.4 to 1.8 m, with measurements every 10 cm. For the height 1.6 m have also three different elevation angles been tested, $0°$, $10°$ and $20°$. The measurements were performed at two different instances. The figures containing only graphs based on measurements from $0°$ elevation were done using only BeamForce 42, whereas the graphs plotted in the figures with several elevation angles were done using BeamForce 42 together with BeamTilt.

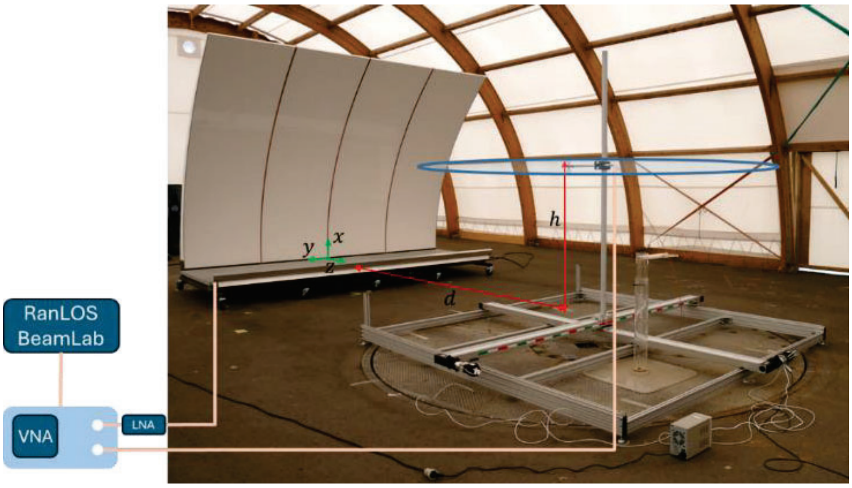


Figure 4-82, Test setup for characterization of test zone with BeamForce 42. Origin is defined at the base of the reflector.

The field strength was sampled by mounting a small biconical dipole antenna (Schwarzbeck SBA 9119 (1 GHz -6 GHz) [*46*]) on a test fixture, see Figure 4-82, equipped with two stepper motors which are controlled through RanLOS BeamLab. A low noise amplifier (LNA) was used in the setup to get high enough S21 levels in order to avoid the noise floor. The vector network analyser (R&S ZNB 8-4) was swept from 3 GHz to 6 GHz with 301 frequency points.

Due to a large number of results and data, just a subset of the verification measurement results will be shown in this report. The field variation along the parallel line to the reflector, i.e., along *y*, centered at *z* =5.5 m, is shown for both amplitude and phase for both vertical and horizontal polarization at height 1.6 m above the ground in (Figure 4-83-Figure 4-84). The results are shown for the frequency 4 GHz and $0°$ elevation.

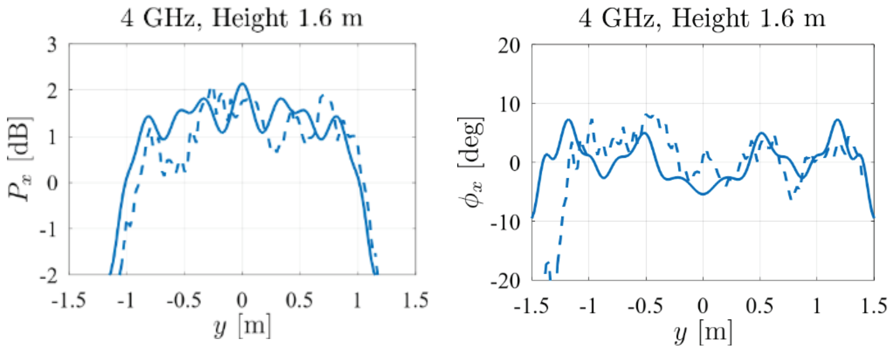


Figure 4-83, Measured (dotted) and simulated (solid) power density, vertical (x) polarization, x=1.3 m (height 1.6 m) at 4 GHz and $0°$ elevation. Left – Amplitude, Right – Phase.

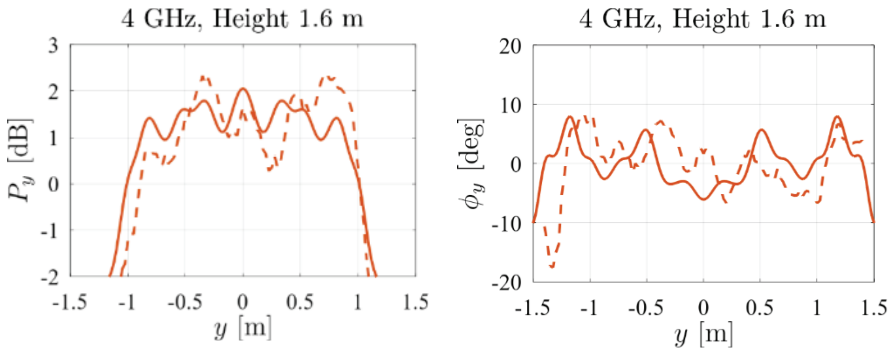


Figure 4-84, Measured (dotted) and simulated (solid) power density, horizontal (y) polarization, height 1.6 m at 4 GHz $0°$ elevation. Left – Amplitude, Right – Phase

The corresponding power density variation along *y*, as in Figure 4-83-Figure 4-84, but for the elevation angles $0°$, $10°$ and $20°$, are shown in Figure 4-85**.** The graphs are shown for the four frequency points 3 GHz, 4 GHz, 5 GHz and 6 GHz.

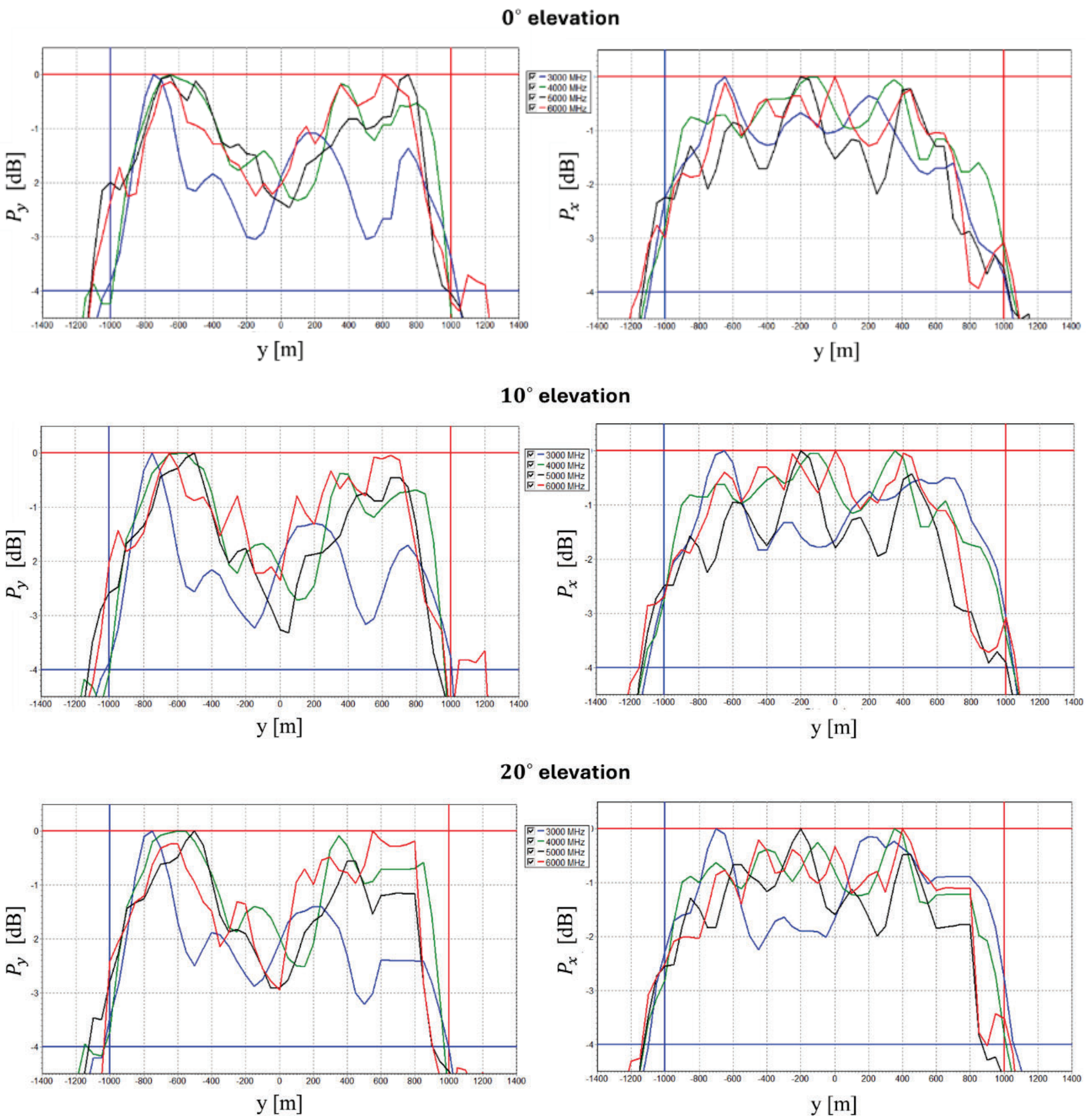


Figure 4-85, Measured power density along y, height 1.6 m for elevation angles $0°$, $10°$ and $20°$ and the frequencies 3 GHz, 4 GHz, 5 GHz and 6 GHz. Left – horizontal (y) polarization, Right – vertical (x) polarization.

We can also plot the standard deviation calculated for the grid/cross within a circle of diameter w_t, (see Figure 4-78). The grid/cross center is placed at height 1.6 m, *y* = 0 m, *z* = 5.5 m and $0°$ elevation. The standard deviation is plotted as a function of the diameter for several different frequencies, see Figure 4-86 and Figure 4-87. The standard deviation of the phase was hard to capture in the measurements, since a dense enough cross needs to be captured in order to unwrap the measurement data properly. This was particularly hard for the higher frequencies, from 5 GHz, so some plots do not include the 5 GHz-6 GHz graphs.

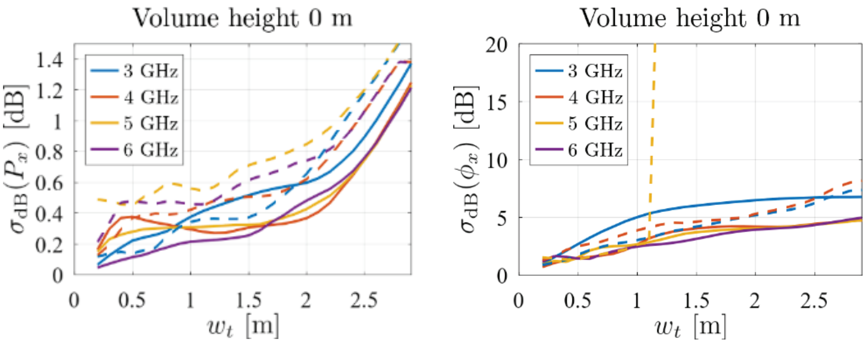


Figure 4-86, Measured (dotted) and simulated (solid) standard deviation for power density, vertical (x) polarization, x=1.3 m (height 1.6 m). Left – Amplitude, Right – Phase.

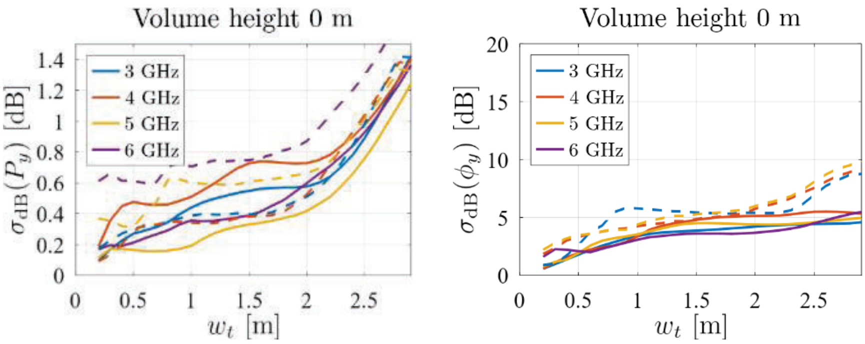


Figure 4-87, Measured (dotted) and simulated (solid) standard deviation for power density, horizontal (y) polarization, x=1.3 m (height 1.6 m). Left – Amplitude, Right – Phase.

All the results so far have been shown for measurements in the *yz*-plane, however it is also of interest to see how the field varies in a volume, i.e., where the height h_t is included as well, see Figure 4-78. Standard deviation within a volume of height $h_t = 0.4$ m, as a function of frequency is shown in Figure 4-88. To get the volume, cross-measurements were performed for five different heights, 1.4 m, 1.5 m, 1.6 m, 1.7 m and 1.8 m and 0° elevation. The volume plots are only presented for the power, not phase. The reason is that a very dense grid in all directions is needed to properly unwrap the phase at these high frequencies.

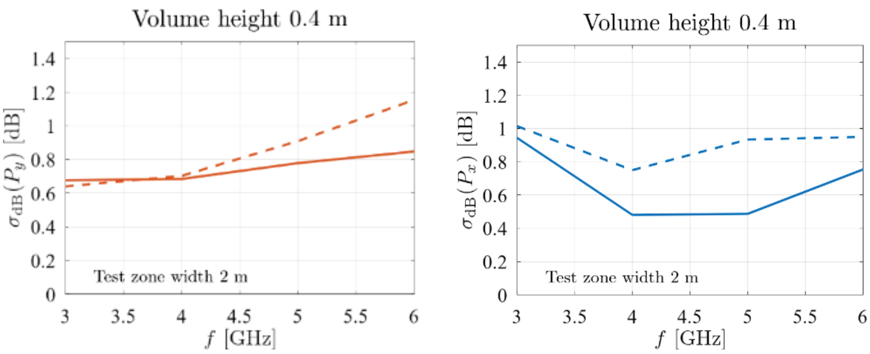


Figure 4-88, Measured (dotted) and simulated (solid) standard deviation for power density within a cylindrical volume of height 0.4 m and diameter 2 m. Left – Horizontal (y) polarization, Right – Vertical (x) polarization.

As can be seen in the figures above, there is a good agreement between measured and simulated results. Thus, RanLOS BeamForce 42 with the 3-6 GHz antenna array behaves as expected. The standard deviation for the measured power density taken over a cylindrical volume with a diameter of 2 m, and height 0.4 m is better than 1.2 dB for both polarizations. It can also be seen that the parallel sweep (along y) keeps the performance throughout the elevation angles $0° - 20°$.

Radiation pattern measurement of stand-alone antenna

The antenna radiation pattern for a stand-alone Quadridge horn antenna (ETS Lindgren, Open Boundary Quadridged Horn 3164-05 [*47*]), was measured. During the radiation pattern measurements were the turntable rotated continuously for faster measurements. The measured radiation patterns are shown as absolute gain-values, which was acquired by doing a calibration measurement first. During a calibration measurement is an antenna with known gain measured as a reference. A small biconical dipole antenna (Schwarzbeck SBA 9119 (1 GHz-6 GHz)) was used as the reference antenna. The measurement setup for the radiation pattern measurements with the Quadridged horn is shown in Figure 4-81. The measured radiation pattern for the stand-alone Quadridged Horn antenna is shown for 4 GHz and elevation $0°$ in Figure 4-89. We will only present data for elevation $0°$, since the reference data sheet was only available for this elevation angle.

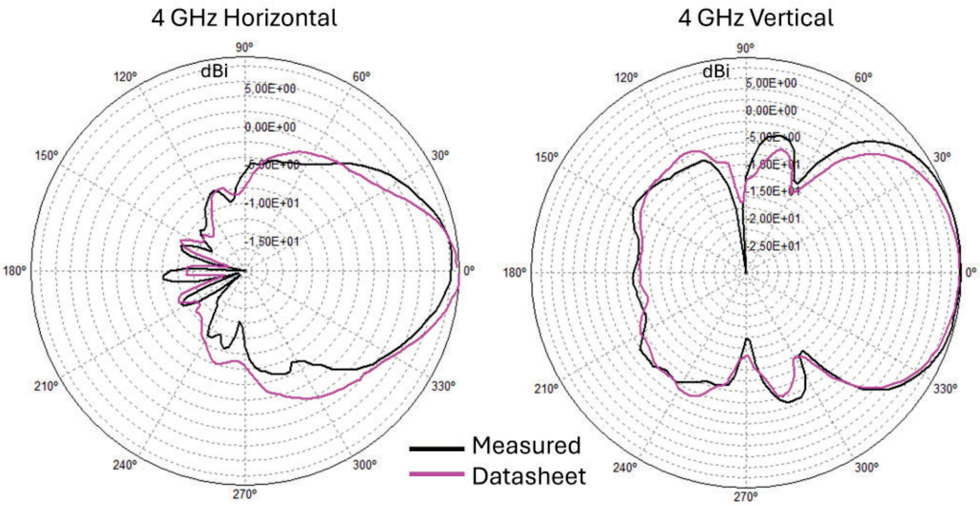


Figure 4-89, Measured radiation pattern of a Quadridged horn antenna. Measured data is the black line and data from Datasheet is the purple line. The result is shown for the frequency of 4 GHz and elevation $0°$. Left – Horizontal polarization, Right – Vertical polarization.

The measured radiation pattern using the RanLOS measurement system compares well to the theoretical data from the data sheet of the Quadridge horn antenna. Both the absolute level and the shape of the curves agree. The reference data from the datasheet has been digitalized from a figure, which reduces the accuracy of the reference data, especially for the low values.

Radiation pattern measurement of vehicle mounted antenna

The antenna radiation pattern measurements were performed using a prototype windshield mounted V2V antenna mounted on a Volvo XC90. The setup can be seen in Figure 4-90. Measurements were both performed using only the BeamForce 42, but also using it together with BeamTilt, to get the elevation angles. For the measurements using BeamTilt was also an RF-absorber wall placed behind the vehicle to reduce reflections from the outdoor tent, see the left figure in Figure 4-77. A calibration measurement was done such that absolute gain values could be measured. The calibration measurement was done with a small biconical dipole antenna (Schwarzbeck SBA 9119 (1 GHz-6 GHz)) with known gain. This was done without the vehicle on the turntable, but with the small biconical dipole antenna mounted on an antenna holder throughout the calibration.

Figure 4-90, Setup for measuring radiation pattern of a windshield V2V antenna on Volvo XC90.

The measurement cables out to the test tent are very long, which means that the attenuation is high for these high frequencies (5.9 GHz), and both a Power Amplifier (PA) and a Low Noise Amplifier (LNA) were used for the measurements. The PA was placed close to the reflector outside in the tent (close to the output from the VNA) and the LNA was placed inside the vehicle, see Figure 4-90.

When measuring the radiation pattern the turntable was configured to rotate continuously. The VNA (R&S ZNB 8-4) [*48*] was swept from 5.5 GHz to 6 GHz with 101 frequency points. Measurements were performed every 3 degrees for a full turntable rotation of 360 degrees. The S21 measurements were triggered by RanLOS BeamLab when the turntable had moved to the next desired rotation angle, however since the turntable was continuously moved, the first frequency points will be measured at a slightly different angle than the last frequency points in a sweep. Linear interpolation is used between the measurement points. The results are presented for 5.885 GHz in Figure 4-91. Each figure contains two curves; one obtained as described above and the other represents measurement results from a near-to-far-field (NF/FF) range. The NF/FF measurements were performed for every 1-degree angle.

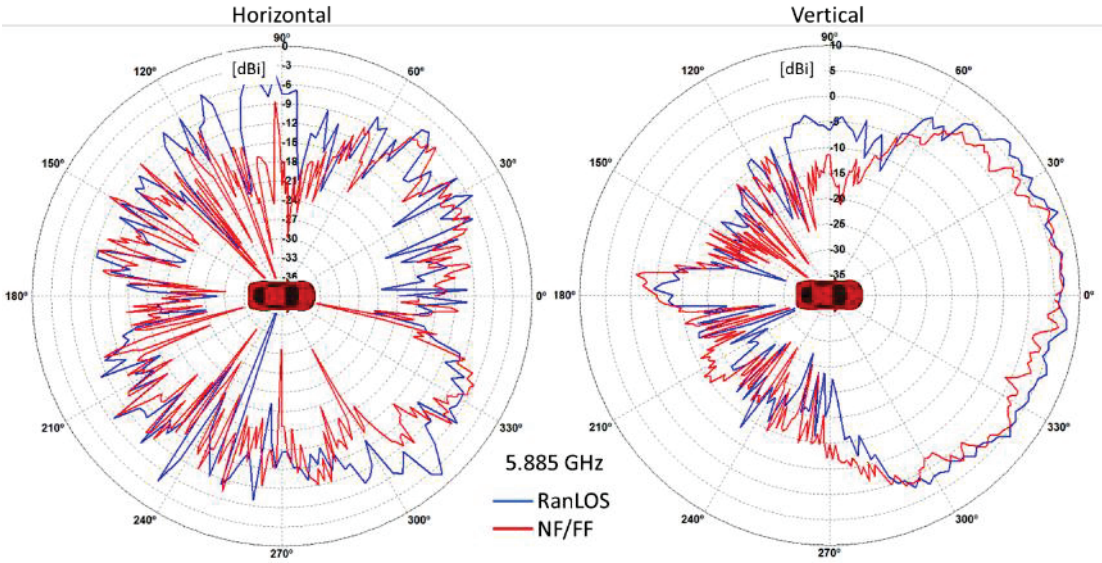


Figure 4-91, Radiation pattern of a windshield V2V antenna(prototype) on a Volvo XC90. Left – Horizontal polarization, Right – Vertical polarization.

The measured results in Figure 4-91 agree well with the NF/FF range, both in terms of shape of the curves as well as in absolute gain level. It is worth noting that the horizontal polarization has very low gain with a lot of noise, which makes it harder to compare the RanLOS measurements with the NF/FF measurements.

The corresponding semi-3D radiation pattern, for the windshield V2V antenna mounted on XC90, measured with RanLOS BeamForce 42 and BeamTilt and plotted in RanLOS BeamLab for the vertical polarization is shown in Figure 4-92.

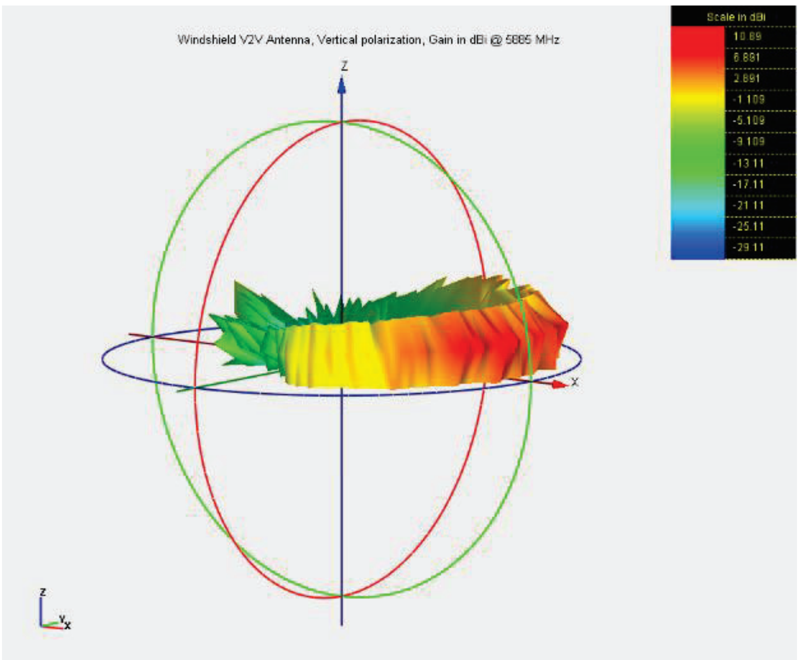


Figure 4-92, Semi-3D radiation pattern results, in dBi, for the vertical polarization of the windshield V2V antenna(prototype) on the XC90.

Active measurements

Capability for active measurements for V2V communication has been implemented in the BeamLab software and a simplified setup has been tested, see Figure 4-93. Two IEEE 802.11p nodes from Autotalks were used, the same nodes as in Section 4.3.4.2 One of the nodes was used as Tx and one as Rx. Two monopole antennas were connected to the two RF-ports on the Rx node and one monopole antenna to the RF-port on the Tx node. The Tx node transmits with constant power, but to measure the PER as a function of the power one needs to vary the output power. Therefore, a programmable attenuator (Mini-Circuits RCDAT-8000-60 [*49*]) is added on the Tx side between the antenna and the node. The attenuator can be controlled through BeamLab, such that the attenuation can be adjusted from 0 dB-60 dB, in 0.25 dB steps. By varying the attenuation one can sweep the output power while measuring how the RSSI and PER changes on the Rx side.

Figure 4-93, Simplified V2V measurement setup.

This simplified setup can be extended into a setup with BeamForce 42 (and BeamTilt) instead of the monopole antenna on the Tx side, see Figure 4-94. By placing the vehicle on a turntable one can sweep the output power and measure PER as a function of the output power for every measurement angle. This would then provide the active system performance of the full vehicle in the horizontal plane. However, these full V2V measurements have not been performed with the complete BeamForce 42 system, turntable and vehicle setup due to limited access to the measurement site at the end of the project.

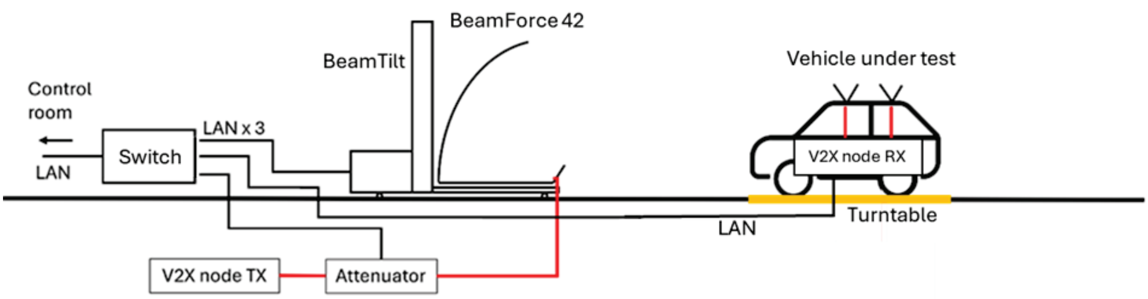


Figure 4-94, Schematic overview of a V2V measurement setup with the full BeamForce 42 and BeamTilt setup.

4.3.5 Work Package 2 Conclusions

The SIVERT2 project has successfully advanced OTA testing methodologies for 5G and V2X communication, building on the foundation laid in the original SIVERT1 project. The work carried out in WP2B and WP2C has led to several key achievements:

WP2B – 5G V2N Communication

Integration of Amarisoft Advanced: The Amarisoft Advanced base station simulator was successfully integrated into the OTA test environment. Despite its initial complexity, it proved to be a flexible and cost-effective solution. Calibration procedures and tailored configuration files were developed to ensure accurate and repeatable testing across various scenarios.

Robust OTA Methodology: The RC OTA methodology was adapted for full-vehicle testing, demonstrating high repeatability and sensitivity to antenna configurations. Both component-level and full-vehicle tests validated the method's ability to differentiate between good, nominal, and bad configurations, with consistent results in throughput and sensitivity. Some future work is needed to ensure accuracy of the test method for all 5G bandwidths and numerologies etc., for example in terms of chamber loading conditions.

Field Testing and Scenario Tool: Field tests conducted at Scania's test track provided real-world data for validating the scenario tool. This tool enables flexible testing of large-scale fading and integrates with channel emulators to simulate small-scale fading, supporting realistic and repeatable test conditions.

WP2C – V2V and V2I Communication

VDT Tool Implementation: A virtual drive test tool was developed and validated, enabling detailed emulation of realistic driving scenarios. The tool integrates ray-tracing GSCM simulations from WP1 and preserves spatial consistency, allowing for high-fidelity channel emulation.

Scenario-Based Testing: The project demonstrated a complete test chain, from simulation to OTA testing, by comparing simulated scenarios with real-world field tests. This validated the accuracy of the simulation framework and the effectiveness of the test methods developed in WP2.

The RanLOS measurement system: The upgraded RanLOS measurement system with BeamTilt and the new 3 GHz-6 GHz feed array have shown to perform well and as expected according to simulations. The verification measurements show good agreement between simulated and measured data within the test zone. The standard deviation for the measured power density taken over a cylindrical volume with a diameter of 2 m, and height 0.4 m is better than 1.2 dB for both polarizations. The BeamTilt which lifts and tilts BeamForce 42 works as intended and gives additional semi-3D performance. It is also shown that it can keep the test zone performance throughout the elevation angles $0° - 20°$. Additionally, successful semi-3D radiation pattern measurements have been performed on a prototype windshield V2V antenna mounted on a Volvo XC90 and the pattern measurements agree well with measurements performed in a NF/FF range. Since all the verifications went well with both the BeamTilt and the 3-6 GHz feed array, it means that both are now ready as products on the market.

Recommendations for Future Work:

To build on the success of SIVERT2, the following areas are recommended for future research and development:

Expansion to FR2 and mmWave Testing: Extend the current methodologies to support 5G FR2 (mmWave) frequencies, which pose unique challenges in terms of propagation, antenna design, and OTA testing.

Integration of Real-Time Feedback in VDT: Develop closed-loop VDT systems that allow real-time feedback between simulation and hardware, enabling adaptive testing and dynamic scenario adjustments.

Enhanced QoS Evaluation Framework: Refine the mapping between functional use cases and NFRs to better capture interdependencies and identify performance bottlenecks.

Automation and Scalability: Automate the configuration and execution of OTA tests to support large-scale testing across multiple vehicle platforms and communication technologies.

Electromagnetic Interference (EMI) Characterization: Investigate the impact of internal and external EMI on V2X performance, especially in dynamic environments and during vehicle operation.

Cross-Platform Validation: Apply the developed methodologies to a broader range of vehicles and communication modules to ensure robustness.

V2V measurements using RanLOS BeamForce 42 with BeamTilt: Test the full RanLOS measurement system and its semi-3D capabilities for active V2V measurements on a full vehicle setup.

4.4 Work Package 3: End-2-End Verification

The overall objective of WP3 is to bridge the gap between the E2E verification in field with live cellular networks and the verification on link-level with emulated environments. This WP enables E2E verification in controlled lab environment with typical test scenarios as well as corner cases ("what-if" scenarios) that are not possible or desirable to test in live networks. The cellular communication has been investigated on both 4G and 5G networks. Applications connected to the public internet or to a dedicated OEM server have been investigated.

4.4.1 WP3A: V2N use cases & Quality of Experience (QoE)

The analysis of the use cases has identified the significant non-functional requirements (NFRs) for end-user experience at level Bad, Acceptable and Good. These NFRs together with the use case descriptions are provided as input to Chapter 4.4.2.

A modern vehicle provide many types of services that is dependent on connectivity and digitalization drives continuous deployment of new services. Relevant sample services have been selected as use cases in SIVERT2 and the use cases that have a similar demand on E2E connectivity have been grouped into use case categories. The use case categories and corresponding use cases are described in Table 4-4.

Table 4-4, Connectivity related use-case categories.

Category	Description	Example Use-Cases
Best effort messaging	Small set of data or messages. Periodic or event based. No real-time constraints (best-effort).	Correction Services Positioning Services
Time-sensitive messaging	Small set of data or messages. Soft time constraints on the level of few seconds.	Lock/unlock Remote services
Best effort bulk	Large set of data is transferred in a best-effort manner. Can be in small or large chunks. No real-time constraints (best-effort). Can be divided into download and upload subcategories.	Download: OTA software update Map tiles download
		Upload: Probe data collection
Data streaming	Streaming of data (Mb/s) with medium time constrains.	Streaming video
Seamless real-time streaming	Streaming of data (Mb/s) with real-time constraints. No interruptions of the stream due to network structure or country borders.	Real-time situational awareness
Voice Call	Prioritized voice call or video call with real-time demands.	eCall/NGeCall

Quality of Experience (QoE) is used as a measure of how a user experiences a service. The QoE focuses on the entire service experience to understand overall human quality requirements. The QoE is influenced by so-called "influence factors" [*50*]. This includes categories of influence factors such as human, system and context influence factors, see Figure 4-95 for an overview of these influence factors. The analysis of the significant use cases focuses on system influence factors, due to the possibility of relating them to the Quality of Service (QoS) characteristics. Example of such system influence factors are:

- content-related
- device-related (vehicle range, screen resolution, display size, …)
- media-related (encoding, resolution, …),
- network-related (bandwidth, delay, jitter, …)

In this project, the analysis focuses especially on the network-related system influence factors, as illustrated in Figure 4-95.

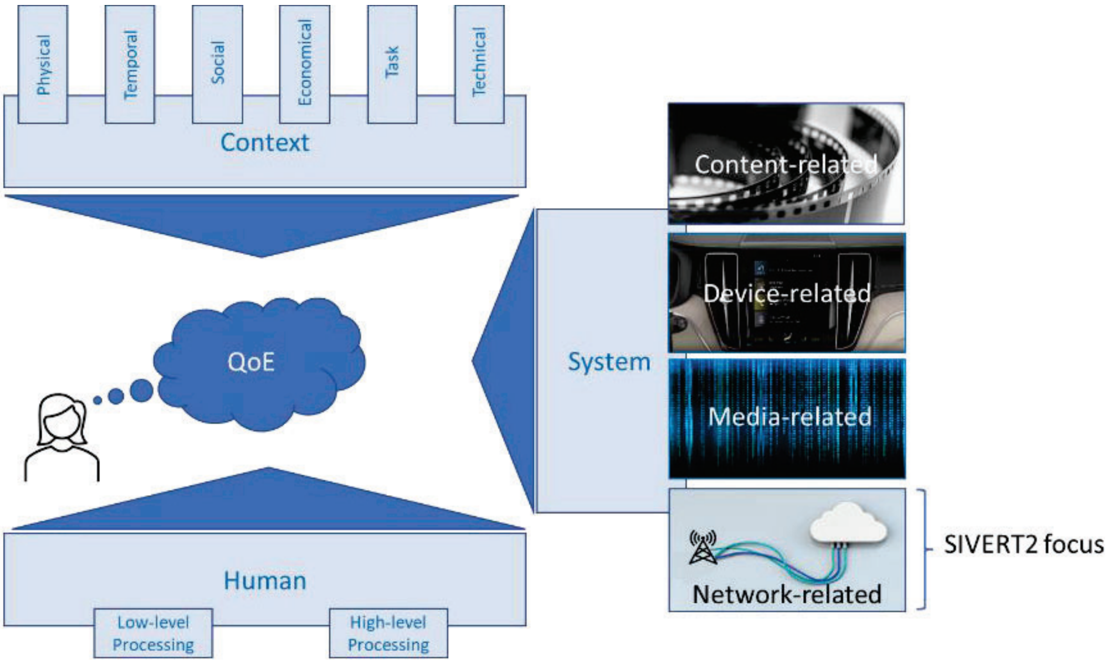


Figure 4-95, Influence factors on QoE.

QoS characteristics represent some aspect of a system, service or resource that can be identified and quantified. The QoS characteristics models the actual behaviour of the system that they represent rather than the observed behaviour. For example, the characteristics of the transit delay between two points is the actual time that occurs. The transit delay can never be known exactly, due to limitations in accuracy of measure and influence introduced by measuring, although it can be approximated by measurements. Further, QoS requirements can state that the transit delay must not exceed a specified value.

QoS requirements originate from the service user. It can be either conveyed dynamically to the service provider at initiation of the service as QoS parameters or provided statically. The entity that receives the QoS requirements analyse them and determine the QoS management function or mechanisms that are required to meet them.

QoS management refers to all the activities relating to the control and administration of QoS within a system, i.e. authentication of the request, admission control, establishment, monitor and control of the service. Admission control is a validation process where a check is performed to see if available resources are sufficient to guarantee satisfaction of an admitted request (service).

The QoS requirements are important when designing a system. Requirements for a system can be divided into Functional Requirements (FRs) and Non-Functional Requirements (NFRs). The FRs describes the behaviour of the system, while the NFRs describes the system characteristics. The NFRs can include requirements on characteristics for operating and maintaining a system by the service provider as well as the characteristics of the service(s) provided by the system to the service consumers. A summary of the QoS terminology is presented below, Table 4-5.

Table 4-5, Summary of QoS Terminology.

Term	Definition	Example
Functional Requirements	The desired system behaviour	System sends a message
Non-functional Requirements	The desired system characteristics	A response is sent within a certain time
QoS Characteristic	An aspect of a system, service or resource that can be identified and quantified	Transit delay, i.e. the elapsed time between a request to transmit a data packet and an indication at the receiving end that the corresponding packet has been received and is ready for further processing
QoS Requirement	Target for a QoS Characteristics	Transit delay must not exceed a specified value
KPI – Key Performance Indicator	Measurable metric used to convey the health, status, performance or usage of a system, a set of related components or a chain of related components	A metric giving the min, mean and max packet transit delay (for all or a class of packets) through the system.
SLI – Service Level Indicator	A derived measurable metric used as the base for evaluation of a service provided to users	A metric giving statistics like min, mean and max packet transit delay for a user or category of users
SLO – Service Level Objective	Target for SLI	Max packet transit delay must be below 50 milliseconds for 98% of the sample periods over a 30 day period
SLA – Service Level Agreement	Business Agreement between consumer and provider based on SLO	Packet delivery shall be fast (less than 50 milliseconds transit delay 98% of the time over a 30 day window)

While there are many connectivity use cases in the automotive sector, this analysis focuses on a deep dive into three key examples, OTA SWDL (Over the Air Software Download), RTSA (Real Time Situational Awareness) and GAS (Google Assistance Services). These use cases are covering different types of use case categories, as presented in Table 4-4.

4.4.1.1 Use Case – OTA SWDL

The OTA SWDL use case is a best effort data transfer use case. Our analysis is focused on the mobile connectivity part of the OTA software upgrade; the installation of the software is out of scope.

Description

Modern vehicles rely heavily on software and require regular updates to maintain and enhance their functionality. The software upgrade is necessary to add new features, improve existing features and correct bugs in existing software. OTA software upgrade is a use case for upgrading the software in a vehicle without the need to bring it into a support centre.

The use case covers the automatic software upgrades and focuses on the cellular OTA to the TCU and does not consider the distribution of the software to the different nodes in a vehicle. In Figure 4-96 the software deployment and notification flow are described.

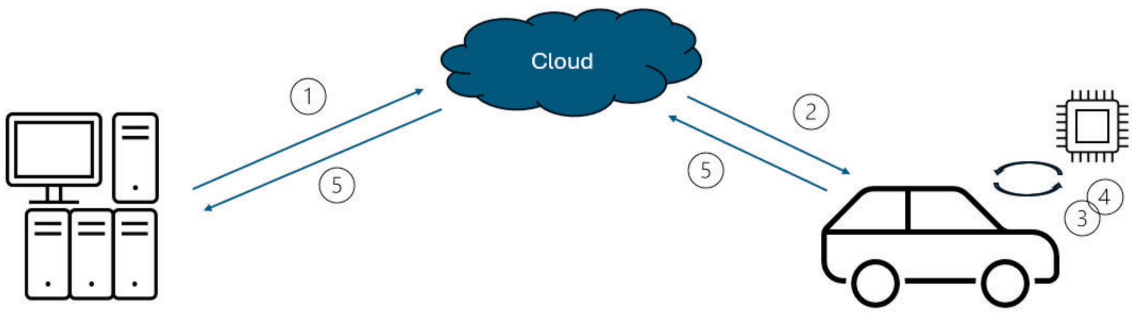


Figure 4-96,OTA SW deployment and notification flow.

1. The software provider makes the software available for download and selects what vehicles to update
2. The vehicle downloads the software upgrade package from the software provider
3. When SW is downloaded, the user is prompted to start the installation (Optional)
4. The vehicle changes the running software in the vehicle to the downloaded upgrade package
5. At completion of software change, the vehicle informs the software provider of the successful change.
   The alternative flows are not covered in this analysis.

QoE Demand

To be able to perform a successful OTA SWDL within the time of a drive cycle could be considered as a good user experience and within four drive cycles could be considered as Acceptable. Drive cycles are usually longer for a truck compared with a car which means that for a good user experience, the car needs a higher data rate than a truck if the SW-package is of equal size. The resulting QoE demands for the OTA SWDL use case is then according to Table 4-6

Table 4-6, QoE for OTA SWDL

End-user experience	Bad	Acceptable	Good
The software download is degrading the safety of the vehicle (Device-related, V2N => Network-related)	X		
The software download is degrading other services provided by the vehicle, such as infotainment services, navigation services and metering services. (Network-related)	X		
Perception of software download. Downloaded within four drive cycles (Network-related)		X	
Perception of software download. Downloaded within one drive cycle (Network-related)			X

Non-Functional Requirements (NFR)

A drive cycle for a passenger car is measured in minutes, while for a truck the typical drive cycle is much longer, measured in hours. Based on drive cycles the NFR has been approximated according to Table 4-7.

Table 4-7, Example calculation of NFR values for the use case OTA SWDL

Passenger Car, 1GB data 15 min drive cycle	**Bad**	**Acceptable**	**Good**
Network Throughput	<2 Mbps	2 -10 Mbps	>10 Mbps
Truck, 1GB data, 2 hours' drive cycle	**Bad**	**Acceptable**	**Good**
Network Throughput	<0,3 Mbps	0.3-1 Mbps	>1 Mbps

4.4.1.2 Use Case – Real Time Situation Awareness

The real-time situational awareness, used in autonomous driving, use case is part of the seamless real-time streaming and time-sensitive use-case category. It is a throughput-sensitive real-time video streaming Uplink use-case. This chapter provides the result of the analysis of the use case. This includes the subjective QoE demand of the actors in the use case and the relation to testable significant NFRs on connectivity level. The use case includes upload video streams from vehicle such as camera videos from the autonomous driving vehicle.

Description

Real-time situation awareness in autonomous driving works by using a combination of sensors, cameras, and communication technology to transmit data from the vehicle to a remote operator (Uplink). In normal operation the vehicle makes decisions and drives autonomously but is supervised by an operator who can monitor and control the vehicle in real-time.

The vehicle is equipped with various sensors and cameras that capture real-time data about the surrounding environment, including the road, other vehicles, pedestrians, and obstacles. This data is then transmitted, when needed, to the remote operator who can use it to make decisions about how to control the vehicle.

The remote operator is typically located in a control centre and uses specialized software and interfaces to monitor the vehicle and interact when needed. They can receive a video stream from the vehicle's cameras, along with other important information such as speed, direction, and vehicle status. The operator can then use this information to make decisions about how to navigate the vehicle through the environment or send new assignments. In the event of an unexpected stop during autonomous driving, the operator must be able to see a real-time video from the vehicle to obtain situational awareness.

In this use case, we will focus on the video uplink streaming part and the requirements of such a link. The QoE and NFRs will be defined for one video stream, i.e., one camera to one operator screen.

QoE demand

The analysis of the QoE demand focuses on the steps in the main flow that are related to the E2E connectivity, i.e., from the autonomous driving vehicle to the remote operator Figure 4-97.

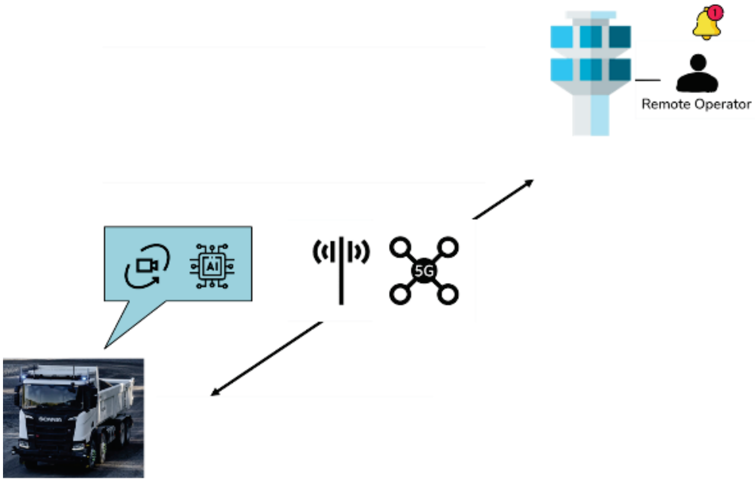


Figure 4-97, Example of Real-Time Situational Awareness used in autonomous driving. A vehicle uploads data to the control tower and a remote operator provides assistance.

The operator of the vehicle expects the video stream to have an acceptable frame rate and video quality, i.e., when the vehicle is in autonomous driving mode. The resulting end-user experience demands are then according to Table 4-8.

Table 4-8, QoE for RTSA use case

End-user experience	Bad	Acceptable	Good
The operator is not able to stream video, or video has too low frame rate, to bad video quality or the delay of video stream is too high. (Device related if vehicle having cellular coverage.)	X		
The operator is not able to stream video. (Network related if vehicle is out-of-coverage.)		X	
The operator can stream video with acceptable frame rate, video quality and delay.		X	
The operator can stream video with video high resolution, good frame rate and minor delay.			X

From an end customer point of view, three parameters are important. The video resolution, frame rate and real-time experience. The video resolution and frame rate depend on uplink throughput limitation (System Uplink Bandwidth). The real-time experience depends on the latency value. The latency is the time the video stream takes from vehicle camera to the video stream is shown on the control centre screen.

The throughput is the amount of data moved successfully from the vehicle camera to the control centre screen in a given time period. In Figure 4-98 a visualisation of the E2E latency and data flow of the use case is presented.

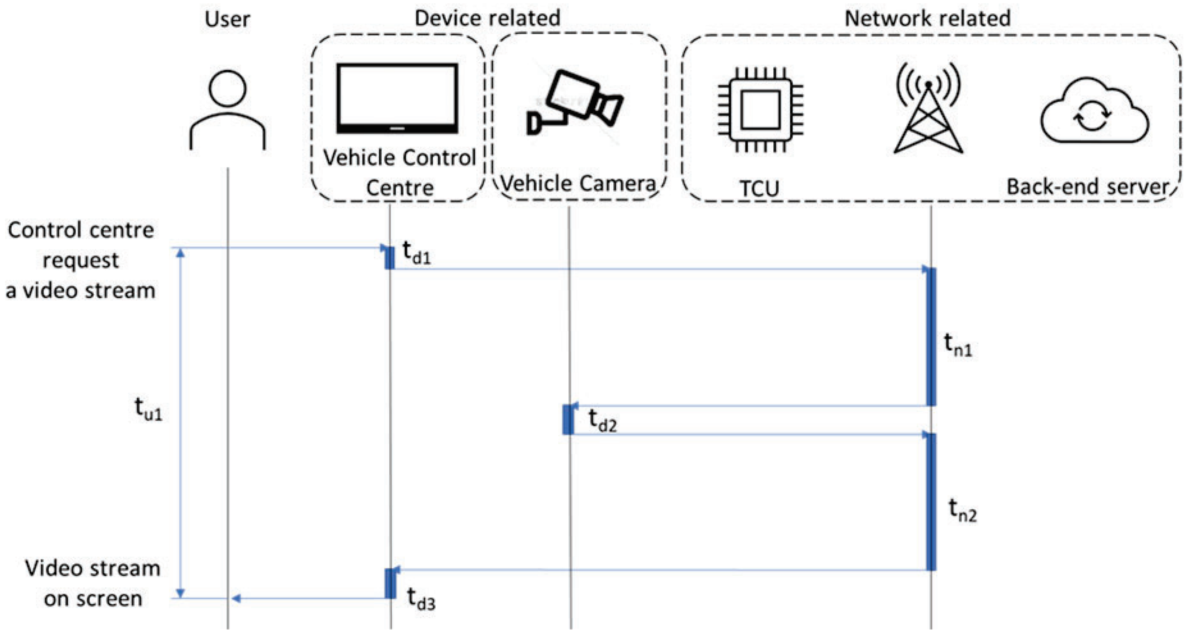


Figure 4-98, E2E latency and dataflow analysis of Real-Time Situational Awareness.

Non-Functional Requirements (NFR)

NFRs are important in the Real Time Situation Awareness cases, to set a firm and measurable limit on the major influence factors evaluated in the real time dependent Quality of Service (QoS). The most important influence factors are the network throughput capacity and latency. Throughput limits both the resolution and the frame rate of a video. Insufficient throughput will also impact latency and trigger other influence factors like jitter and packet loss (mainly at connection drop). Latency is an influence factor which is continuously increasing through the packet transport chain from the video creation in the vehicle to the evaluation in the Vehicle Control Center.

Table 4-9 shows one example of NFRs on throughput and latency related to an acceptable or good QoE, with references to t_{n1} and t_{n2} shown in Figure 4-98. The data is an approximation based on the information in [*51*].

Table 4-9, Example of NFR values for a RTSA use case

KPI	Acceptable	Good
Network throughput	> 3 Mbps	> 5 Mbps
Network latency	$t_{n1} + t_{n2} < 300$ ms	$t_{n1} + t_{n2} \leq 150$ ms

Use Case – Google Assistant Service

The remote Google Assistant use case is a part of the time-sensitive messaging use case category, see Table 4-4 for the use case categories. This chapter provides the results of the analysis of the use case. This includes the subjective QoE demand of the actors in the use case and the relation to testable significant NFRs on connectivity level.

Description

The Google Assistant use case involves voice-controlled assistance within a vehicle, enabling users to access navigation, operate the infotainment system, and perform other tasks simply by saying "Hey Google." Figure 4-99 illustrates the integration of Google Assistant in a passenger car.

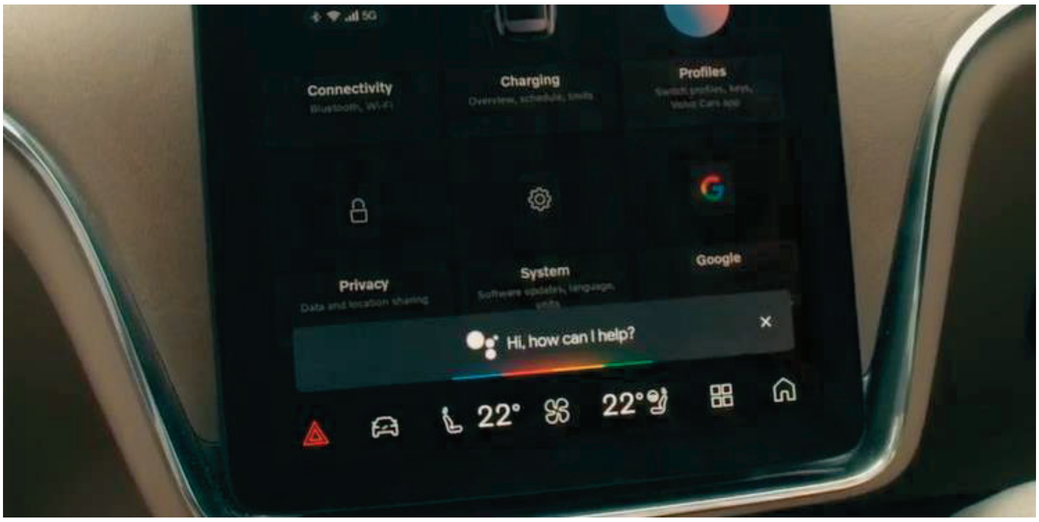


Figure 4-99, The integrated Google Assistant in a passenger car.

QoE demand

The analysis of the QoE demand focuses on the steps in the main flow that are related to the E2E connectivity, i.e., from the customer ask/give Google a question/command until Google gives an answer, or the vehicle have reacted to the command. In Table 4-10, the identified end user experience demands are listed.

Table 4-10, QoE for GAS use case

End-user experience	Bad	Acceptable	Good
The vehicle user is not able to use the Google assistant. (Device related if vehicle having cellular connection.)	X		
The vehicle user is not able to use the Google assistant. (Network related if vehicle is out-of-coverage.)		X	
The car user to get a response, tu1, by the Google Assistant within X s.		X	
The car user to get a response, tu1, by the Google Assistant within Y s.			X

As seen in the table, from an end customer point of view, the latency time (t_{u1}) it takes from asking Google Assistant a question/an action until you get a response, is important and in Figure 4-100 response time is described.

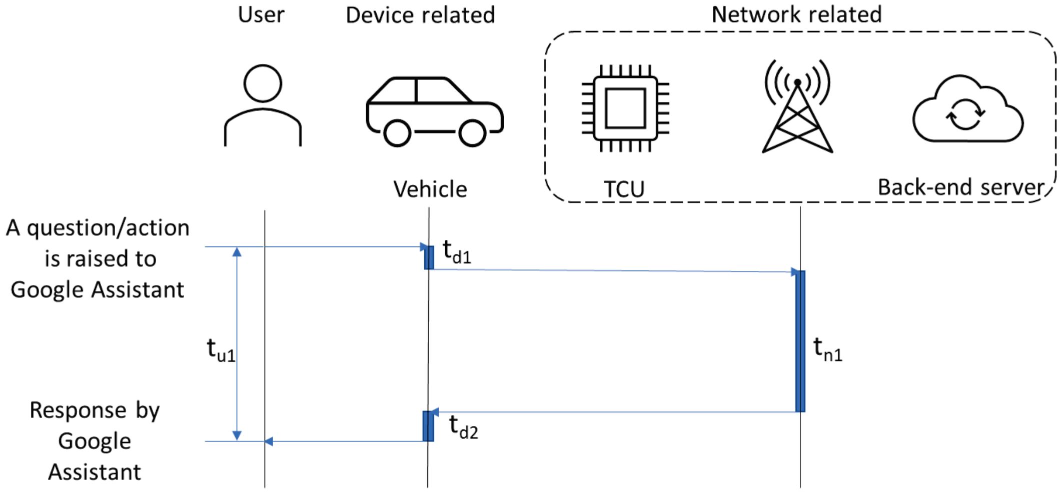


Figure 4-100, E2E analysis of Google assistant.

The analysis of the QoE demand for this use case has resulted in identification of NFRs for Network Latency and Network throughput, latency being the key parameter.

Non-Functional Requirements

The analysis of the QoE has given limits in time, assuming the same question/action gives the same processing time (t_{d1} + t_{d2} + t_{n1}) the response time requirement is used as NFR.

4.4.2 WP3B: Network Behaviour

The network behaviour affects the QoS characteristics of the connectivity service used by the vehicle. In this deliverable, the following categories of network scenarios have been analysed regarding the effect on the connectivity service:

- Border crossing
- Network overload
- Poor coverage
- Network outage
- Network configuration faults
- Blocked service

Three use cases defined in Chapter 4.4.1 have been further investigated: OTA Software Update, Real-time Situation Awareness and Google Assistant.

The use cases are tested under different conditions, defined as test scenarios. These test scenarios are defined in this deliverable, and they realize conditions according to one or more of the analysed network scenarios, mentioned above. These test scenarios are grouped into:

- Static test scenarios for testing under static conditions,
- Semi-static test scenarios with varying conditions of a characteristic over time
- Dynamic test scenarios with varying conditions of multiple characteristics over time.

The characteristics of the connectivity service is affected by many varying factors. If these factors influence the characteristics to deviate from the expected targets, the resulting condition would be regarded as a network anomaly.

The communication service providers have means to observe the internals of their part of the network. The E2E communication service may depend on multiple subnetworks. It is the responsibility of each communication service provider to ensure the quality of their system. The E2E communication service used by the vehicle is dependent on multiple stakeholders. Detecting the cause of the anomaly in the E2E characteristics may be difficult, but the symptom of the anomaly is possible to observe. This section provides a model of the connectivity service providing an understanding of factors that can influence the E2E characteristics, examples of KPIs and methods for collecting metrics of the E2E characteristics, possible symptoms that can be detected and list of categories for the analysis of network scenarios that are described in following sections.

The network in the V2N connectivity service is modelled as a bit-pipe with one or more flows. Each flow has an endpoint in the vehicle and another remote endpoint, see Figure 4-101.

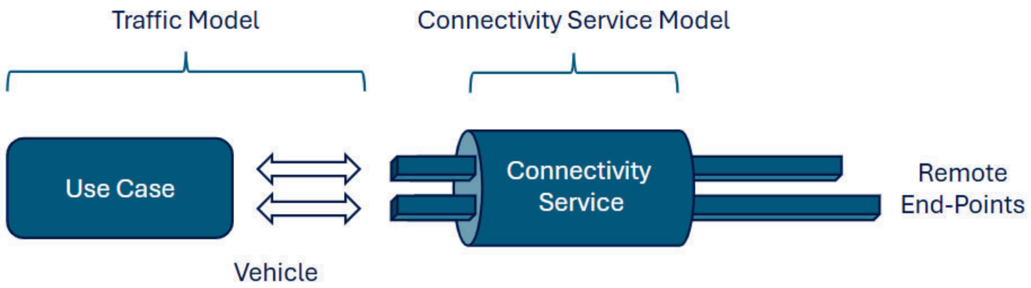


Figure 4-101, Connectivity service model

The different flows may terminate in different remote endpoints, for example one endpoint in a Business-to-Business (B2B) backend server and another endpoint in a Business-to-Consumer (B2C) internet server. A flow has its E2E characteristics that depend on multiple factors. It can be seen as a chain of links where each link influences the E2E characteristics.

The analysis of a connectivity service model spans over multiple nodes and links such as the air interface (Link A1 in Figure 4-102), radio access network (e.g. gNB, eNB), back-haul (Link B1 in Figure 4-102), Core Network (e.g. SGW, PGW, UPF), operators connection to Packet Network (Internet Exchange Points or directly to Internet. Link C1 in Figure 4-102) and the service back-ends connection to the Packet Network (Link D1 in Figure 4-102).

Network Throughput (or *packet rate*) describes how many packets are transmitted through the flow during a period of time. It is limited by the minimum packet rate in all the links of the E2E chain, as illustrated in Figure 4-102.

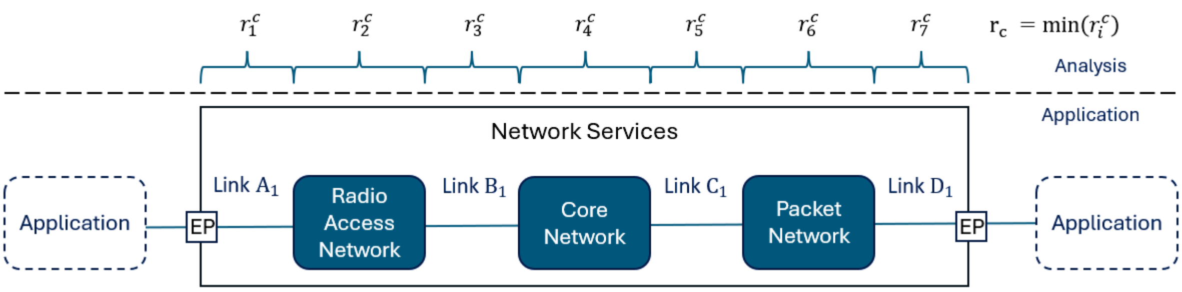


Figure 4-102, Forwarding Graf for Network Throughput

The packet drop rate describes the ratio of the sent packets that are dropped. It is the sum of the packet loss rate in all the links of the E2E chain, as illustrated in Figure 4-103. The Packet Delivery rate can be derived from the packet drop rate.

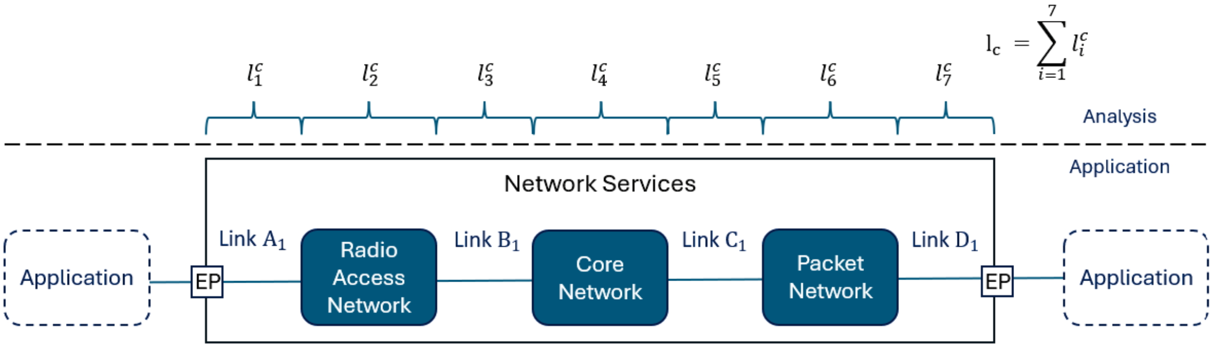


Figure 4-103, Forwarding Graf for Packet Drop Rate

The network latency describes how long time it takes for a packet to travel from one endpoint to the other endpoint. The packet delay is usually provided as the mean delay. The actual latency in a network is a distribution between a minimum and a maximum latency. This can be expressed as a (min, mean, max) tuple or simplified as a normal distribution with a mean value and with a standard deviation.

In the network, the latency may depend on the load on the network. The mean network latency can be calculated as the sum of the mean network latency in all the links of the E2E chain. In case it is a normal distribution, and the standard deviation is available, the E2E variance can be calculated as the sum of variance in all the links, i.e. the variance is the square of the standard deviation. See Figure 4-104.

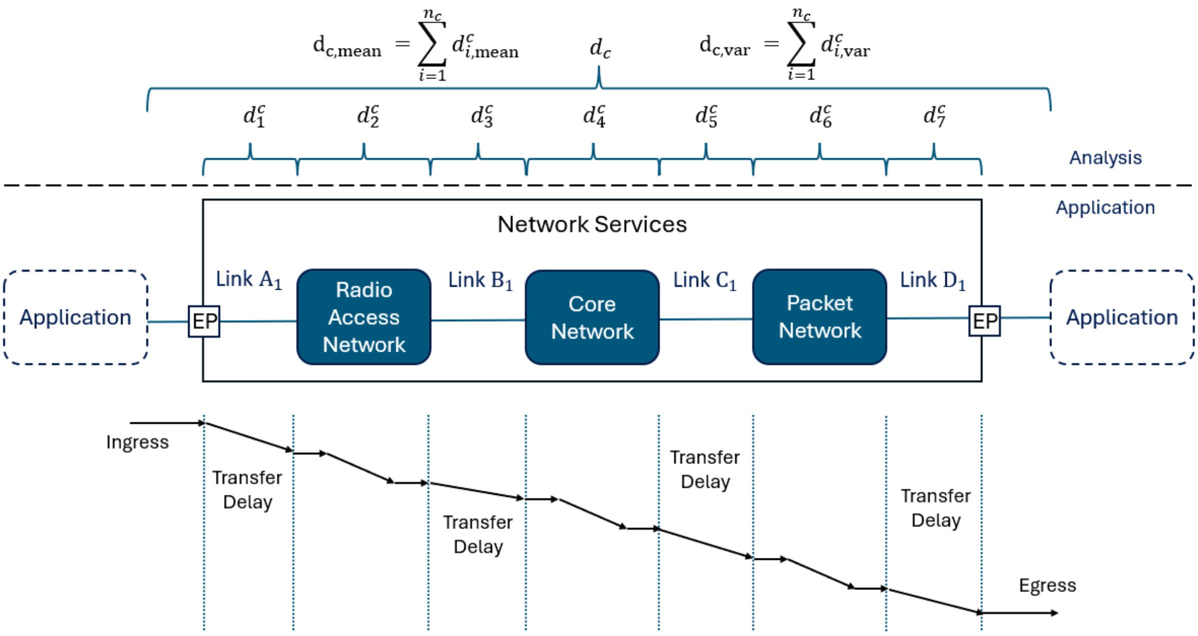


Figure 4-104, Forwarding Graph for Network Latency

The conclusion from the network behaviour evaluation is that a connectivity service is modelled as different flows that may have different characteristics. The characteristics vary over time due to that:

- Flows with different QoS requirements can be prioritized differently in the networks when competing for resources shared with other flows,
- Different flows may have different paths through the network (different forwarding graphs) and could thereby have different limitations in the characteristics of the links of their respectively forwarding graph.
- The forwarding path can change over time, due to load balancing or failures of links
- The characteristics of a link may vary due to physical conditions, i.e. the radio conditions of the air interface.

Network anomalies in a network can be observed through symptoms such as:

- Extensive signalling on the control-plane between UE and network
- High latency
- High packet loss / out of sequence
- Different network reject responses
- Data contexts/sessions with degraded or no throughput

The terminology presented in the chapter is defined in Table 4-11.

Table 4-11, Terminology for the Network Behaviour and testing method

Term	Definition	Example
Connectivity NFR	See QoS requirements.	Throughout, packet latency
Device related	The factors or components related to presentation of a service used by a service consumer.	Components: Application and its runtime environment. Factors: Display size, screen resolution, vehicle range…
Network anomaly	Network behaviour which differs from ideal / normal QoS characteristics. An anomaly is a degradation in QoS characteristics. A network anomaly is considered to be the opposite of typical network behaviour.	Delayed response, reduced throughput.
Network behaviour	The behaviour of the network seen from the perspective of a single vehicle. It is not describing the complete behaviour of a networking serving massive number of vehicles seen from the network perspective.	A vehicle moving from point X to point Y experience good characteristics followed by degraded characteristics followed by change of radio technology.
Network related	The factors or components related to the transport of a service between the device of the service consumer and the service provider.	Components: TCU, mobile network, and back-end server Factors: See QoS characteristics.

Network scenario	Network behaviour from a vehicle is complex and influenced by many combined factors that may be difficult to formalize. A scenario is describing one sequence of events and the corresponding network behaviour. Multiple network scenarios within a similar situation are grouped into a network scenario category. See Network scenario category.	Border crossing with a sequence of events, including change of radio conditions and change of radio access technology (4G/5G and 2G coverage).
Network scenario category	Multiple network scenarios within a similar situation.	Border crossing has e.g. four different network behaviours for the same sequence of events. These four scenarios differ depending on how the network has been realized.
System	A set of related components or a chain of related components that interacts to form a unified whole.	The complete system of a connected vehicle consists of content, device, media and network related parts. These can be seen as separate subsystems. The network subsystem can be divided into further subsystems, i.e., a TCU, mobile network and back-end. We have a system of systems.
Test case realization	Realization of a test case specification in a specific test setup. There may be different test case realizations for different test setups (unless an abstraction layer is used).	Test case scripts for test setup 2.
Test case specification	Specification of input parameters and expected results for testing one perspective of a use case or set of parallel/interacting use cases	Evaluation of QoE during a border crossing scenario (generic for all test setups)
Test scenario	Network scenario reproduced in lab environment. The test scenario focuses on the symptoms of the network behaviour, i.e., the resulting characteristics during a sequence of events.	Representation/Realization of a border crossing network scenario.
Test setup	A setup including test environment and system under test (SUT) capable of reproducing a test scenario. Realized with a combination of network simulation HW and/or SW, TCU (if applicable), and test tools. May include actual use case application or a simulated use case application / device.	Standalone TCU + network simulator

4.4.2.1 Test Scenarios

In a vehicle, there are some situations that are more likely to cause network anomalies. The network behaviour is structured into category of network scenarios, which are likely root causes for the observed symptoms. Some network scenarios are listed below. The term Test Scenario is defined in Table 4-11.

Border crossing

A PLMN (Public Land Mobile Network) is associated to a country. Crossing a border from one country to another country means that the vehicle at some point need to change to a new PLMN. The border crossing scenario of a connected vehicle consists of two phases. In the first phase the UE of the vehicle is connected to the originating PLMN. In the second phase the UE connects to the destination PLMN, i.e. roaming from one operator in one country to another operator in another country.

Public network border crossing is a complex scenario where typically several cells of different RATs from different PLMNs in each country are visible for the UE. Each operator having specific cell configurations for signal level thresholds, priorities etc., and its own Mobility Management logic based on measurement reports received from the UEs, and other internal business logic. The Mobility Management logic controls which cell the UE is connected to in connected mode. In idle mode, the cell selection logic in the UE controls which cell and RAT the UE is camping on within the frames defined by the PLMN selection logic.

Network overload

Service characteristics may be degraded, or services may get rejected from the network due to limited network capacity in a geographical area. The area depends on the bottleneck causing the overload and can range from affecting a single cell, a group of cells, a tracking area or in the worst case affecting the whole network of an operator.

Simplified, the capacity of the network is not matching the demand. This could be due to that the capacity is not dimensioned for the specific demand, the demand could be higher than normal, or it could be due to a failure resulting in lower capacity.

The network overload can be both on the control-plane and the user-plane. The capacity limitations could be related to control-plane bandwidth (signalling overload), control-plane capacity (number of UEs, sessions, bearers, flows), user-plane characteristics (throughput).

The capacity limitation on the user-plane could affect all the flows of the vehicle or individual flows. A flow can be a best-effort flow or a flow with guaranteed bitrate. Flows can also have different priorities, which results in that certain flows can be prioritized before other flows. The prioritising is affecting how much a flow is degraded at network overload. For example, a high priority flow may have good characteristics in an overloaded scenario, while the best-effort low priority flow has bad characteristics resulting in congestions and possibly dropped packets.

Poor Coverage

Coverage refers to the area where a vehicle can obtain network access. If there is no coverage, then there is no connectivity for the vehicle. Poor coverage refers to that the signal is strong enough for the device to obtain network access, but the characteristics is poor due to low signal strength and/or signal quality. This can be due to the distance to the base station(s) as well as interference from other transmitters on the same frequency and time slot. Simplified, this occurs at the edge of cells. Two common reasons for poor coverage are distance to a cell tower and being in a radio shadow (due to buildings, natural obstacles etc).

Network configurations faults

When moving between many different roaming operators, it may happen that certain operators network nodes does not have optimal or even a faulty configuration which may have serious impact on the connectivity. Examples of configuration faults are:

- Incompatible QCI values and priorities
- IP routes (IPv4 or IPv6) not correctly configured.
- IPX routes or DNS for IPX network not properly configured.

4.4.2.2 Test Cases

Several test cases have been investigated during the project; the three main ones are presented in more detail below. The term Test Case is defined in Table 4-11.

OTA SWDL

The intention with this test case is to validate the defined test setups by executing one or more SW file download from a file server to a TCU to emulate a real OTA SW download procedure. This test case will focus on the actual download and not include verification of the succeeding ECU SW upgrade procedures in the vehicle. As described in Figure 4-102 the throughput of the E2E bandwidth is limited by the link with the lowest bandwidth.

Real Time Situational Awareness

The intention with this test case is to validate the defined test setups by executing a video stream from a Dashcam (in a vehicle) via the TCU, to an external server (in a control center) to emulate a Real-Time Situation Awareness procedure. This test case will focus on the actual upload of a video stream but not include verification of the succeeding procedures in the control tower. Figure 4-105 illustrates the use-case with a video stream starting at a vehicle dashcam and forwarded to a control center. Delays should continuously be added through the flow since it is expected to be the most crucial KPI.

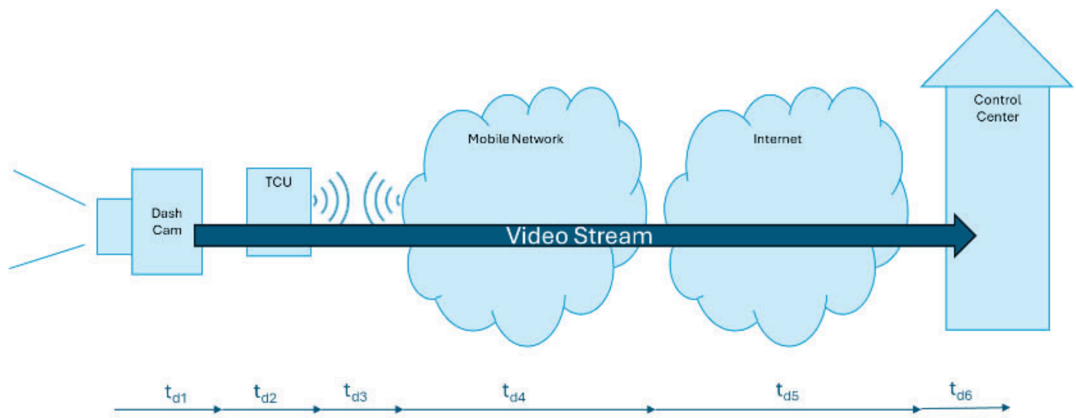


Figure 4-105, The real time situation awareness use case.

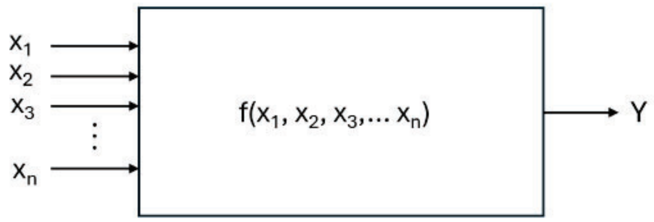
Google Assistant Services

The intention with this test case is to validate the defined test setups by executing a command to the Google Assistant in a vehicle or HIL and measure the response time. The command used in the use case is "What time is it?" (the process is described in Figure 4-112). This test case focuses on response time, assuming a constant request processing time, as the complexity of the request remains unchanged across all tests.

4.4.2.3 Network influence factor analysis

This section introduces a model developed in SIVERT2 WP3 for how different network related factors are influencing the perceived QoE of a Use Case and a method to identify such a model. The concept of "influence factors" was introduced in Chapter 4.4.1.

This is one method to model how different network related influence factors are affecting the perceived QoE of a Use Case (Mean Opinion Score), i.e. an application model with influence factors as input and QoE as output, as seen in Figure 4-106.



Rating	SIVERT2 MOS Label
5	Good (G)
3	Accepted (A)
1	Bad (B)

Figure 4-106, Application Model

The vector (x_1, x_2, x_3, … x_n) are the factors that influence the QoE Y of a specific use-case. The function $f(x_1, x_2, x_3, \ldots x_n)$ describes the relationship between the factors and the result Y.

Example of network influence factors are QoS characteristics such as throughput, packet drop, latency and jitter. See the QoS Model defined in Chapter 4.4.1 for more details. Note that influence factors may be related to different flows or services provided by the network terminating at different endpoints, e.g. DNS service.

The analysis of how various Network Influence Factors (NIFs) affect Quality of Experience (QoE) in each use case was conducted using a stepwise approach. This involved either employing different test setups to control specific NIFs or introducing new use cases.

The purpose of this work in WP3 has been to describe and evaluate a method for NIF analysis that is documented in this report. The main steps in the procedure are shown in Figure 4-107. Multiple iterations of one or several steps are expected depending on the results and conclusions from other steps in the procedure.

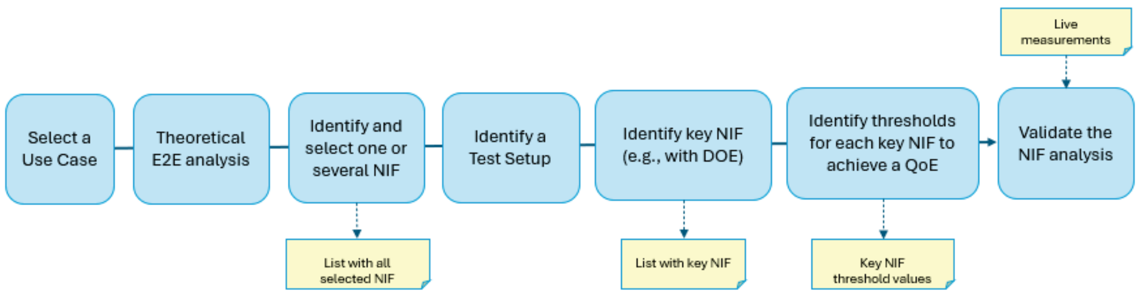


Figure 4-107, NIF Analysis Procedure with main output and input artifacts

To make the testing and analysis efficient the Design of Experiment (DoE) methodology has been used. DoE is a systematic and efficient methodology for investigating the relationship between input variables and process or product outputs, to read more about DoE [*52*].

Use Case: OTA SWDL

The QoE that has been measured for the OTA SWDL use case is the "perception of software download", which is the time required to download a software package to the car from a cloud via a cellular network as shown in Figure 4-108. The QoE has been stated as Good if the OTA SWDL is finalized within one drive cycle.

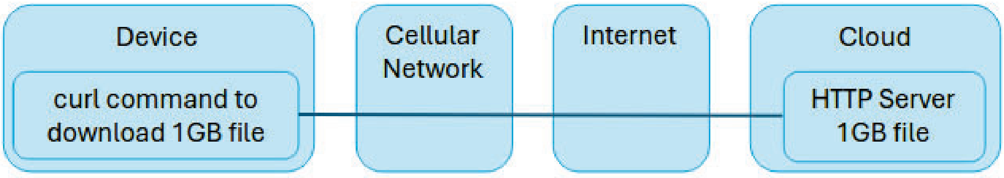


Figure 4-108, OTA SWDL Test Case

An E2E analysis of all nodes and connections that are involved in the OTA SWDL use case can result in many different variants and they can have very different levels of granularity. The number of influence factors is basically unlimited.

Because of this huge number of possible E2E variants, the first important decision to make in the NIF E2E analysis is which of these variants to use and which NIF to select for further analysis.

For this report, the first selected level of breakdown of the E2E path for OTA SWDL use case is shown in Figure 4-109. It shows the E2E path with the identified network nodes and the major protocols involved to achieve Internet connectivity for download via HTTP in a roaming 4G network. See [*53*] for further descriptions of 4G roaming architectures. The software package to download is provided by a HTTP server located in a cloud host.

In the E2E path diagram in Figure 4-109, there are two variants of interest identified with different granularity. The first variant is to replace all the nodes handling the IP packets with one single node representing their accumulated impact on the IP level behaviour as shown in Figure 4-110.

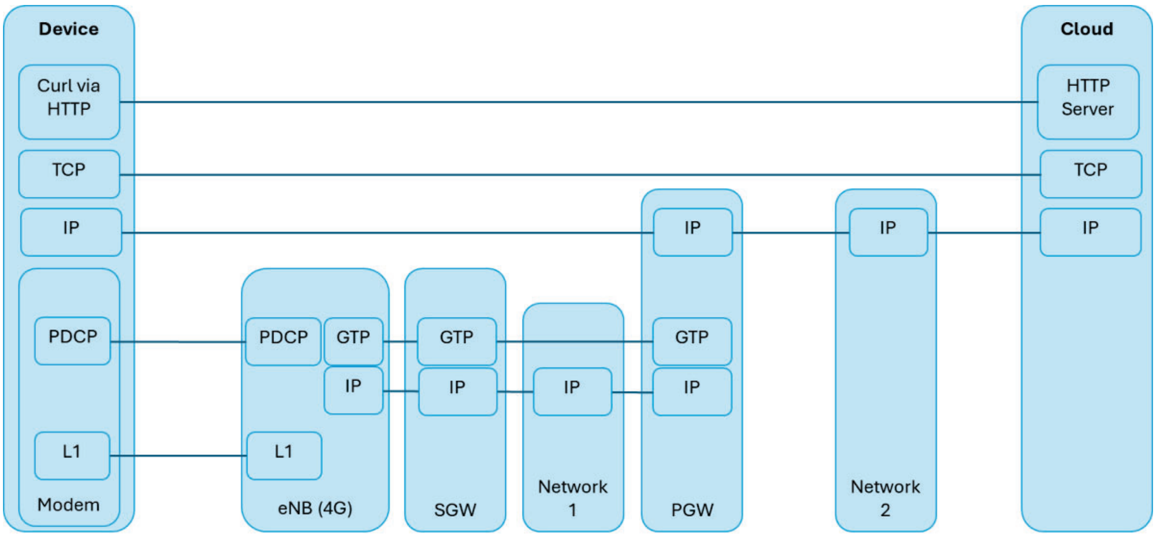


Figure 4-109, E2E path with major network nodes and protocols for the OTA SWDL Use Case in case of 4G roaming with home routed traffic

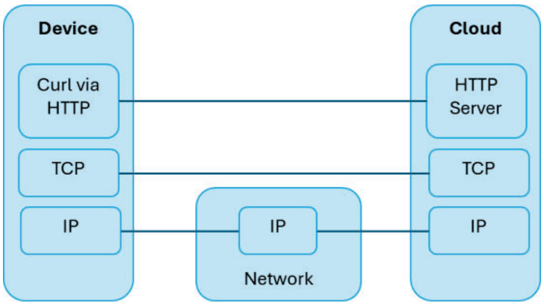


Figure 4-110, E2E path with all the nodes handling the IP packets replaced with one single network node

The second variant is to replace all the nodes in the 4G Radio Access Network (RAN) and Core Network (CN) with one single node representing the complete roaming 4G mobile network, see Figure 4-111. This variant also results in a simplification of the required test setup as well as on the number of NIFs to consider compared with the initial E2E path.

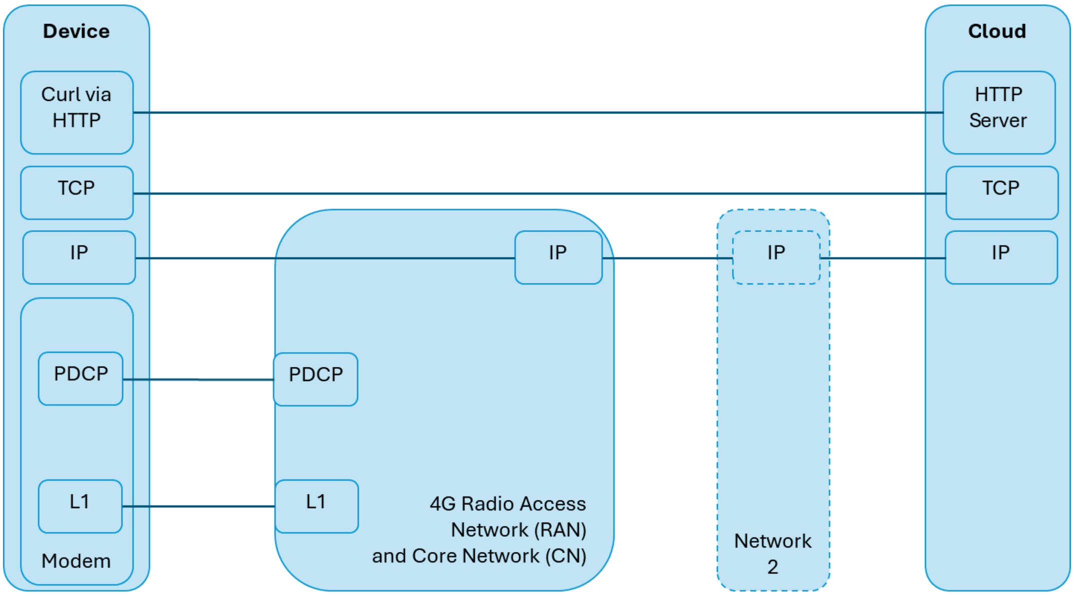


Figure 4-111, E2E flow with all 4G RAN and CN nodes replaced with one single mobile network node

The E2E path in Figure 4-111 has an optional “Network 2” that is indicated with dashed lines. It can be used to represent all the packet networks and corresponding NIF between the roaming mobile network and the cloud. If “Network 2” is excluded, it means that all the networks between the roaming mobile network and the cloud are considered to not have any impact on the resulting QoE and consequently no NIF for this part of the E2E path are then considered.

There are, as mentioned, almost unlimited E2E paths, but for the current case, it was decided to only use the first two paths in the NIF analysis as the main purpose has been to evaluate the method, not to perform a complete and fully accurate use case NIF analysis.

The summary of the above E2E path analysis is that three E2E paths were identified, to use in the NIF analysis for OTA SWDL in a single passenger car:

- E2E path 1: All the nodes handling IP packets are replaced with one single network node
- E2E path 2: All 4G RAN and CN nodes replaced with one single mobile network node and Network 2 is not present

- E2E path 3: All 4G RAN and CN nodes replaced with one single mobile network node and Network 2 is present

When the E2E paths have been defined, the identification and selection of NIF for each path is performed. It then also must be investigated if each NIF can be controlled using any of the available test setups.

Following the definition of the E2E paths, the next step involved identifying and selecting relevant NIFs for each path. The selection was based on engineering judgment, and due to time constraints, only two E2E paths were analysed in detail.

- E2E path 1: All the nodes handling IP packets are replaced with one single network node:
    - Downlink IP Packet Rate (bps)
    - Uplink IP Packet Rate (bps)
    - Downlink IP Packet Delay (ms)
    - Uplink IP Packet Delay (ms)
    - Downlink IP Packet Loss (%)
    - Uplink IP Packet Loss (%)
    - HTTP Server Response time (ms)
    - HTTP Server Data Rate (bps)
- E2E path 2: All 4G RAN and CN nodes replaced with one single mobile network node and Network 2 is not present
    - DL channel bandwidth
    - Signal power
    - Signal to noise ratio
    - Modulation

For E2E Path 1, DOE testing using the TCS test setup (described in Chapter 4.4.3) revealed that Downlink IP Packet Loss has the most significant impact on QoE for the OTA Software Download (SWDL) use case. Additionally, Downlink IP Packet Rate, as well as Downlink and Uplink IP Packet Delay, were found to have a notable influence.

For E2E Path 2 with a CMX500 test setup (described in Chapter 4.4.3), the most influential parameter was DL Channel Bandwidth, followed by Signal-to-Noise Ratio. In contrast, Signal Power and the Modulation and Coding Scheme Table did not show a significant impact on user experience in this use case.

Use Case: GAS

The google assistant use case has been analysed and broken down in the flow-chart in Figure 4-112. The flow-chart depicts the use case of asking the GAS service what time it is. The response time from when the question is asked until a response is received is collected.

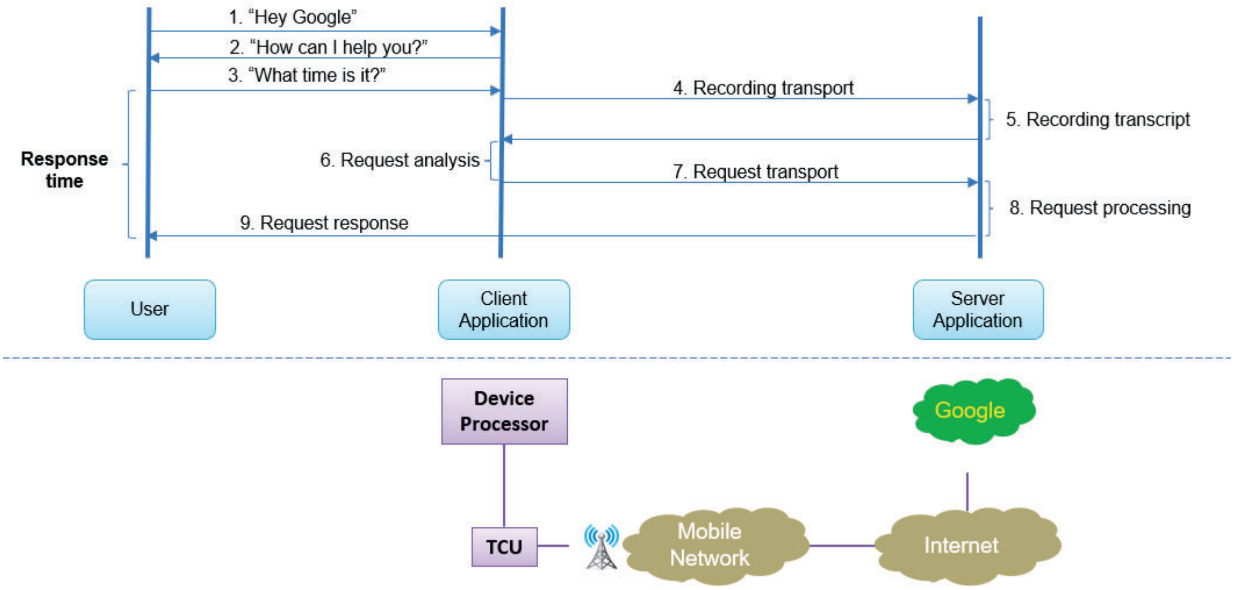


Figure 4-112, Outline of the Google Assistant Test Case

Like the OTA SWDL use case, the NIF analysis for GAS covers the "single passenger car" scenario and focuses on the network-related aspects. Device-related influence factors are not included in this analysis. The QoE for GAS is measured by the responsiveness and accuracy of voice commands processed via a cellular network, as shown in Figure 4-113.

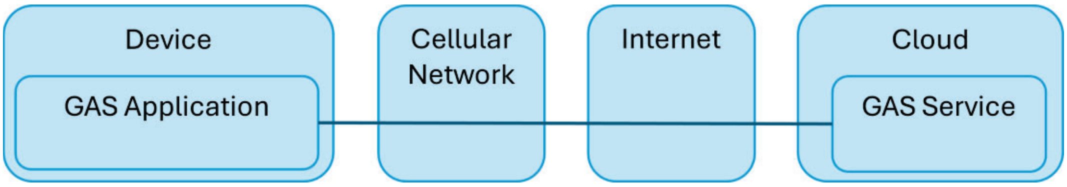


Figure 4-113, GAS Test Case

Given the complexity of potential E2E variants, the first crucial decision in the NIF E2E analysis is selecting which variants to use and which NIFs to analyse further.

For this report, the selected level of breakdown of the E2E path for GAS is shown in Figure 4-114. It depicts a typical scenario with key nodes and protocols involved for a vehicle to access GAS via 4G roaming.

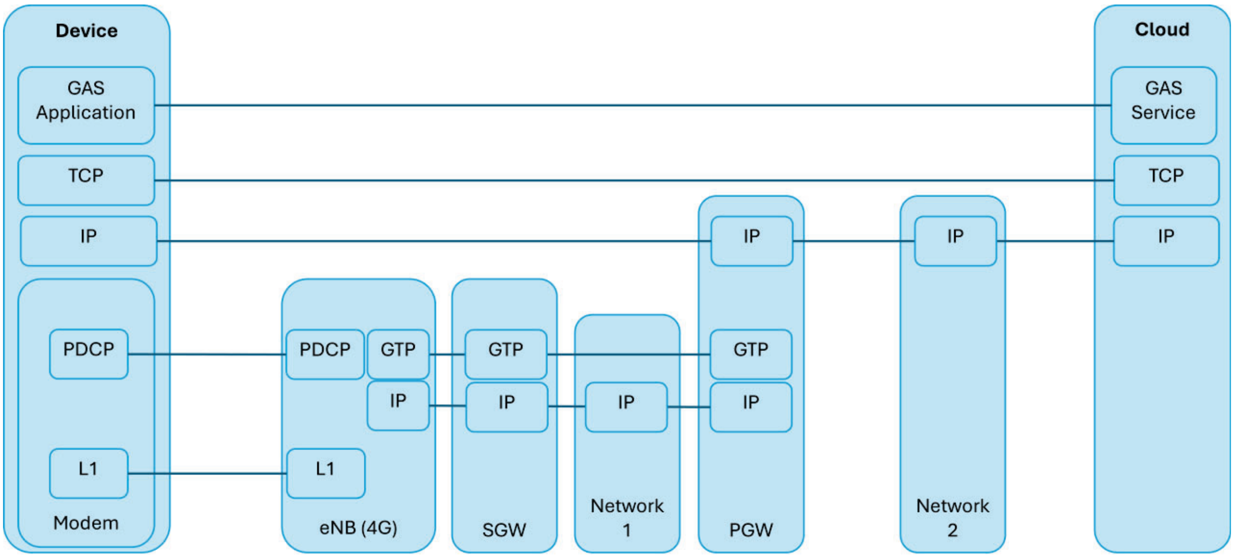


Figure 4-114, E2E flow with major network nodes and protocols for the GAS Use Case in case of 4G roaming with home routed traffic

From the initial E2E flow diagram in Figure 4-114, two E2E variants of interest have been identified, like the OTA SWDL use case, with different granularity levels.

The first variant replaces all nodes handling IP packets with a single node representing their cumulative impact on IP-level behaviour, as shown in Figure 4-115. This variant simplifies the test setup and reduces the number of NIFs to consider.

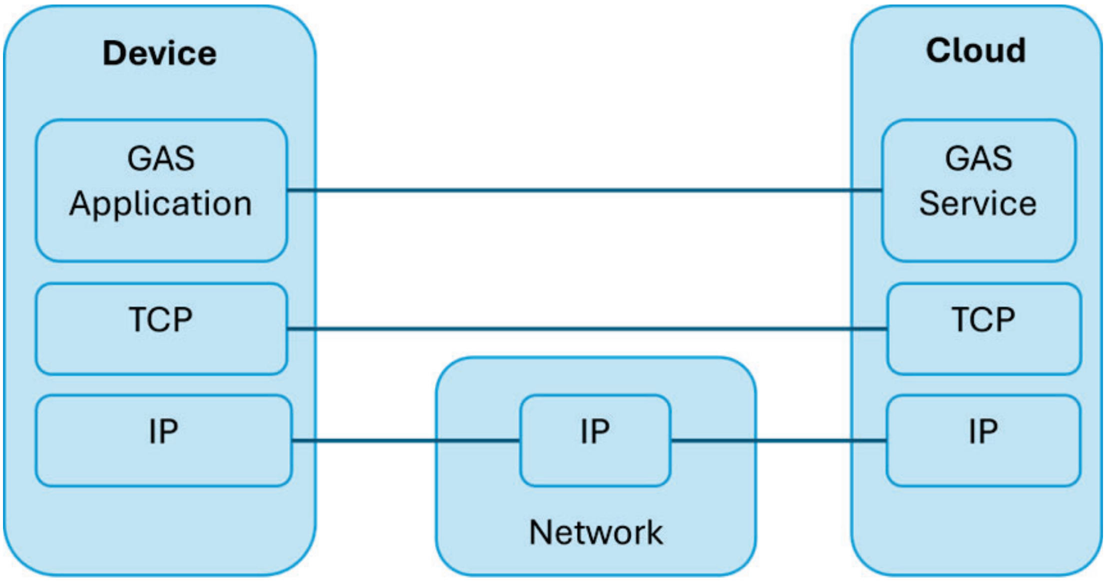


Figure 4-115, E2E variant for the GAS use case with all the nodes handling the IP packets replaced with one single network node

The second variant replaces nodes in the 4G Radio Access Network (RAN) and Core Network (CN) with a single node representing the complete roaming 4G mobile network, as shown in Figure 4-116. This variant also simplifies the test setup and reduces the number of NIFs compared to the initial E2E flow in Figure 4-116.

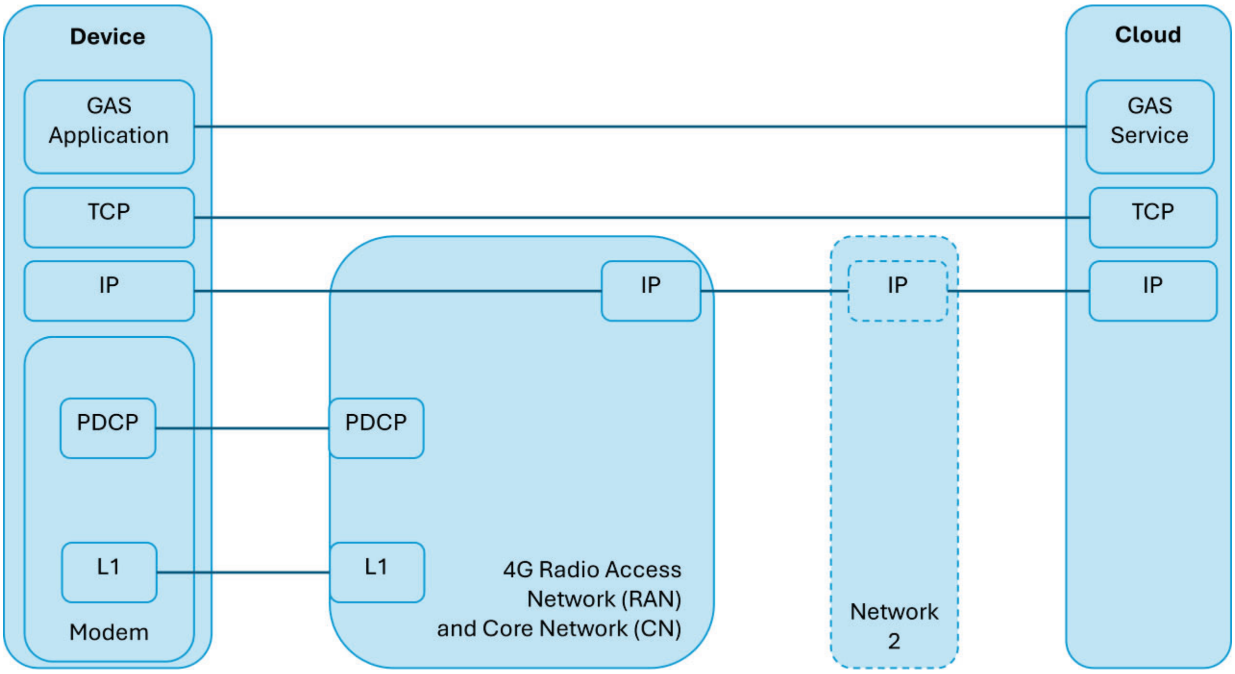


Figure 4-116, E2E variant for the GAS use case with all 4G RAN and CN nodes replaced with one single mobile network node.

The E2E variant in Figure 4-116 includes an optional "Network 2" indicated with dashed lines, representing all packet networks and corresponding NIFs between the roaming mobile network and the cloud. If "Network 2" is excluded, it implies that these networks do not impact the resulting QoE, and no NIFs for this part of the E2E path are considered.

As with the OTA SWDL use case, the analysis identifies three E2E paths:

- E2E path 1: All the nodes handling IP packets are replaced with one single network node.
- E2E path 2: All 4G RAN and CN nodes replaced with one single mobile network node and Network 2 is not present.
- E2E path 3: All 4G RAN and CN nodes replaced with one single mobile network node and Network 2 is present.

After defining the E2E paths, the next step was to identify and select relevant NIFs for each path. For the GAS use case, signal strength was chosen as the sole NIF for further analysis. The experiment was repeated several times, and the results consistently showed that QoE does not decline gradually as signal strength decreases. Instead, there is a sudden drop in QoE at a certain point, which varied between test runs. This variation suggests that other factors, such as environmental conditions or hardware differences, may be affecting the outcome.

Due to the observed inconsistency, it’s not possible to reliably associate specific signal strength levels with a predictable QoE for the GAS use case. Additionally, there is no live public network data available for comparison. These findings highlight the complexity of the relationship between radio conditions and user experience and point to the need for further investigation and targeted data collection in real-world environments.

According to the defined NIF analysis method, a follow-up analysis should have been conducted to explore other network influence factors. However, this was outside the scope of the current project.

Network Influence Factor Analysis Conclusions

The iterative NIF analysis procedure, as outlined in Figure 4-107 and applied in two different use cases, demonstrates its value as a tool for identifying influence factors that significantly affect the resulting

QoE. By pinpointing the most impactful NIFs in advance, it can reduce both the effort and scope required for live measurements. Additionally, the method enables the determination of NIF threshold values necessary to maintain a desired QoE level.

A key challenge lies in conducting a precise E2E path analysis, translating it into a test setup, and validating the findings through appropriate live measurements. These challenges can be effectively addressed through multiple iterations of the analysis steps.

4.4.3 WP3C: Evaluation of E2E Test Setup

This chapter presents a comprehensive description of the alternative test setups investigated, selected test cases, and selected network scenarios available for component-level and HIL-level E2E verification. It outlines the criteria, testing procedures, and evaluation methods for these setups. The core of the document provides an in-depth analysis of the evaluation results, covering both qualitative and quantitative aspects.

Before evaluating a test setup with a specific use case under a particular network scenario, it is essential to conduct a general assessment of the test setup. This preliminary evaluation aims to provide a quick, comparable overview of all test setups based on common criteria. The criteria evaluated include usability, fit for use, controllability, deployment flexibility, cost, licensing and maintenance, and customization. Table 4-12 provides the general description of each criterion.

Table 4-12, Table template to be used as base for general evaluation of each test setup.

Criteria	Description
Usability	Providing normal behaviour with minimal effort. Alternative behaviour possible to control to a certain level. Possible to automate and reconfigure for different scenarios in the automated tests
Fit for use	Rich feature set supporting the test scenarios and use cases. For example, LTE (4G), NR (5G). Performance and capacity
Controllability	Behaviour: How the different behaviours of the setup can be controlled. Characteristics: Possible to shape traffic characteristics (embedded or with external tool).
Deployment flexibility	Dedicated hardware boxes vs scalable cloud solution
Cost, Licensing & Maintenance	Scalable from a cost perspective (License). Cost per capacity and performance License limitations.
Customization	If there are shortcomings in other criteria, can they be addressed through customization. Flexibility in selecting combination of components (commercial, reference designs and open source)

To evaluate the test setups, two statistical evaluation methods have been used: Measurement System Analysis (MSA) and Design of Experiment (DoE). MSA is a method used to evaluate the repeatability and reproducibility of a test setup. DoE is a systematic and efficient methodology for investigating the relationship between input variables and process or product outputs. For the evaluation process of both methods, the Minitab Software program has been used [*52*] [*54*].

Defining evaluation criteria is crucial in any testing process as it ensures that the tests are structured, relevant, and capable of providing meaningful insights. By establishing clear criteria, the feasibility and impact of different scenarios and test cases can be systematically assessed, leading to more reliable and actionable results.

Evaluation criteria are identified as following questions:

1. Is it possible to feed relevant input data into and control the test setup?
2. Is it possible to evaluate the effect on the use case from different scenarios in the test setups?
3. Which use case and scenario/test case combinations can be evaluated in the test setups?
4. What are the reasons a test setup is not suitable for a given use case and scenario/test case combination?
5. How long does it take to prepare and execute a test?
6. How difficult is it to configure the test setup to control its behaviour?

Several different types of vehicle connectivity test setups have been identified. No test setup is feasible for all kind of QoE evaluations because each type of setup has different capabilities, pros, and cons. There are numerous test setups used by the partners of the project, the chosen test setups are a combination of currently available HW and setups purchased for the project. The chosen test setups are covering different areas of testing, Figure 4-117 shows an overview of the test setups that have been used and evaluated in the report.

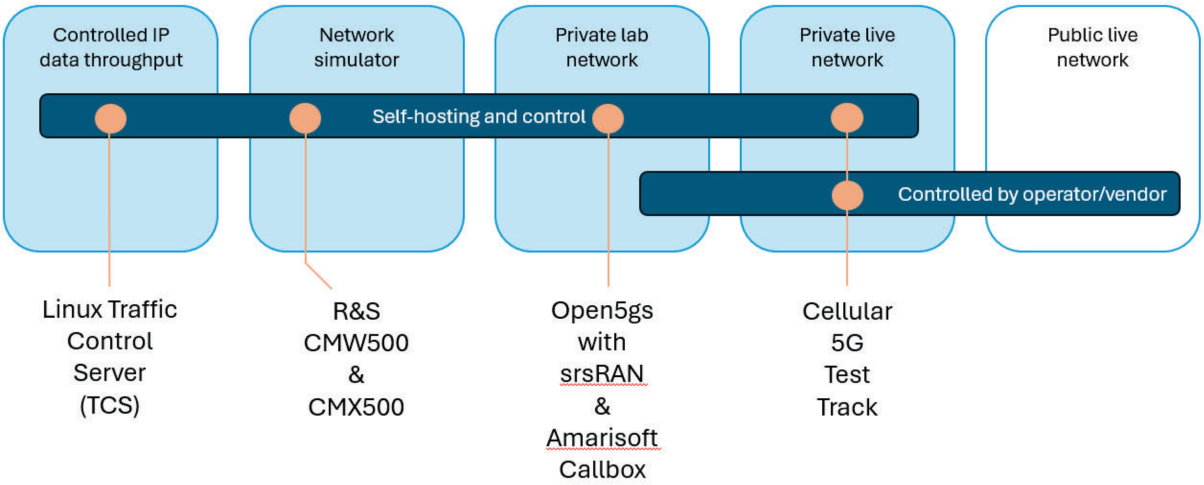


Figure 4-117, Overview of E2E Test Setups categories

In general, looking from left to right in the figure, the test setups are becoming more and more like a real public live network. User QoE evaluations are made in a real network when there is no suitable test setup and as a reference towards the test setups.

The reasons behind the selection of test setups for evaluation in this report are described in the overview for each type of test setup. In general, the availability and cost have been important drivers for the selections. To evaluate different types of test setups has also been important in the choice.

Each type of test setup in the above overview focuses on different areas in the architecture required for vehicle connectivity. Figure 4-118 shows some of the most important parts of the architecture that are involved in the vehicle connectivity and related use cases when the vehicle gets connectivity via a public mobile network. The figure is used in subsequent chapters to show the scope for each type of test setup that has been evaluated.

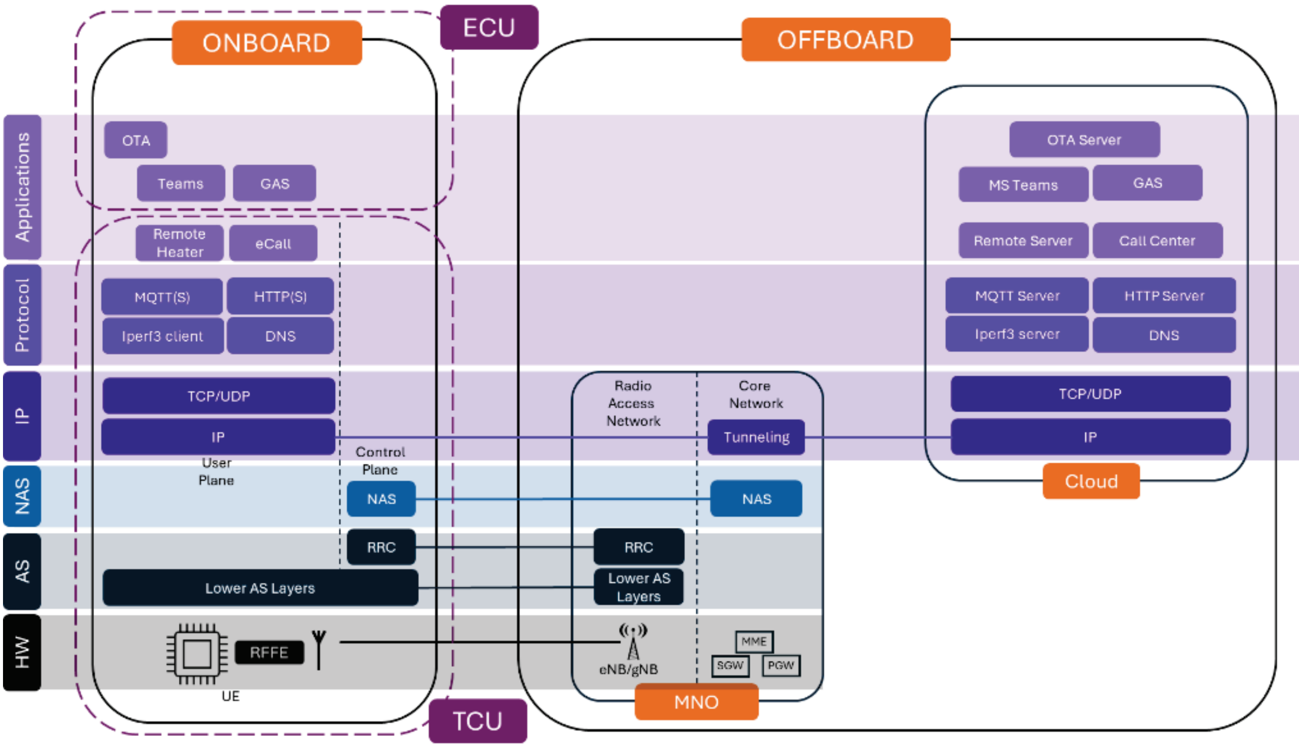


Figure 4-118, Important parts in the Vehicle Connectivity framework and corresponding Use Cases.

Note 1. Access Stratum (AS) includes protocols like PHY, MAC, RLC, PDCP, SDAP and RRC and Non-Access Stratum (NAS) includes protocols like MM, SM, CM.
Note 2. In the core network part (MNO) of the figure, it is mentioning MME, SGW and PGW which are all used in the LTE network. This is just an example of core network nodes. The corresponding nodes in other mobile generations like 5G NR is also used in SIVERT2.

4.4.3.1 Controlled IP Data Throughput

IP connectivity in a TCU with a cellular modem is provided via the Access Stratum (AS) and Non-Access Stratum (NAS) protocols in the modem and the Mobile Network Operator (MNO) network. The TCU has an IP stack with Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) that are used by applications in the TCU or in other devices connected to the TCU. The IP stack is terminated in the packet gateway (PGW) in the mobile network which is connected to IP based packet networks to which these applications communicate. This is what we refer to as “connectivity” in the UE, i.e. the UE can transmit and receive IP packets to and from IP based packet networks.

For many evaluations of user QoE, it is sufficient to use a test setup that can vary the IP stack behaviour in a way that simulates the IP stack behaviour in a UE connected via a mobile network during certain live network conditions. Such test setup does not require any cellular modem nor mobile network.

Example: In case of bad coverage, the IP downlink throughput in a live mobile network will decrease and impact the user QoE. This can then in some cases be properly simulated without any UE or mobile network by instead decreasing the throughput directly in the IP stack on e.g., a laptop with some appropriate tool. In Figure 4-119 the scope of the test setup is described.

To be able to simulate the IP behaviour in live networks with such test setup, it must be known what this behaviour is like, either via theoretical calculations or via measurements in live networks.

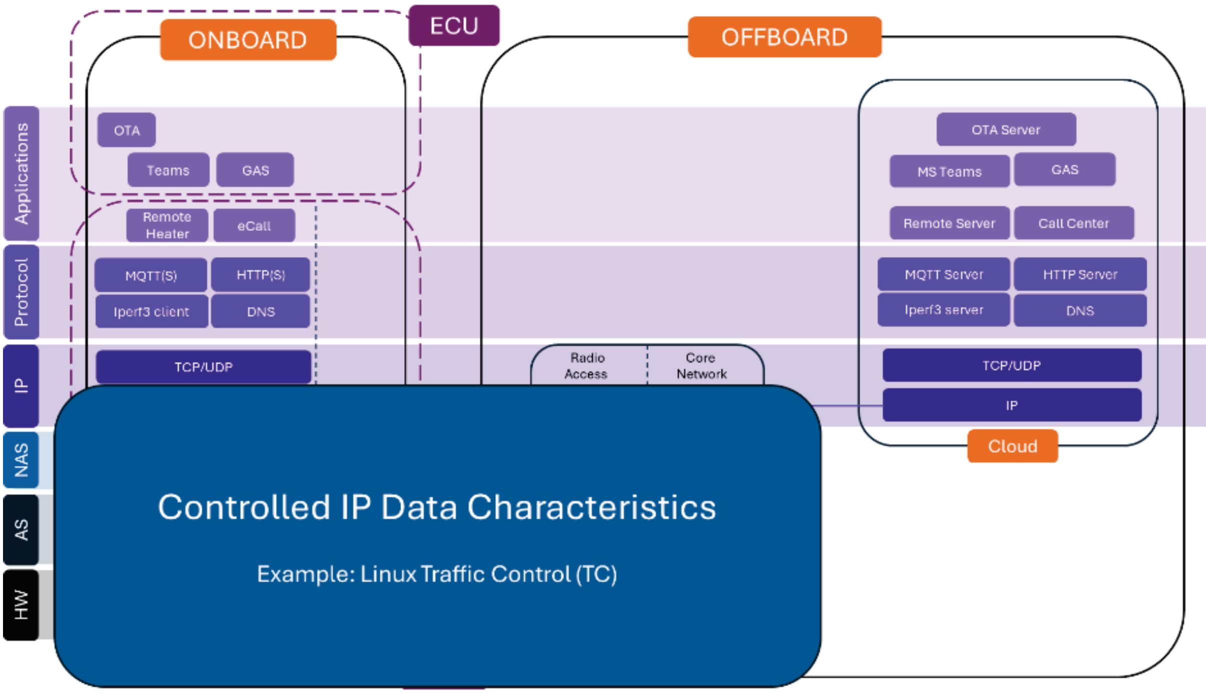


Figure 4-119, Scope for a Test Setup with Controlled IP Data Throughput

Even though this test setup is used without any cellular modem or mobile network, the tools used to control the IP stack can also be deployed in other test setups where both a UE and a simulated mobile network are present. The purpose then is to vary the IP throughput between the nodes in the mobile network and/or between the PGW and the external packet networks. This can typically be used to examine what the impact on user QoE will be in case there are IP issues inside or between networks.

One well-known and mature tool for controlling the IP data throughput is the Linux Traffic Control (TC) which is included in most Linux distributions. TC is used for managing IP traffic shaping and policing in the Linux kernel. It has been selected for evaluation because it is available for free and has many options of interest.

In the evaluated test setups, TC has been deployed on a Raspberry PI acting as a bridge between two nodes in an IP network. This setup is referred to as the "Linux Traffic Control Server (TCS)". An overview of the test setup is shown in Figure 4-120.

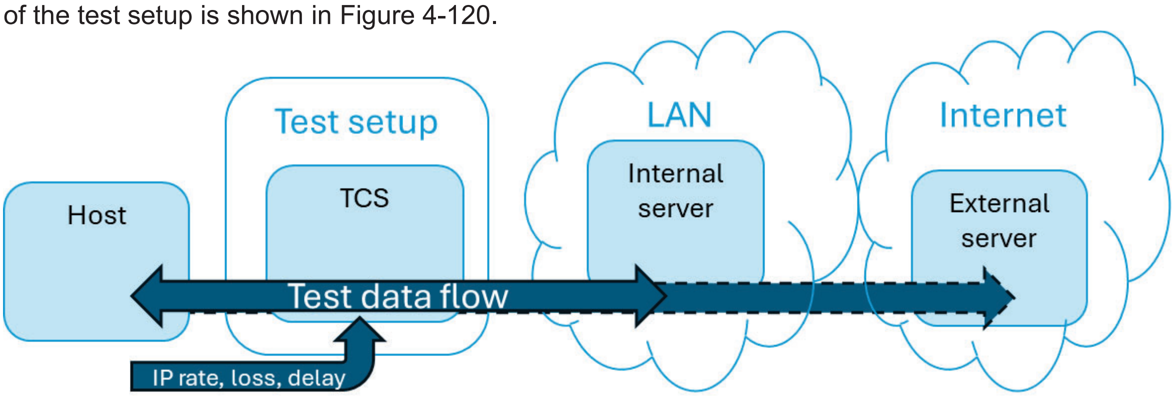


Figure 4-120, TCS Test Setup Overview

A standalone test setup with TCS running on a Raspberry PI with a Linux OS and three physical network interfaces (eth0, eth1, and eth2) is shown in Figure 4-121. The TCS server is then acting as a controllable network switch between two IP stacks, and it can alter the packet rate, delay, and packet loss. In this figure, the node connected to eth2 is a laptop and the node connected to eth1 is the LAN switch to which the laptop was connected. The third interface in TCS (eth0) is used for controlling the TCS.

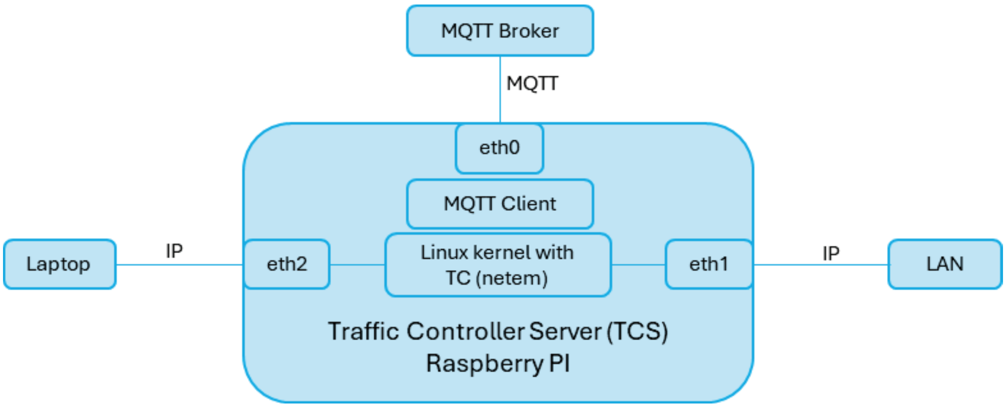


Figure 4-121, TCS in a standalone setup

A general evaluation of the test setup has been made and can be seen in Table 4-13 and an evaluation based on testing has been made. The scenario “poor coverage” and use case SWDL has been used for the test-based evaluation.

Table 4-13, General evaluation of TCS

Criteria	Description
Usability	The TCS is easier to manage and use compared to, for example, a mobile network simulator, as it operates solely at the IP level and does not require familiarity with 3GPP specifications. This assumes that users of the test setups and developers of the use cases are generally more experienced with IP than with 3GPP standards.
Fit for use	Using a TCS to change and/or disrupt the IP flow can be a simple but still an appropriate way to investigate the impact on User QoE where the NFRs are related to the IP stack behaviour like IP download rate or packet loss. It will not reflect the same IP behaviour as in a real mobile network, but it can give a similar behaviour that in many cases are sufficient for the User QoE verification.
Controllability	TCS is exposing the Linux TC which provides an extensive interface for manipulating the traffic control settings on IP level.
Deployment flexibility	TC is included by default of most standard Linux distributions which makes it very flexible to use whenever a Linux host is present. With the TCS MQTT wrapper it can be controlled remotely resulting in many different deployment options.
Cost, Licensing & Maintenance	No software or licensing cost as TC it is part of Linux. The cost of the hardware varies based on need.

Customization	Has not been investigated, but combining the TCS with other test setups has been investigated.

The TCS setup does not intend to reproduce any live network poor coverage behaviour, it only impacts selected KPIs (e.g. download rate) that are assumed to be relevant for poor LTE coverage scenarios. The setup can however be used during the development and troubleshooting of use cases. The setup does not require any mobile network so it can be used to evaluate the expected use case behaviours also in future RATs where the expected download rates can be applied in TCS.

The TCS has also been investigated in combination with other test setups, this can be read further down in the report.

4.4.3.2 Network Simulators

Device manufacturers need to test that their device functions properly over a range of network configurations and that the device conforms to the standards that define the protocols for communicating in a cellular network. In addition, tests to evaluate how well a hardware or software component of a device works under certain network conditions can be important. One way to perform these tests is to do a drive test and verify/evaluate the devices' behaviour. However, device owners typically have limited control over cellular network configurations that dictate the type of exchanged messages and radio conditions that QoS experienced in their devices. This is where network simulators come in. Figure 4-122 illustrates the scope of a test setup using a mobile network simulator with an optional usage of TCS.

A cellular network simulator allows testing of the networking functionalities of mobile devices without the effort and limitations of cellular network drive tests. The test setups selected as Network Simulator have been chosen based on the simulators available to the partners in the project.

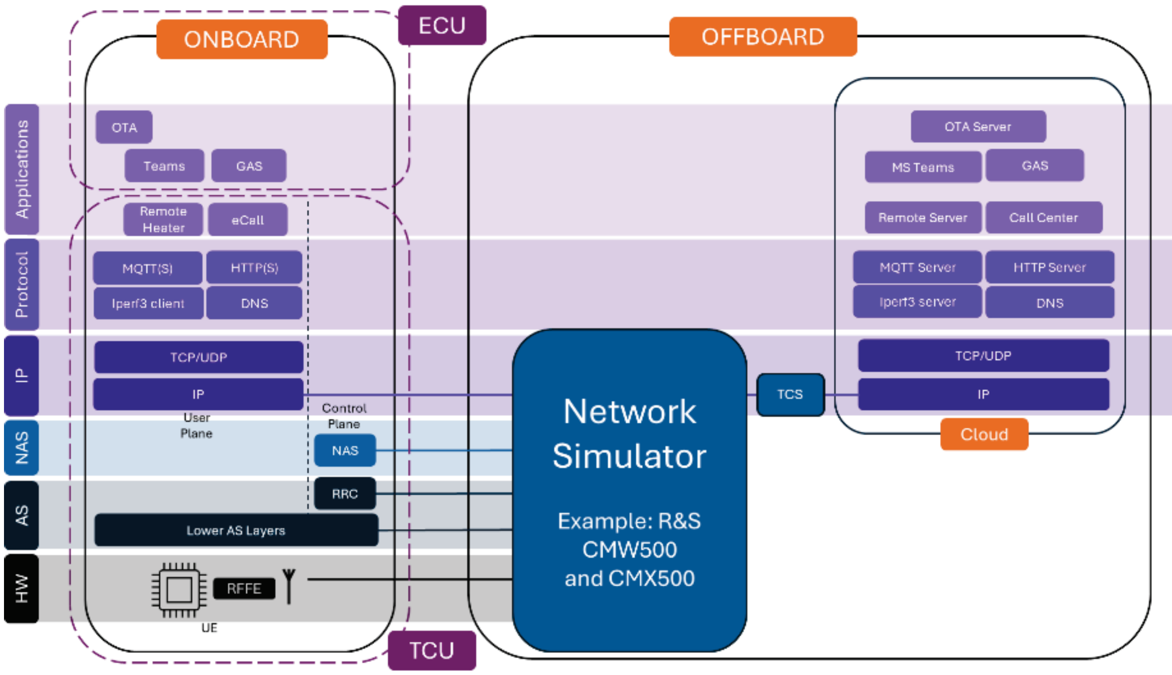


Figure 4-122, Scope for a Test Setup with a Network Simulator (with an optional usage of TCS).

In the project, a CMW500 with CMWcards and a CMX500 from the company Rohde & Schwarz have been used. The CMW500 is not 5G capable but the CMX500 is. In Figure 4-123 a block diagram of the test setup is presented.

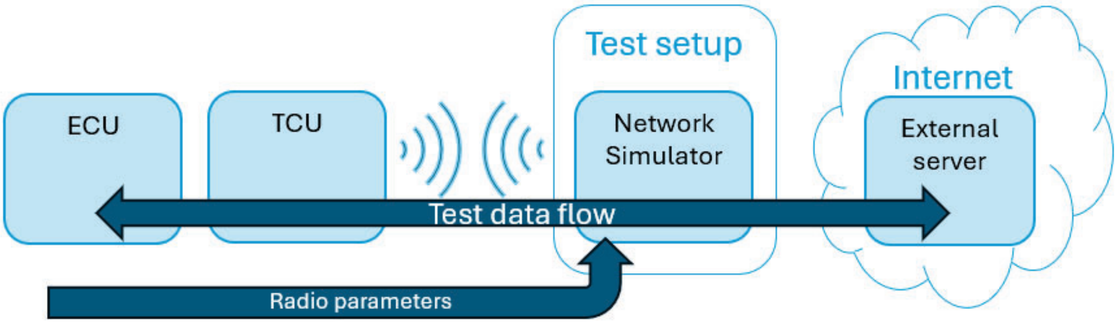


Figure 4-123, Network Simulator Test setup

The number of RF connections of the CMW500 depends on the number of receiver antennas required for the test and can range from 1 to 4. A CMWcards script running in the CMW500 simulates different network conditions, internally adapting to those conditions as well as carrying out the proper signalling with the TCU. CMW500 assigns each TCU cellular network interface an address when the device establishes a cellular connection with the simulator. An external test control unit (not shown in the figure), can be used to monitor events in the devices and to automate commands to the CMW500 and TCU. Through a LAN connection, the CMW500 provides the TCU access to the internet and external application servers (e.g. an amazon server hosting files of different sizes).

The CMX500 is set up to share internet through its Data Application Unit (DAU) interface. The TCU is connected to the CMX DAU over the mobile network connection. The R&S CMX500 simulator supports 4G and 5G technologies.

A combined test setup with the CMX500 and TCS can be used. The TCS is used to impact user plane traffic between the CMX500 and an external server(s) (one or more external servers could be involved depending on the test scenario). Figure 4-124 shows an overview of a test setup using a TCU/CMX500 together with a TCS.

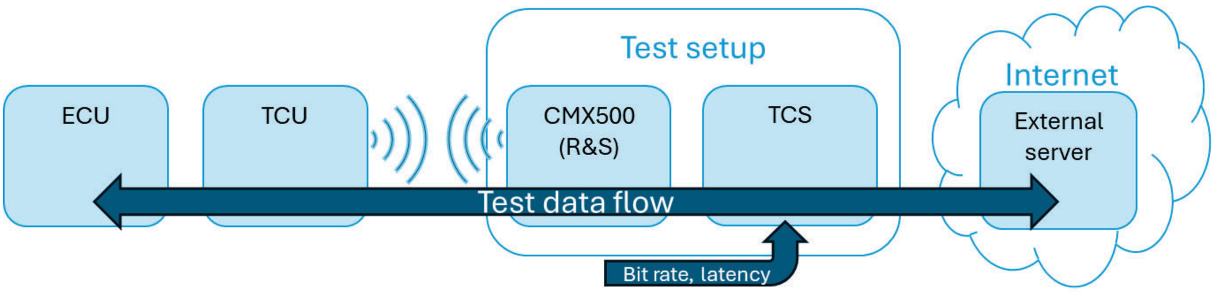


Figure 4-124, Overview of a TCU/CMX500 based test setup with TCS.

A general evaluation of the CMW500 with CMWcards test setup has been made and can be seen in Table 4-14 and an evaluation based on testing has been made. The scenario “poor coverage” and use case SWDL has been used for the test-based evaluation.

Table 4-14, General evaluation of CMW500 with CMWcards

Criteria	Description
Usability	Can be used for test scenarios that require a cellular modem to realize. CMWcards GUI based testing framework that visualizes expected sequence of network behaviour as a sequence of cards. The tool also helps with providing feedback on creating a valid sequence of cards. The strict adherence required to the specified sequence of cards enforces conformance to desired sequence and spotlights any major deviation. Provides detailed logs of tests for monitoring, verification or diagnosis. Requires a good knowledge of the expected sequence of network behaviour or messaging. Testing can become complicated when doing multiple tests that require long sequence of cards (e.g. conditions/configurations that change frequently) since the card scripts are created manually.
Fit for use	Capability for testing 3G and 4G network scenarios. Does not support 5G.
Controllability	CMW500 provides a service that allows execution of scripts in an automated way. Expected behaviour must be preconfigured before test begins, i.e. inability to change the behaviour of the simulated network dynamically in runtime. Some quantities that can be extremely variable (e.g. SNR) lack support (a card) that allow the configuration of the variability in an easy way.
Deployment flexibility	The test device is already available for use, and it is light enough to be moved to a different testing location if required. The test setup can also be configured to be accessible through remote access without relocation. The test setup functions only on specialized hardware and custom software built for the hardware. Extended continuous usage might require placing the device in a heat regulated environment.
Cost, Licensing & Maintenance	Dedicated support and continuous upgrade provided by the vendor. Relatively expensive initial purchase compared to the other test setups considered here (TCS and Open5Gs). Licenses are purchased for specific features and can be costly.
Customization	Customer can pick and choose the type of available features by purchasing the licenses that cover the needed features only. If the customer has specific needs (e.g. support for a given release), then it is dependent on R&S for adding new features and capabilities.

In general, the CMW500 with CMWcards test setup is shown to have the capability to allow configuration of multiple parameters that can affect OTA SWDL performance in poor coverage scenarios. However, CMWcards does not offer a way to apply SNR in the same way as it varies in real networks. Evaluation results show that applying the static mean SNR of the live parked in poor coverage test in CMWcards does not necessarily produce the same download time as the live test. Nevertheless, results over the semi-synthetic configurations suggest that it could be possible to estimate the range of download times that are likely include the live-test download time. This can be achieved by testing over SNR values around the expected mean SNR of a parked in poor coverage scenario. Estimating the most suitable SNR range around the expected mean SNR to test in CMWcards for a specific poor coverage case is left for future work. Future work can also explore application of SNR by applying the means of a sequence of smaller intervals instead a single mean for the entire duration.

The CMX500 can impact the user experience by altering the wireless signals used to communicate with the TCU. The ways to affect this are bandwidth/resource blocks, MIMO/SISO, scheduling slots and modulation. A general evaluation of the CMX500 test setup has been made and can be seen in Table 4-15 and an evaluation based on testing has been made. The scenario “poor coverage” and use cases SWDL and RTSA has been used for the test-based evaluation.

Table 4-15, General Evaluation of CMX500

Criteria	Description
Usability	Doing manual tests are quite simple with a straightforward web-GUI for setting up and controlling the network. For automated tests a dedicated back-end framework needs to be built to integrate its remote API over IP (either dedicated python-libraries or industry standard SCPI) into the rest of the test environment. Once this framework has been developed adding individual control of the various parameters is pretty fast.
Fit for use	The CMX500 have a very wide span of capabilities with emulation capabilities of 4G, 5G NSA and 5G SA and simultaneous usage of over 8 cells in various frequencies allowing for complex handover and border-crossing scenarios.
Controllability	With the highest level of licenses, it is possible to adjust individual bits of messages being sent from the simulator to the TCU through the dedicated python libraries. However more overarching control like adjusting modulation control scheme, bandwidth, attach procedure etc. are available on a much easier level by using the web-GUI, python-libraries or SCPI.
Deployment flexibility	Since the CMX500 is a dedicated hardware device it is very inflexible. It is however possible to split the radio signals coming from the CMX500 to the various test devices meaning a single simulator can be a shared resource for different test areas.
Cost, Licensing & Maintenance	The total cost of a CMX500 is high. Licenses can be added after the initial purchase and therefore some money can be saved until it is understood that the license is required.

Customization	The device itself is slightly customizable by having different hardware and licensing options allowing for functionality to be available. However, the hardware needs to be decided at the point of purchase.

The CMX500 is capable of controlling data throughput by manipulating the radio signals between the mobile network and mobile device. The ways of controlling the parameters worked quite well, Resource Blocks, Slots and Modulation. However, these are parameters that the OEMs do not have much impact over since they are all controlled by the network operators' algorithms. Developers have some impact of these when deciding which modem hardware to put into the device but that is more of a max limit vs cost decision.

When considering signal power instead of throughput, the correlation becomes less straightforward. While the simulator can be used in broad terms to evaluate performance under good, average, or poor coverage conditions, it is not suitable for directly translating real-world signal power measurements into simulator settings. However, if the goal is to simulate general behaviour, such as 20 seconds of good coverage followed by 10 seconds of average coverage, then 15 seconds of good coverage again, this can be roughly approximated using signal power data and automatic cell configuration. Due to the instability in the outcome throughput, it will also be hard to verify if a measured sequence of cell powers from a real road will be able to sustain enough data traffic throughout the trip.

During the video stream tests, the results showed that the cell parameters that worked well impacting the download rate of data to a device, does not work as well when trying to impact the upload rate of a camera stream. There are several possible explanations for this. A likely explanation is that the camera stream does not fully utilize the cell's capacity. As a result, when the cell's capabilities are reduced, it only affects the unused surplus, leaving the user experience unchanged, until the coverage deteriorates to the point where the connection is lost entirely.

A possible future experiment would be to get a different type of stream set-up that allows for higher data-rates and therefore pushing the cell to its limits with default settings that can later be changed to reduce capacity.

The tests show that the simulator is capable of doing tests by artificially setting specific network behaviours. This provides some benefits, since it changes the radio signals but is still a more complex solution compared to a simpler TCS setup.

Next evaluation that has been made is a combination of using the CMX500 and the TCS. The general evaluation can be seen in Table 4-16 and an evaluation based on testing has been made. The scenario "poor coverage" and use case SWDL has been used for the test-based evaluation. Since the setup is a combination of the TCS and the CMX500, the general evaluation of the two separates setups are presented in Table 4-13 and Table 4-15.

Table 4-16, General Evaluation of CMX500 with TCS

Criteria	Description
Usability	The usability of the test setup depends on how the lab is configured, how well the components are integrated, and how the Traffic Controller is managed. When the test is designed as an automated test case, it can be quite user-friendly. In the scenarios evaluated, the setups were largely similar, with the main differences being changes to configuration files in the automated test case to simulate different types of disruptions.

Fit for use	The main limit in this setup is the limits of the CMX500, therefore referring to Table 4-15.
Controllability	The CMX500 with its own GUI or through code, and the traffic shaping is made through the Traffic Controller which is controlled by code. Rather easy to control them, even if they are more separated and not in an automatic test case.
Deployment flexibility	In this setup the deployment flexibility was great, easy to change to parameters in test cases.
Cost, Licensing & Maintenance	Need a controlled environment where the two major components for this test are in use, the CMX500 and something driving the Linux Traffic Controller like a Linux computer or Raspberry Pi.
Customization	The main hardware used and that is customizable are the two components CMX500 and the Raspberry Pi Traffic Controller.

Overall, the setup provided stable download rate and realistic deviations that could be seen during real OTA downloads in field. Out of the total 58 downloads made for this setup there were two abnormal deviations that occurred, which could have several different causes. In general, this test setup gives a good understanding of how different forms of disruptions from the traffic controller could affect the time to download software out in the field.

The conclusion of this chapter regarding the evaluation criteria is that it is possible to feed relevant input data and control for the test setup as we have done successfully through the Traffic Controller. It is possible to evaluate the use case effect of different scenarios/test cases.

4.4.3.3 Private Lab Network

A telecom private lab network, often referred to as a private lab cellular network, is a dedicated communication infrastructure designed for the exclusive use of a specific organization or entity. Unlike public networks, a private network provides controlled access and enhanced security, allowing for the customization and flexibility required by the entity it serves. It operates using technologies such as 4G LTE or 5G NR to offer dedicated coverage for a specific area, which can range from a small office to an entire campus or even across multiple geographic locations. The network typically includes a Radio Access Network (RAN), which consists of small cells, base stations, access points, and antennas that transmit and receive radio frequency signals within the network's coverage area.

The “Lab” in Private Lab Network means, in the context of this document, that the network is limited to a lab environment. The private lab network has a limited number of connected devices and a limited network coverage area.

Instead of simulating the behaviour of a cellular network, a private cellular network is an actual cellular network. It consists of real implementations of the core network nodes. The behaviour of the private network should be comparable with the behaviour of a live public network. To evaluate different user QoE, the private lab network can be configured to achieve the wanted result. For example, the user database can be configured in different ways or the signal gain from the cellular network can be altered. Another advantage of using a private live network compared to a live network is the repeatability of a test.

The evaluated test setups are based on:

i. an open-source based network using Open5GS and srsRAN among other open-source projects to realize an LTE and 5G core network with RAN capabilities.
ii. a commercial Private Lab environment called Amarisoft Callbox (Amari Callbox) with the capability to emulate both LTE and 5G SA mobile networks[2].

Figure 4-125 shows an overview of the private lab network test setup. The intention with the transparent "Private Lab Network" box is to show that some network configurations and setups can easily be modified to enable wanted network scenarios. This makes the private lab network more flexible with the possibility to impact different core network functions to realize different scenarios requiring different, specific core network behaviours.

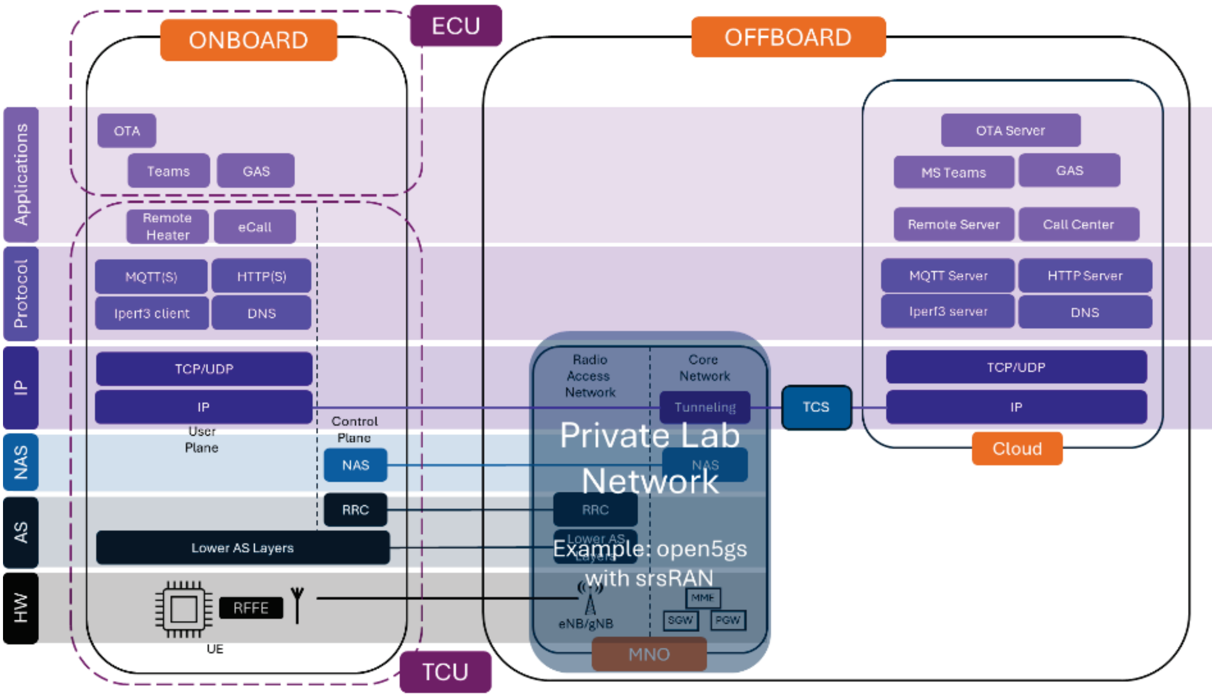


Figure 4-125, Scope for a Test setup with a Private Lab network and an optional usage of TCS

Two setups with the open5Gs and srsRAN have been made, firstly an LTE setup, and later in the report a 5G SA evaluation; the setups have used different but similar components.

Utilizing Open5GS with srsRAN and an SDR card presents a flexible solution for setting up 4G and 5G networks. Open5GS provides a free and open source 4G/5G core network (CN) which, when combined with the srsRAN software suite, allows for the deployment of a complete 4G/5G system architecture. The use of an SDR card, such as the USRP B210, enables the transmission and reception of signals, effectively replacing traditional hardware components with software processing. Some disadvantages are that it may require a high-end PC depending on the performance need, and it is more complex to configure and maintain compared with other solutions that either work out-of-the-box or comes with dedicated support channels. The general evaluation of an Open5GS-based LTE network with variable attenuator test setup is described in

Table 4-17.

[2] *The evaluation of the Amarisoft has been limited in WP3 but extensively used in the WP2 testing.*

Table 4-17, General Evaluation of Open5gs, LTE Network with Variable Attenuator

Criteria	Description
Usability	This is not an out-of-the-box solution ready to be plugged in. The hardware components must be prepared and connected. The software needs to be installed with all the requirements. The components in this test setup forms a 4G/5G system. As such it needs to be configured to function as intended. The Docker project helps a lot when it comes to configuring the components for deployment. After the core network has been deployed it must still be configured with the intended subscribers as an example.
Fit for use	This test setup is an LTE core network with an eNB. As a result, it aims to provide the UE with the best possible service. Therefore, it may not be the most suitable solution for use cases where we need to shape the traffic or make modifications to core network behaviour.
Controllability	It is not easy to change the traffic characteristics in runtime. The parameter we have identified, that can be changed in runtime, is the cell gain. srsRAN has support for setting up some test scenarios before starting the eNB.
Deployment flexibility	This test setup offers great deployment flexibility. The setup that is evaluated in this document is deployed on a single host as Docker containers.
Cost, Licensing & Maintenance	Open5GS: AGPL-3.0 srsRAN: AGPL-3.0 Docker-open5gs: BSD 2-Clause The cost of the hardware varies based on need.
Customization	Great flexibility in selecting combination of components. This lets us choose components based on need and cost. This suite of software is open source. This means that it is possible to add any functionality needed.

Utilizing open sources solutions like Open5GS and srsRAN to build the test setup offers a high degree of deployment flexibility and customization, allowing users to configure and manage various aspects of the network. However, based on our preliminary experiment results, the selected test setup is not stable enough or unable to control the network factors that can give an impact on the user experience.

A general evaluation of the 5G SA test setup using Open5GS and srsRAN with a traffic controller in the Core network is presented in Table 4-18. The scenario “poor coverage” and use cases SWDL and RTSA has been used for the test-based evaluation.

Table 4-18, General evaluation of the 5G SA Network with traffic control in the Core Network.

Criteria	Description
Usability	Open5GS follows the common idea of the 3GPP standard strategy to make the evolution from EPC (used by LTE and 5G NSA) to 5G NR in a well-defined way. (The 5G core in Open5GS is implemented in line with the 3GPP standard but in an

	optimized/simplified way compared to the commercial mobile network implementations.) The traffic flow (control and user plane) can be followed via predefined logs. Control and user plane traffic can be impacted both with built in functions as well as with external functions like Linux traffic control. The Open5GS 5G SA implementation supports the possibility to scale up the network in different areas like adding multiple UEs, gNBs, AMFs and UPFs (for the new slicing function defined in 5G NR). A high level of knowledge of cellular networks is required to configure the setup and to be able to utilise it fully. This setup has limited user support. Documentation, user interfaces, script frameworks, etc. are more developed in commercial setups, and the setup is less user friendly than out-of-the-box available options.
Fit for use **Controllability**	This 5G SA setup provides most of basic standard features. A general view (but not verified in SIVERT2) is that it is suitable for basic test cases of a TCU and could also be used as a complement to other emulators in larger setups. Evaluated Open5GS 5GC and gNB implementations are not as mature as the EPC/eNB SW implementations. The EPC SW has as an example supporting functions for impacting the radio network. On the other hand, it looks like the Open5GS team have a target to make improvements in the overall 5GC implementation compared to EPC. So, it is probably a matter of time until the 5GC and gNB are on a level comparable with their predecessors. Note! As example is TX gain control during run time supported in the EPC docker setup but not in the evaluated version of srsRAN gNB used in the docker setup (version 23.10). This has been released in the main srsRAN version of gNB (24.04) though.
Deployment flexibility	This test setup offers great deployment flexibility. The setup that is evaluated in this document is deployed on a single host as Docker containers.
Cost, Licensing & Maintenance	Setup is based on software released under open-source licenses: Open5GS: AGPL-3.0 srsRAN: AGPL-3.0 Docker-open5gs: BSD 2-Clause High-capacity demands will require high-capacity radio cards and SW server(s) which will give an additional cost. 5G NR complexity will require higher competence and cost in hours in Open5g/RAN setup and maintenance compared to a commercial setup. **Note:** The mobile networks have continuously evolved during the last 50 years to manage higher performance and lower latency which means that an implementation of a new generation like 5G NR requires both higher processing capacity as well as higher requirements on signaling synchronization etc. This is managed by high performing, customized HW in real networks meaning that an

	emulated environment like Open5GS and especially the RAN setup might get challenges depending on what setup is required.
Customization	As this is an open source. Both configuration and code adaptations are possible to make. This is a complex SW setup, emulating a simplified version of the live 5G SA networks. There is by nature some default setups/network scenarios that have been prioritized. This means that it might be a challenge to make customizations of the configuration and/or introduce new code to get wanted setups/scenarios outside of the mainstream configurations.

The Open5GS setup (5G SA including traffic control on IP level in the Open5GS UPF core node) works well for the chosen network scenario and use cases. The setup used have some limitations in capacity (with no impact on made evaluations with lower capacity demands) which might be improved with a radio card with higher capacity (more expensive).

This setup also has a lot of unexplored possibilities which might require more man-hours and high competence to make use of compared to a commercial on the shelf solution. Nevertheless, it has been possible to feed relevant input data and control for the test setup in evaluated test cases as well as to evaluate the use case effect of different scenarios/test cases.

The test setup can be integrated into a test framework and by that be automatically controlled via standard scripts. However, the test setup configuration could be a bit challenging depending on what configuration to use. The test setup behaviour is normally possible to control before a test is executed.

4.4.3.4 Private Live Network

A telecom private live network, often referred to as a private live cellular network, is a dedicated communication infrastructure using commercial mobile network hardware in a dedicated geographical area for exclusive use within a private organization. Unlike public networks, a private live network provides controlled access and enhanced security, allowing for the customization and flexibility required by the entity it serves. It operates using technologies such as 4G LTE or 5G NR to offer dedicated coverage for a specific area, which can range from a small office to an entire campus or even across multiple geographic locations. The network typically includes a Radio Access Network (RAN), which consists of small base stations with antennas that transmit and receive radio frequency signals within the network's coverage area. It is a good option for tests requiring real mobile network setups without using a public network.

Figure 4-126 shows the private live network test setup. The intention with the transparent “Private Live Network” box is to show that some network configurations and setups can easily be modified to enable wanted network scenarios. This makes the private network more flexible for live testing compared to a public network. A live network is still needed to be controlled by an approved network operator as the private network is acting in parallel to the existing public networks.

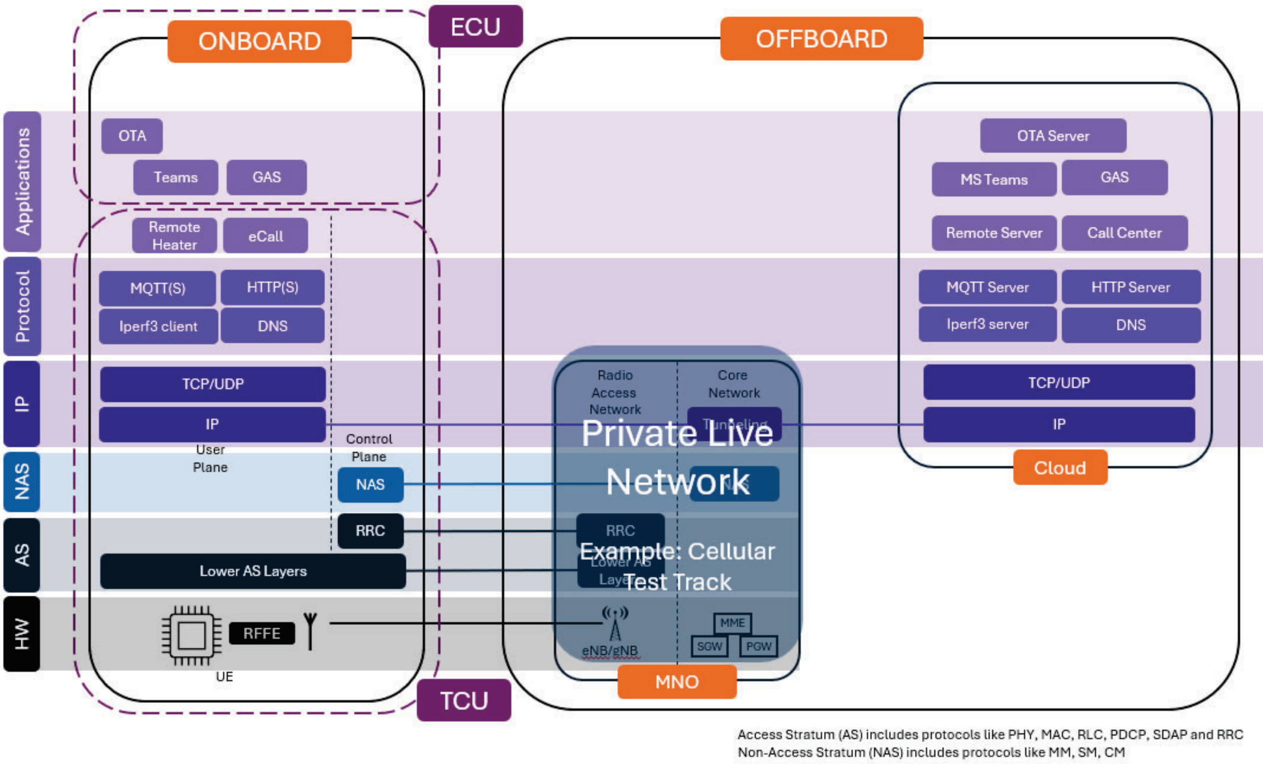


Figure 4-126, Scope for a Test Setup with a Private Live Network

Figure 4-127 shows an example of a private network installed with 2 cells covering a vehicle test track. This type of installation makes it is easier, compared to a public network, to impact the cells in different ways like changing cell power, shutting down one cell and using the other cell to get an optimized bad coverage area and other scenarios.

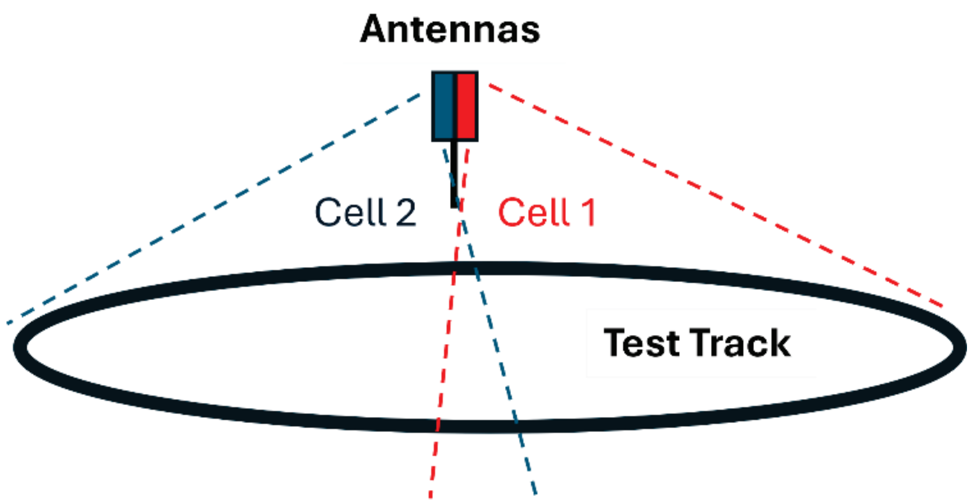


Figure 4-127, Private network example used on a vehicle test track

The usage of a private network in SIVERT2 has been to execute the different test scenarios, measure expected KPIs and provide required data to be used as reference to the evaluations in the other 5G SA related test setups. Tests and data collections were made by vehicles on different round trips on the test track.

4.4.3.5 Test Setup Conclusion

Table 4-19 and Table 4-20 summarize WP3 test setups evaluation with regards to the two selected test cases: OTA SW UL and RTSA, respectively under different network scenarios. A cell marked with "x" indicates that the evaluation has been successfully conducted and obtained results. A cell marked with "-" indicates that it is not possible to configure the test setup to simulate the poor network coverage condition or due to some other reasons. A cell marked with "n/a" indicates that the evaluation of the test setup is not applicable in the corresponding scenario. An empty cell indicates that the evaluation has not been conducted in the test setup due to time constraints or other reasons.

Overall, as seen from these tables, no test setup is fitting for all kind of QoE evaluations because each type of test setup has different capabilities, pros, and cons. So, it really depends on the specific requirements and objectives of the evaluation.

For example, the TCS-based test setup is found to be the most promising candidate for test cases concerning IP-level performance testing, irrespective of the radio access technology. When it comes to examining the radio level impact on QoE, different test setups are required.

As can be seen from the tables, we have also successfully explored the testing of different mobile network technologies, including 4G and 5G. This exploration involved establishing corresponding test setups using either network simulators or open-source tools.

Table 4-19, Summary of test setups evaluation for OTA Software Update use case.

Test Setups	Test case: Over-The-Air (OTA) Software Update					
	Parked in Poor LTE		Parked in Poor 5G SA		Driving in Poor 5G SA	
	Live data	Synthetic data	Live data	Synthetic data	Live data	Synthetic data
Traffic Control Server (TCS)	X	X				
R&S CMW500 with CMW cards	X	X	n/a	n/a	n/a	n/a
R&S CMX500					X	X
R&S CMX500 with TCS			X	X	X	
Open5GS-based LTE with Variable Attenuator	-	-	n/a	n/a	n/a	n/a
Open5GS-based 5G SA with Traffic Control in Core Network	n/a	n/a		X		X
Open5GS-based 5G SA with RU	n/a	n/a	-	-	-	-
Amari Callbox	-	-				
5G SA Private network	n/a	n/a	X		X	

Table 4-20, Summary of test setups evaluation for RTSA use case.

Test setups	Test Case: Real-Time Situation Awareness (RTSA)			
	Parked in Poor 5G SA		Driving in Poor 5G SA	
	Live Data	Synthetic Data	Live Data	Synthetic Data
Traffic Control Server (TCS)				
R&S CMW500 with CMW cards	n/a	n/a	n/a	n/a
R&S CMX500	-	-	-	-
R&S CMX500 with TCS				
Open5GS-based LTE with Variable Attenuator	n/a	n/a	n/a	n/a
Open5GS-based 5G SA with Traffic Control in Core Network		x		x
Open5GS-based 5G SA with RU	-	-	-	-
Amari Callbox				
5G SA Private Network				

4.4.4 Work Package 3 Conclusions

Table 4-21 starts the WP3 conclusions by comparing the general evaluations made for chosen test setups.

Table 4-21, General conclusions for WP3 test setup evaluations

Criteria	Description
Usability	The usage of a Traffic Control Service (TCS) to emulate traffic disturbance on user plane level is easier to manage and use compared with e.g. a mobile network simulator. It is especially good to use if no mobile network is needed in the test. R&S (CMX500/CMW500) based setups are important for specific, complex test cases including different, detailed mobile sequences not including the core network behaviour. More basic scenarios can be implemented using other setups like Amari Callbox or Open5gs. Amari Callbox or Open5gs includes simulation of the complete network. They are suitable for test scenarios wherein the internal network behaviour might be of interest. This opens up the possibility to impact traffic between different core nodes. Private live network* data is useful for smaller, controllable network scenarios to be reused in the lab setup. Public network data is the alternative when test data in larger networks with impact from surrounding networks etc. are needed. * Not evaluated as test setup. Only used as live data source.
Fit for use	Linux Traffic Control (TC) can be used directly as a manual CLI command or integrated as a service (TCS). The service can be used both standalone or integrated in a lab-framework, either as an application within a common server or standalone in a smaller server (e.g. Raspberry Pi).

	The R&S (CMX500/CMW500) have a very wide span of capabilities with detailed emulation capabilities of (2G/3G), 4G, 5G NSA and 5G SA. The simulators fit best placed in a lab as services in a lab-framework. Amari Callbox has a series of dedicated hardware of different size depending on capability. Fits both in a lab-framework as well as in stand-alone test setup. It supports 4G, 5G NSA and 5G SA. Open5gs is flexible and can be used in small server setups together with a separate radio card. This makes it more flexible to move around if needed (GPS synch must of course be possible).
Controllability	A TSC is exposing the Linux TC which provides an extensive interface for manipulating the traffic control settings on IP level. R&S (CMX500/CMW500) has the ability to easy adjust modulation and coding scheme, bandwidth, attach procedure etc. This is available by using a web-GUI, python-libraries or SCPI. In an Open5gs setup it is not easy to change the mobile network characteristics in runtime. In SIVERT2 the cell power is the only KPI changed during testing. Amari Callbox has possibilities to some extent control/shape radio characteristics such as modulation and coding scheme, bandwidth, attach procedure etc. A private live network can be reconfigured on a high level to emulate certain basic scenarios.
Deployment flexibility	A TCS-solution is very flexible based on the fact that TC is a standard function within most Linux distributions on different HW setups. R&S (CMX500/CMW500) is based on fixed HW-setups but can be connected to multiple test devices. The R&S environment can be a shared resource for different test areas. An Open5gs setup is very flexible and can be installed in one or multiple servers depending on the requirements. The srsRAN capacity is dependent on chosen radio card. This large level of freedom can also be a challenge as the compatibility of the component is not guaranteed. Amari Callbox is based on fixed HW-setups and is based on a monolithic solution with single embedded core network instance. The Amari Callbox is available in several different HW-configurations, from basic to advanced versions. A private live network requires authorization from PTS which makes the deployment to be strictly in line with made application.
Cost, Licensing & Maintenance	The TC function is included in the Linux distributions without any additional cost. A TCS is normally built and maintained by the team using it. R&S (CMX500/CMW500) is within the premium branch with higher purchase and maintenance cost compared to the other test setups in this study. On the other hand, the R&S provide usability on a high level making the usage cost in hours a bit lower.

	Amari Callbox is in this study within the mid-range regarding functionality and purchase cost, cost depending on size required. It is still a commercial tool with good usability making costs for usage acceptable. Open5gs (including srsRAN) is based on open-source SW licenses. Still there is a need for commercial HW like one or more servers, radio card, synch modules etc. The purchase is cheaper than a commercial emulator but the usage cost in hours could be a lot higher depending on complexity.
Customization	As the TCS usually is a user internal implementation, it can be tailored for each setup. From a standalone solution to a solution integrated into a more complex test framework. R&S (CMX500/CMW500) can be bought on a basic level and continuously be improved with both HW-capacity as well as SW-licenses depending on required functionality. Amari Callbox Interfaces are compliant to standards, so possible to replace components ending up in a hybrid setup and different sizes are available. Open5GS has high flexibility regarding different commercial hardware components as well as the possibility to scale the SW in different ways. The code itself can also be changed or adapted as this is open source. But all this requires high mobile network competence and knowledge of the actual Open5gs implementation (including existing limitations).

Based on the evaluation and comparison presented in Table 4-21, Open5GS-based and Amari Callbox based test setups look promising for further exploration in the future due to their cost efficiency, flexibility and suitability for rapid prototyping and testing, as compared with the R&S network simulators. Additionally, these can be combined with the TCS solution to offer an extended E2E testing capabilities, providing a comprehensive approach to evaluating network performance and QoE.

In summary, even though we haven't conducted evaluations for all test setups due to time constraints, the insights gained from current evaluations provide a valuable foundation for further testing. By building on these initial findings and lessons learnt, we can develop more precise and effective testing frameworks for the vehicle connectivity, ultimately leading to significantly improved QoE for end-users. This iterative process will also help gain essential knowledge, build competences as well as identify potential gaps and areas for innovation, driving continuous improvement and excellence in the field of network performance evaluation for the vehicle connectivity.

The iterative network influence factor analysis method, applied across two use cases, proved effective in identifying key influence factors that impact QoE. This analysis was found to be a good way to get to know the use case and can be a good tool for developers to get to know their function and how it is affected by different influence factors. By highlighting the most relevant factors early in the process, the approach can help streamline live measurements and focus efforts where they matter most. It also supports the determination of threshold values needed to maintain acceptable QoE levels. Furthermore, the outcome from this analysis can be used when evaluating different test setups.

This groundwork will be instrumental in refining and enhancing future QoE evaluations, ensuring more comprehensive and robust testing methodologies. For example, the outcomes from this work, together with other efforts in this work package and the whole SIVERT2 project, could potentially provide valuable inputs to form a comprehensive simulation and verification strategy or to serve as a reference framework for others in the field of performance evaluation and testing for vehicle connectivity.

WP3 Discussions

This chapter discusses reflections made in the WP3 team on the challenges encountered and the lessons learnt during the evaluation of the test setups.

The process of configuring and tuning parameters to achieve specific network conditions proved to be complex and multifaceted. Configuring the test setup to simulate a poor coverage network condition presents significant challenges. Some test setups are limited in the number of parameters that can be altered, while others offer a wide range of parameters, making it time-consuming and challenging to tune all available parameters without knowing which ones have the most significant impact on performance. For instance, altering cell power can be challenging as mobile networks are designed to manage resources optimally. Another example is that, while the SNR is known to significantly impact performance, it is not feasible to adjust it in a simple, minimalistic setup, such as the Open5GS-based 5G SA network with a field-deployable RU test setup. In other words, depending on the use case, the available parameters might not be sufficient to influence the user experience. Therefore, it is crucial to consider these limitations when selecting a test setup.

Furthermore, another challenge when conducting experiments is obtaining data from live networks. Measurements in live networks are difficult to perform reliably due to the numerous uncontrollable and variable factors. This variability makes it challenging to isolate the impact of specific connectivity influence factors. Moreover, using the obtained live data as input to create a model of the live network to get a similar behaviour with a test setup is also challenging when parameters such as resource blocks and modulation control schemes, managed by the network operators' algorithms, are not easy to control or configure in test setups.

One suggestion could be to use the test setup to examine how different influence factors impact the QoE and then analyse what the typical values for these are in live networks and foresee what the expected QoE will be. By doing that, we can identify which factors that have the most influence on QoE. This will also help to minimize the tunning effort caused by the challenge discussed above. In WP3, the DoE method was used to evaluate impact from different influence factors.

It was also found that the usage of synthetic or semisynthetic input data has shown to be a good alternative compared to pure measured data from a live network. Synthetic data is especially good for evaluation of specific corner cases which are not easy to find in a live network.

Initially, as the requirements for the test setup were unclear, the selection of the test setups was done mainly based on the two criteria:

a) if we can build the test setup using open-source tools and inexpensive hardware.
b) if we can reuse any existing tools from Volvo Cars or Scania to save cost.

Based on the first criteria, the Linux traffic control-based implementation in Raspberry Pi, and Open5GS together with srsRAN were proposed to be the candidates. The second category was to use the existing R&S mobile network simulators; CMW500 and CMX500. During the experiments, our findings indicate that the identification of test setups requires good knowledge and understanding about the NFRs at the connectivity level, as well as the corresponding QoE demand of each use case. For instance, when use cases are based on IP, tools such as the TCS can fulfil the need for getting an understanding of how the IP layer behaviour impacts the QoE. Conversely, if a use case requires a TCU/modem with an antenna then tools like R&S simulators or srsRAN with a radio interface are essential for connecting the TCU. Moreover, even in IP-based use cases, radio information from the modem may be utilized for internal optimization, making tools like TCS unsuitable. In other words, the selection of a test setup depends heavily on the NFR and QoE demands of each use case. Analysing the costs and expenses associated with building and configuring each test setup is also important. However, it is challenging to evaluate solely based up on the capital investment, as open-source tools and inexpensive hardware do not necessarily equate to being cost-effective. The complete life cycle including usage and maintenance must be considered. Additionally, the competence about mobile networks and networking, in general, is important for understanding the relevant NFRs and KPIs.

Due to the complexity of the E2E connectivity flow, a pure theoretical analysis proved to be difficult. This challenge was overcome by selecting a few test setups to gain hands-on experience and build competence. Concurrently, we conducted live measurements to better understand typical values for parameters such as LTE signal strength and TCP download speed across different RAT and locations. This approach gradually enhanced our understanding of network influence factors and QoE.

Configuring and tuning the test setups have provided valuable insights into the network performance testing. The ability to experiment with different configurations has highlighted the importance of understanding the interaction between various parameters and their collective impact on user experience. Moreover, having a test setup in a controlled lab environment offers several advantages over real network testing. It allows for control over various parameters, enabling a thorough investigation of their impact on performance. Additionally, lab test setups provide a safe and repeatable environment for testing without the risk of disrupting live network services.

5 Disseminations and Publications

The findings from the SIVERT2 project have been shared via numerous publications and disseminations throughout the project. Internal demos at Scania and Volvo Cars have been held and a series of videos have also been made to spread interest for the project externally. The simulation framework developed within WP1 is also planned to be made publicly available. This section summarizes all disseminations and publications within the scope of the project.

5.1 Knowledge and Results Dissemination

Table 5-1 shows a summary of how the results from the project has been or is planned to be used or disseminated.

Table 5-1, Knowledge and Results

How has/will the project results be used and disseminated?	Defined in App-lication	Outcome	Comments
Increase knowledge within the area	Yes	Fulfilled	Several publications and dissemination have been made and videos to promote the final outcomes have been shared externally. Internal demos have been held for Scania/TRATON and Volvo Cars with a high level of participation. Volvo Cars and Lund University submitted and presented a technical document, " A realistic V2X real-time simulation with spatially consistent channel modelling", within scope of COST ACTION CA20120 The Intelligence-Enabling Radio Communications for Seamless Inclusive Interactions (INTERACT) in January 2023. The SIVERT2 simulation tool will be made publicly available.
Carried over to other advanced technical research projects	No		The simulation framework developed within WP1 may be further used within the VINNOVA funded Chalmers competence center WiTECH. OTA test methods in WP2 were partly developed in collaboration with the EU funded MEWS project (21NRM03 MEWS - Metrology for emerging wireless standards).
Carried over to product development projects	Yes	Fulfilled	Volvo Cars is using the developed test methods and simulation framework within the scope of the cellular verification strategy for upcoming projects. Scania is integrating both relevant test methods into the verification process for development and testing of new and existing connectivity products. The goal is to shorten lead time, reduce cost and increase the quality in connectivity projects. For RISE, the results have been applied in commercial OTA testing for OEMs and as tools in

			EU projects, proving their value. They also strengthen our position in international project applications. For RanLOS, the development of the 3 GHz-6 GHz array feed in the project has led to ideas for further product development for the RanLOS measurement system.
Market introduction	No	Fulfilled	The lift and tilting device, RanLOS BeamTilt, that was developed during the project is now ready as a product on the market. The same goes for the new feed array that was developed for the RanLOS measurement system. RISE has introduced several OTA test services for 5G evaluation. These services are primarily designed to support the Swedish industry but are also available to international customers.
Be used in investigations /regulations/ political decisions	Yes	Fulfilled	The framework was presented and discussed in the COST action INTERACT (CA20120), which is seen as a pre-standardization community with participants from academia, institutes and industry.

5.2 Internal Demo – Volvo Cars

An internal Volvo Cars demo for the SIVERT2 project was held on the 3rd of June 2025. The invitation to the event was sent out to personal at Volvo Cars working with connectivity or wireless communication and to the research community within Volvo Cars. The demo/exhibition was held at the Volvo Cars Lindholmen office and approximately 100-150 people attended. The demo was in an exhibition style and therefore difficult to estimate the exact number of participants. In addition to the exhibition a presentation was held, with focus on the achievements and how Volvo Cars can incorporate the project outcomes into the vehicle development projects.

The exhibition was done in collaboration with the project partners. WP1 had one station showing both the simulation framework for cellular 5G and one for V2X. WP2 had three stations, one showing the Amari Callbox and explaining the RC tent, one station to show the RanLOS measurement system with a miniature reflector and turntable. The last station was the wireless cable setup with the channel emulator. The wireless cable station also showed how the simulation framework from WP1 can be used in the channel emulator. WP3 had three stations, one station to show how Volvo Cars has built an internal webpage to collect and display fleet data, focusing on connectivity parameters. The second station showed the TCS, and the last station used the open5Gs test setup, connected to a HIL rig, testing the Google Assistant use case.

Figure 5-1, The Volvo Cars Demo

Volvo Cars would like to thank RISE, Tietoevry, Lunds University and RanLOS for assisting the demo, without their help the demo would have not been as successful.

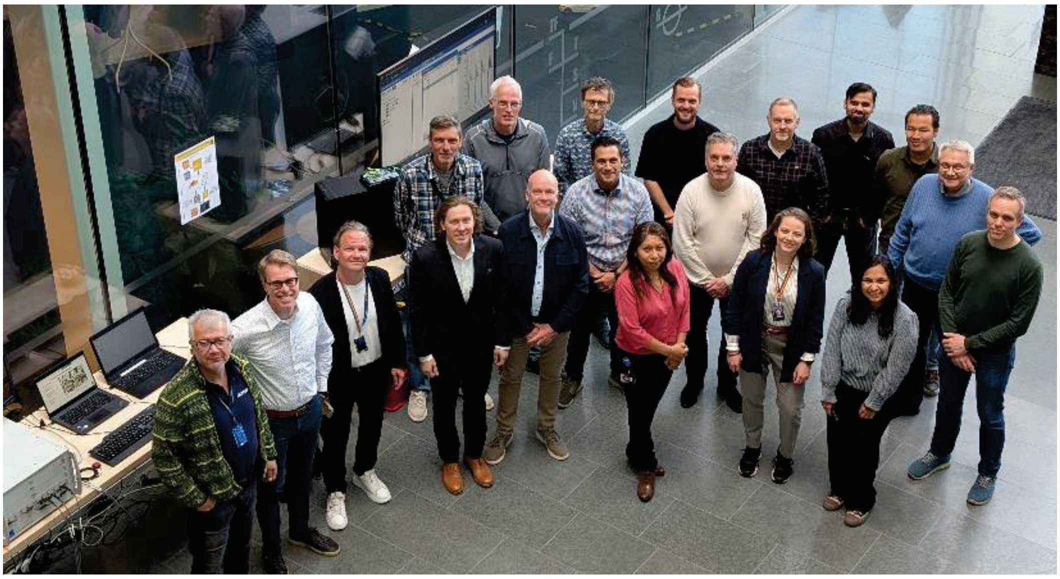


Figure 5-2, The people organising the Volvo Cars demo

5.3 Internal Demo – Scania

An internal Scania/TRATON demo for the SIVERT2 project were held 4th of June 2025. The invitation to the event was sent out to the management teams within TRATON Group R&D responsible for connectivity and hardware as well as relevant test teams. The demo was held in the Tietoevry office in Karlstad with one full day reserved for the project. TRATON had approx. 20 people visiting onsite in Karlstad and additional participants online. The demo was organized in two parts. The first part was organized as a hybrid session for both onsite and online participants with a walkthrough of the results in respective work package with pre-recorded demo videos and a concluding session with key

Figure 5-3, onsite demo visitors and the Scania project team

takeaways from the project. The second part was a live demo for the onsite participants with demonstrations of representative test setups and discussions with the team members. Scania would like to thank Tietoevry for hosting this event and RISE for assisting with the demo. Our joint effort made this a very successful and appreciated event.

5.4 Papers

Y. Feng, "Study of a Hybrid Solver Method for Vehicle Installed Antenna Simulation" in 2025 19th European Conference on Antennas and Propagation (EuCAP), Stockholm, Sweden, Apr. 2025.

K. Karlsson, A. Fedorov, N. Lyamin, F. Tuvesson, "Channel emulation for OTA test based on a simulated channel in a V2V drive scenario" in 2025 19th European Conference on Antennas and Propagation (EuCAP), Stockholm, Sweden, Apr. 2025.

D. Radovic, M. Hofer, F. Pasic, E. M. Vitucci, A. Fedorov, T. Zemen "Methodologies for Future Vehicular Digital Twins", arXiv:2312.09902, Dec. 2023

X. Cai, M. Zhu, A. Fedorov, F. Tufvesson, "Enhanced effective aperture distribution function for characterizing large-scale antenna arrays", IEEE Transactions on Antennas and Propagation 71 (8), pp 6869-6877, 2023

W. Tärneberg, A. Fedorov, G. Callebaut, L. Van der Perre, E. Fitzgerald, "Towards practical cell-free 6G network deployments: An open-source end-to-end ray tracing simulator", 2023 57th Asilomar Conference on Signals, Systems, and Computers, 1000-1005, 2023

5.5 Disseminations

- M. S. Kildal, Microwave Road event February 2023, "Why continuous measuring is needed for automotive industry to reduce connectivity errors"
- K. Karlsson, Microwave Road event February 2023, "OTA test methods for cars, trucks, and other connected machines"
- M. S. Kildal, J. Carlsson and L. Rosdahl, ”RanLOS vehicular measurement system for 3-6 GHz", Abstract to Swedish Microwave Days 2023, Stockholm, Sweden, May 2023.
- L. Granbom, Microwave Road event March 2025, "RanLOS solution for OTA and antenna Measurements"

- N. Lyamin, Microwave Road event April 2025, “Vehicular Wireless Communication Evaluation using SIVERT2 Simulation Framework”
- N. Lyamin, F. Tufvesson, A. Fedorov, "A realistic V2X real-time simulation with spatially consistent channel modelling", Technical Document within scope of COST ACTION CA20120 The Intelligence-Enabling Radio Communications for Seamless Inclusive Interactions (INTERACT), Dubrovnik, Croatia, January 2023.
- K. Karlsson, “5G OTA Testbed for full-sized Vehicles in Reverberation Chamber” in 2024 18th European Conference on Antennas and Propagation (EUCAP), Glasgow, Scotland, Apr. 2024. Conference Workshop.
- F. Tufvesson, “Channel modelling and characterization for communication and sensing in a 6G era”, Keynote, AES 2023, 9th International Conference on Antennas and Electromagnetic Systems, Torremolinos, Spain, June 2023.

6 Conclusions

The SIVERT2 project has addressed verification of vehicle connectivity modules in a comprehensive manner, from simulations in early phases of a vehicular project to final verification of implemented systems in complete vehicles. The verification methods span the complete OSI model, including both RF level and end-to-end performance. A more extensive conclusion for each work package can be found in the corresponding chapters.

The project has been focused on three research questions.

- Shift left: how to do testing earlier in vehicle development projects?
- How to get a more data driven connectivity design?
- How can we bridge the gap between vehicle applications and connectivity requirements?

The first and the second questions have been addressed by successfully setting up lab test methods that can be applied before there is a driveable vehicle and a simulation framework that can be used in concept phases before any connectivity hardware is available. The reverberation chamber test method can now be applied for 5G RF testing of complete vehicles and the RanLOS measurement system can be used for semi-3D antenna pattern measurements to secure appropriate radiation patterns for complete vehicles. The simulation framework is now capable of full system simulations for both long-range vehicle-to-network and short-range vehicle-to-vehicle communication. By adapting scenarios representative to real-world wireless channel conditions for vehicles, the accuracy of the simulations is ensured.

Using advanced CAD methods like antenna system modelling, system level simulations and hardware in the loop leads to improvement in wireless design, make concepts and prototypes more robust, shorten the design cycles and enable earlier performance evaluation and verification. This should make wireless products more reliable, reduce amount of late project changes, minimise slip-through design and configuration errors.

The third research question was addressed by analysing the end-to-end path of selected connectivity use cases. This involved conducting measurements in live networks and setting up dedicated end-to-end test environments to assess the impact of various Network Influence Factors (NIFs) on user Quality of Experience (QoE). Using the methodology, we gained valuable insights into how different NIFs affect the resulting user experience. Furthermore, the evaluation of the test setups revealed that while certain configurations are better suited for specific test cases, a cost-efficient and versatile testing strategy requires a combination of different setups. Ultimately, the decision was made to forego full vehicle end-to-end testing in a chamber, opting instead to focus on sub-system testing. This approach is more practical and easier to integrate into a broader vehicle verification strategy

Comparing the outcome from the project with the originally defined scope of the work, most of the targets have been met. The findings of SIVERT1 laid the foundation for the Volvo Cars verification strategy for cellular connectivity, which now together with Lund University has been extended to include 5G communication as well as the vehicle-to-network simulations. The provided prototype test setups and scenarios for complete vehicles have been developed and commercialized by RISE and RanLOS. Future work should address details of the test setups for specific scenarios, such as the exact scenarios to use for two-stage methods and loading conditions of the reverberation chamber for all 5G bandwidths and numerologies etc. Finding a link between end-to-end user experience and the non-functional requirements assessed with the lab test methods is a particular pending challenge. Overall the project has laid the foundation for future-proofing the wireless communication verification frameworks for Volvo Cars and Scania.

7 Participating Parties and Contact Persons

The following organizations were part of this project and the main contact persons for each company:

- Lund University: Fredrik Tufvesson and Aleksei Fedorov
- RanLOS: Madeleine Schilliger Kildal, Jan Carlsson, Joakim Lundberg, Pär Westerlund, Louice Rosdahl and Lars Granbom
- RISE: Kristian Karlsson and Fredrik Harrysson
- Volvo Car Corporation: Ida Hagström, Christian Patané Lötbäck, Nikita Lyamin, Mikael Nilsson, Björn Bergqvist, Mujeeb Ur Rehman, Feihong (Fiona) Ou and Edith Condo Neira
- Scania: Tommy Englund and Yi Feng
- Tietoevry: Henrick Bengtsson, Håkan Blomkvist and Patrik Forslund

8 Annex

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8.2 Abbreviations

3GPP 3rd Generation Partnership Project
5GAA 5G Automotive Association
5GC 5G Core
AC Anechoic Chamber
AD Automated Driving
ADAS Advanced Driver Assistance System
ALSE Absorber Lined Shielded Enclosure
APN Access Point Name
B2B Business to Business
B2C Business to Consumer
BLER Block Error Rate
BS Base Station
Cat-M Category M1
CDR Charging Data Records
CE Channel Emulator
CIF Common Intermediate Format
CN Core Network
CMW500 Rohde & Schwarz wideband radio communication tester
COTS Commercial-off-the-shelf
CTS Conducted Two Stage
C3 Connected Car Cloud
DAU Data-Unit-Application
DID Diagnostic Information Display
DL Downlink
DNS Domain Name System
DRO Diagnostic Read-Outs
DUT Device Under Test
E2E End-to-End
ECU Electronic Control Unit
eCall Emergency call using circuit-switched technology
EMI Electromagnetic Interference
eMTC Enhanced machine-type communication
eNB Evolved NodeB (4G)
EPC Evolved Packet Core (4G)
EPS Evolved Packet System
E-UTRAN Evolved-UMTS Terrestrial Radio Access Network
FDD Frequency Division Duplex
FR1 5G, Frequency range 1(410 MHz to 7.125 GHz)
FR2 5G, Frequency range 2 (above 24 GHz)
GA Google Assistant
GB Gigabyte
GERAN GSM EDGE Radio Access Network
gNB Next Generation NodeB (5G)
GSMA Global System for Mobile communication Association
GUTI Global Unique Temporary Identifier
HIL Hardware In the Loop
HD High Definition
IoT Internet of Things
IP Internet Protocol
IPX Internetwork Packet Exchange
IVE In-Vehicle Entertainment
IXP Internet Exchange Point
KPI Key Performance Indicator
LTE Long Term Evolution (4G)
MCC Mobile Country Code
MIMO Multiple Input Multiple Output
MME Mobility Management Entity
MNC Mobile Network Code
MNO Mobile Network Operator
MOS Mean Opinion Score
MSA Measurement System Analysis
ms Milliseconds
MPAC Multi-Probe Anechoic Chamber
NB-IoT Narrowband IoT
NFR Non-Functional Requirements
NGeCall Next generation eCall using packet switched technology
NPN Non-Public Network
NR New Radio (5G)
NSA Non Standalone (5G RAN with 4G CN)
NW Network
OEM Original Equipment Manufacturer
OSI Open Systems Interconnection
OTA Over-the-Air

PDN Packet Data Network
PGW Packet Gateway
PLMN Public Land Mobile Network
PPS Packet per Second
PSAP Public Safety Answering Point
QAM Quadrature Amplitude Modulation
QCI QoS Class Identifier
QoE Quality of Experience
QoS Quality of Service
RAN Radio Access Network
RAT Radio Access Technology
RC Reverberation Chamber
RF Radio Frequency
RISE Research Institutes of Sweden
RSRP Reference Signal Received Power
RTS Radiated Two-Stage
RTT Round Trip Time
SA Stand Alone (5G)
SAC Semi-anechoic Chambers (also ALSE)
SAS Keysight's interoperability test solution
SCPI Standard Commands for Programmable Instruments
SGW Serving Gateway
SIM Subscriber Identity Module
SIVERT2 SImulation and VErification of wiReless Technologies, project 2
SLA Service Level Agreement
SLI Service Level Indicator
SoR Steering of Roaming
SW Software
SWDL Software Download
TAU Tracking Area Update
TCP Transmission Control Protocol
TCU Telematics Control Unit
TDD Time Division Duplex
TDL Tapped Delay Line
TS Technical Specification
TTL Time To Live
UE User Equipment
UL Uplink
UMTS Universal Mobile Telecommunications System
UPF User-Plane Function
URLLC Ultra-Reliable Low Latency Communication
UTRAN UMTS Terrestrial Radio Access Network
UXM Keysight wireless test solution
VRC Variable Reference Channels
VDT Virtual Drive Test
V2I Vehicle to Infrastructure
V2N Vehicle to Network
V2V Vehicle to Vehicle
V2X Vehicle to Everything
VIDA Vehicle Information and Diagnostics for Aftersales
VoLTE Voice over LTE
VoNR Voice over NR
VR Virtual Reality
WC Wireless Cable
WP1 Work Package 1
WP2 Work Package 2
WP3 Work Package 3

8.3 Report Authors

This report has benefited from the contributions of many individuals, with different chapters and sections authored by various writers. As a result, the language and style may vary throughout the document, and we appreciate the readers understanding in this regard. Table 8-1 below identifies the primary author/authors responsible for each part.

Table 8-1, Report Authors

CHAPTER/SECTION	AUTHOR/AUTHORS
4.2	Nikita Lyamin (Volvo Cars), Aleksei Fedorov (LTH), Feihong Ou (Volvo Cars), Yi Feng (Scania), Björn Bergqvist (Volvo Cars)
4.3	Kristian Karlsson (RISE), Mujeeb Ur Rehman (Volvo Cars), Madeleine Schilliger Kildal (RanLOS), Yi Feng (Scania)
4.4	Ida Hagström (Volvo Cars), Henrick Bengtsson (Tietoevry), Håkan Blomkvist (Tietoevry), Tony Bergh (Tietoevry)
6	Ida Hagström (Volvo Cars), Christian Lötbäck (Volvo Cars)
The rest of the report is mainly written by Ida Hagström (Volvo Cars) with contributions from the project participants	

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