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Automotive Intelligence for/at Connected Shared Mobility

Deliverable	***Integrated prototype of fast, reliable and secure V2X communication system***		
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Disclaimer

Table of contents

1 Executive/ Publishable summary

Deliverable 5.12 (D5.12), titled “Integrated prototype of fast, reliable and secure V2X communication system”, is an outcome of task 5.5 (T5.5), titled “Integration of systems for Connectivity and Communications”, which is led by FHG (HHI).

Deliverable 5.12 (D5.12) addresses the integration, deployment and demonstration of the project results of supply chain 5 (SC5). As already mentioned in the past deliverable 1.5 (D1.5), the outcome of supply chain 5 (SC5) will be two demonstrators.

This document discusses both the individual work done by each contributing partner regarding the supply chain demonstrators (SCDs) and also the concept, how to integrate/connect/combine the components that will form the final demonstrators.

Deliverable 5.12 (D5.12) is followed by deliverable 5.13 (D5.13), titled “Report on integration of prototype of fast, reliable and secure V2X communication system”, that is due end of project and will summarize the work in task 5.5 (T5.5).

2 Non publishable information

All the information below is publishable.

3 Introduction & Scope

3.1 Purpose and target group

Deliverable 5.12 (D5.12) addresses the system integration and use case description of the cognitive based V2X connectivity platform for combined connectivity, facilitating different transportation domains and smart mobility services.

To give a better understanding of the deliverable’s position within the project, especially on its relation to the supply chain, work package and task, the next paragraph will give a brief overview.

Deliverable 5.12 (D5.12) is titled “Integrated prototype of fast, reliable and secure V2X communication system” and related to task 5.5 (T5.5). Task 5.5 (T5.5) is titled “Integration of systems for Connectivity and Communications” which is embedded in supply chain 5 (SC5) and work package 5 (WP5). Supply chain 5 (SC5) is titled “Connectivity and cognitive communication” and work package 5 (WP5) is titled “System integration”.

Task 5.5 (T5.5) copes with the integration of the developed methods and functions concerning communication and connectivity. Firstly, the secure in-car communication backbone will be integrated and its services for carsharing platform application will be tested. Secondly, the integration of the 28GHz 5G Connectivity RF Frontend to the onboard components of the connected vehicle will be performed.

Work package 5 (WP5) is dedicated to the integration, deployment and demonstration of the project results of the supply chain. In this case, the integration, deployment and demonstration of the results in supply chain 5 (SC5).

The outcome of supply chain 5 (SC5) are two supply chain demonstrators (SCD). The first one is demonstrator SCD 5.1: Proof-of-concept communication platform. For SCD5.1 the following partners are involved: TTTAUTO (lead), NXP, IMA and AIT. As stated in deliverable D1.5, the demonstrator will target a *prototype reference setup with corresponding SW environment with HW/SW mechanisms to showcase next automotive communication technologies. The demonstration will incorporate HW from TTTAUTO and NXP to showcase fast data channels among different controllers and the in-vehicle decision making module.*

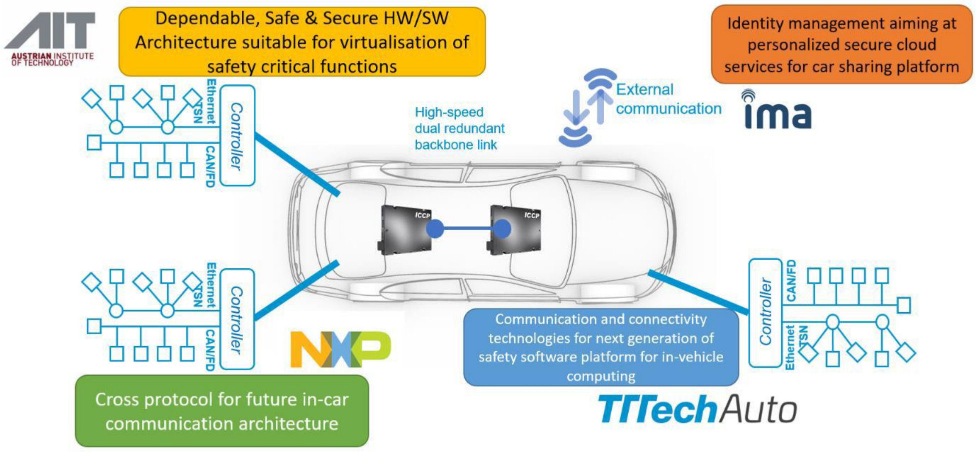


FIGURE 1 OVERVIEW OF THE KEY BUILDING BLOCKS AND PARTNER CONTRIBUTION WITHIN SCD 5.1 DEMONSTRATOR

The second demonstrator is SCD5.2: Proof-of-concept demonstrator novel wireless data transmission (edge/cloud) with the following partners involved: IFAG (lead), TUD, FHG (HHI), TTTAUTO and AIT. The demonstrator targets a setup that *will showcase high bandwidth 5G mmW radio modules incorporating Infineon 28GHz RFICs. The provided hardware will demonstrate unique 360° azimuth angle coverage with optimized low latency beamforming function at small form factor.*

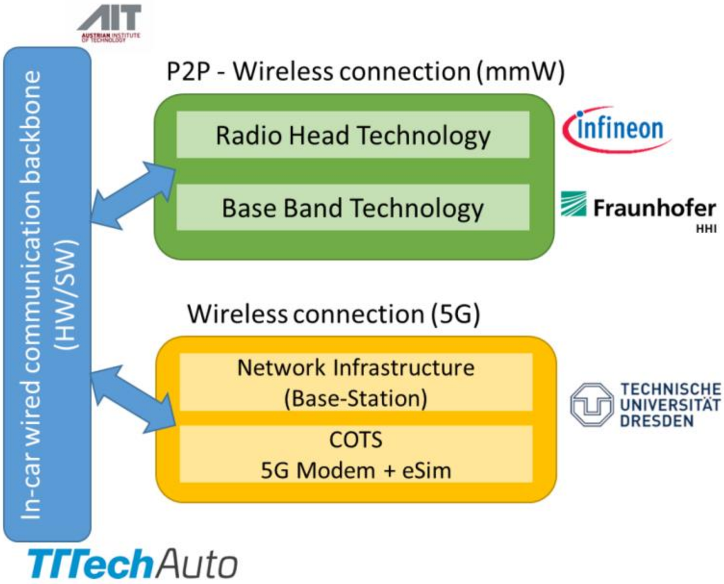


FIGURE 2 OVERVIEW OF THE KEY BUILDING BLOCK AND PARTNER CONTRIBUTION WITHIN SCD 5.2 DEMONSTRATOR

3.2 Contributions of partners

Contributing partners of this deliverable 5.12 (D5.12) are AIT, IFAG, FHG (HHI), TUD, IMA, NXPN and TTTAUTO. FHG is lead of task 5.5 (T5.5) and accordingly the corresponding partner.

The previous section gave an overview of the scope of task 5.5 (T5.5) with special regards to the supply chain demonstrators SCD5.1 and SCD5.2.

All contributing partners can be divided into one or more supply chain demonstrators. TTTAUTO and AIT are contributing both to SCD5.1 and SCD5.2. NXP and IMA are contributing to SCD5.1. IFAG, TUD and FHG (HHI) are contributing to SCD5.2

TABLE 1 CONTRIBUTIONS OF PARTNERS

Chapter	Partner	Contribution
4.1, 5.1, 5.2, 5.3, 5.4, 5.5	AIT	AIT is collaborating closely with SC5 lead TTTAUTOto define a concept for integrating FER prediction technology into the V2X communication system protype. Our work is focused on tackling the reliability aspect of the prototype.
4.2, 5.1, 5.2, 5.3, 5.4, 5.5	IFAG	IFAG is responsible of the mmW Frontend Module FEM Hardware
4.3, 5.1, 5.2, 5.3, 5.4, 5.5	FHG	FHG (HHI) contributed by implementing the LTE Sidelink according to 3GPP Release 14 and 5G NR-V2X Sidelink accord to 3GPP Release 16. Both implementations have been tested on a SDR platform. Additionally, FHG (HHI) has tested the FEMs provided by IFAG with a setup for 5G NR test sequence transmissions. The SDR platform was designed with regards to the IFAG FEM so that an integration of the FEMs is possible without extra hardware.
4.4, 5.1, 5.2, 5.3, 5.4, 5.5	TUD	TUD demonstrates a cloud native compute foundation (CNCF) compliant framework for computation in the network (COIN). One component is responsible for provisioning optionally takes uncertainty levels into consideration. Scaling experimentation and computation offloading under Service Level Agreement (SLA) constraints is shown for an energy-optimising solver.
4.5, 5.1, 5.2, 5.3, 5.4, 5.5	IMA	IMA developed components for improved, mobile device-based vehicle user identification with V2I connectivity for autonomous vehicle sharing use-cases. The individual components are being integrated with strong focus on secure ranging with ultra-wide band ranging technology. The integration and UWB stack implementation are delayed for approximately 4 months due to re-iterated system complexity with integrated robust ranging service. IMA integrated components for car access systems module focusing on wireless and contactless entry and related authentication process. One of the key points describes the integration of UWB ranging into the system.
4.6, 5.1, 5.2, 5.3, 5.4, 5.5	NXPN	At NXPN we have worked on integrating the in-vehicle communication setup with a realistic application to test the safe and secure connections. A self-driving application communicates with an automotive simulator exchanging sensor and actuator data over redundant (IEEE 802.1CB) Ethernet links with MACsec authentication.
4.7, 5.1, 5.2, 5.3, 5.4, 5.5	TTTAUTO	Provided technical description of the integration efforts concerning the communication platform, communication middleware layers developed in SC5 and deployed in SC1.

3.3 Relation to other activities in the project

As stated in a previous section, deliverable 5.12 (D5.12) is an outcome of task 5.5 (T5.5), which is embedded in supply chain 5 (SC5) and work package 5 (WP5). Figure 3 AI4CSM project WPs and SCs matrix. The matrix shows, that work package 5 (WP5) “System Integration” is relevant for all supply chains. Also supply chain 5 (SC5) “Connectivity and Cognitive Communication” is embedded in all work packages.

The AI4CSM description of work states the following, which is a well summary of WP5’s relation to the other work packages:

The objectives of WP5 are to integrate, deploy and demonstrate the results of the AI4CSM project supply chains. The outputs of WP2, WP3 and WP4, will be integrated, tested, and assessed in subsystem demonstrators to demonstrate the features in different vehicle functional domains. Different test set-ups including HW/SW will be implemented to demonstrate different ECAS vehicles functionalities needed to integrate the developed solutions, so they are ready to be demonstrated and tested on a test bench or a vehicle in WP6. The integration results in WP5 will be used to verify/validate the novel concepts, the requirements and technical specifications defined in WP1.

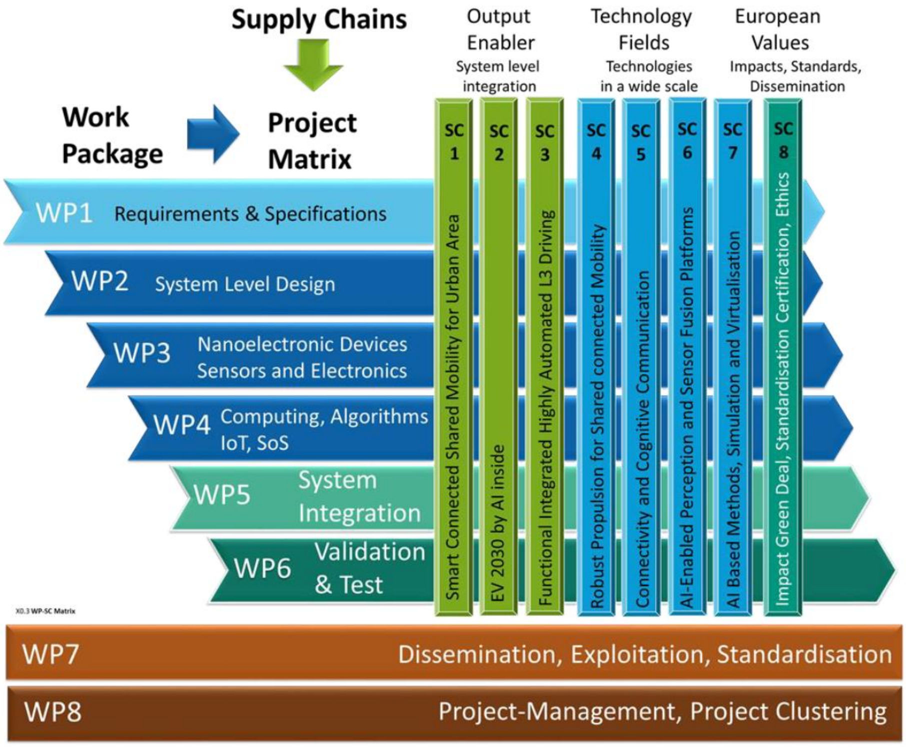


FIGURE 3 AI4CSM PROJECT WPS AND SCS MATRIX

4 Description of the technical work

The following sections give a detailed description of the technical work done within task T5.5 per contributing partner.

Section 4.1 is dedicated to the contribution by AIT. Section 4.2 is dedicated to the contribution by IFAG. Section 4.3 is dedicated to the contribution by FHG (Fraunhofer HHI). Section 4.4 is dedicated to the contribution of TUD. Section 4.5is dedicated to the contribution IMA. Section 4.6 is dedicated to the contribution by NXPN. Lastly, section 4.7 is dedicated to the contribution by TTTAUTO.

4.1 AIT Contribution

AIT is collaborating closely with SC5 lead TTTAUTO to define a concept for integrating FER prediction technology into the V2X communication system protype. Our work is focused on tackling the reliability aspect of the prototype.

4.1.1 Model for prediction

To provide the notion of our model, here we report on its size and structure. Our model consists of 6 layers and 37 million trainable parameters. The estimated total size of the model is 142.66 MB.

4.1.2 Model Interfaces

In order to enable proper integration of our Frame Error Rate (FER) model, here we define the interfaces to our model. Our model takes as input a Channel Transfer Function (CTF), encoded in time frequency domain, encapsulated in MAT or CSV format. As a result, the model gives the Frame Error Rate class in the form of range of the Frame Error Rate between two border values.

4.1.3 Integration challenges

It is important to note that the model was not trained of mmWave data, rather on 5.9GHz. This is due to the technical setup of our experiment: our modems are compliant to IEEE 802.11p standard, which is one of the de-facto standards for vehicle-to-vehicle communication in Europe.

4.1.4 Integration Concept

The integration prototype assumes that the model is successfully deployed on a V2X platform. For a successful integration, the model interfaces need to be satisfied. In addition, the platform has to comply with hardware requirements to be able to run the model and get predictions in real-time. The recommended hardware requirements for the V2X platform, based on the machine we used are the following: Linux-based Operating System, Matlab environment, 64GB RAM and x64 CPU running at 3,70 GHz.

4.2 IFAG Contribution

IFAG has setup a point 2 point (P2P) link in the IFAG lab showing the capability of their 28GHz mmW Frontend Modules. Several FEM's have been powered up and HW bring up is finished. The RF hardware verification was done in unmodulated (CW) mode. The software (Debug SW) for controlling the RF Frontend Module has been proven to be fully functional. A lookup table for beam steering was provided to HHI. Figure 4 shows the block diagram of the Frontend Module (FEM), as it was used for the test setup.

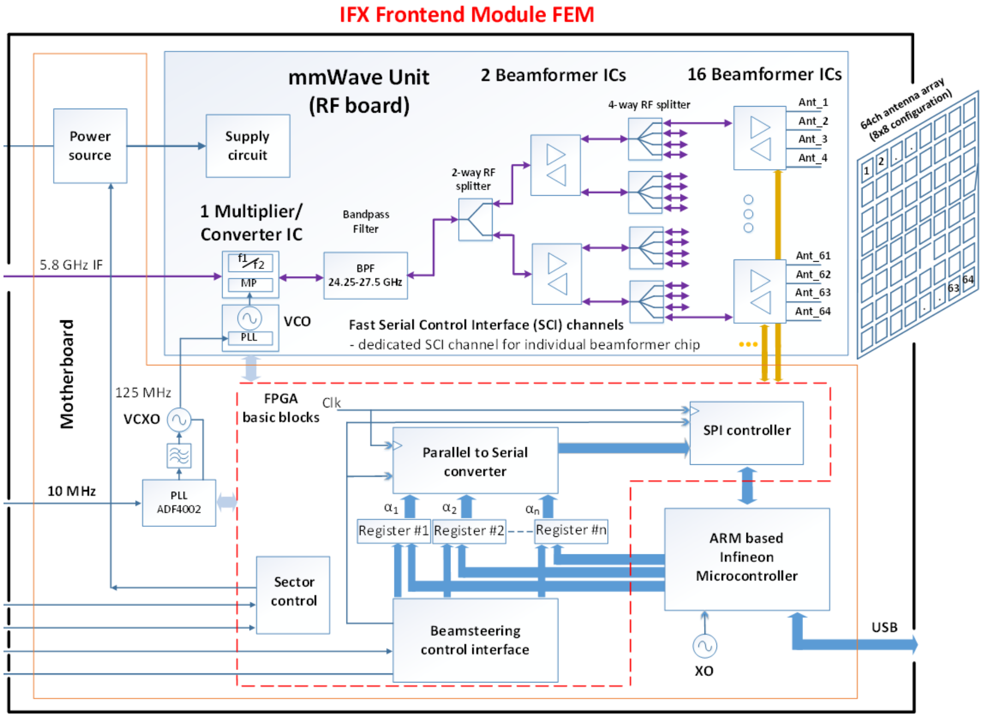


FIGURE 4: BLOCK DIAGRAM OF THE MMW FRONTEND FEM

A P2P testing of 2 FEM's had been done in 4m distance by using bore sight beams. Both FEM's had been controlled via USB debug port by the use of a measurement PC. All configuration data had been uploaded to the FEM for proper beam steering. Figure 5 shows the test setup for P2P CW testing.

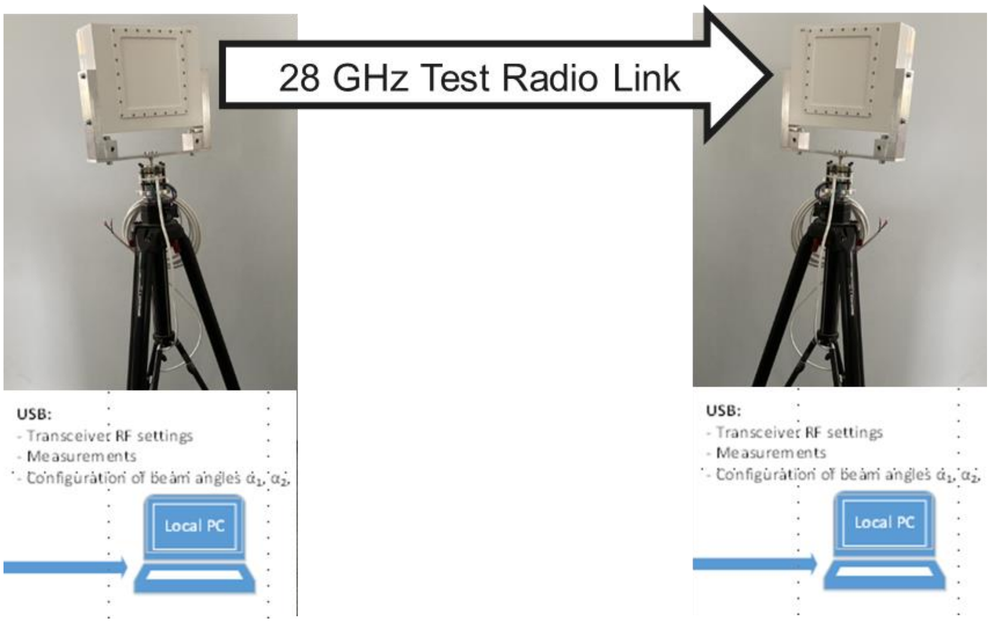


FIGURE 5 BASIC LINK TEST SETUP OF FEM FOR POINT 2 POINT

The same setup has built up at HHI site and FEM functionality was proven during a half day workshop. HHI is now ready to make use of the Modem part and test data transmission. Next step will be to focus on non bore sight beam steering, as it would be in a realistic V2V or V2X environment.

4.3 FHG Contribution

This section is dedicated to Fraunhofer HHI's contributions to the Supply Chain Demonstrator 5.2 (SCD5.2) named "Proof-of-concept demonstrator novel wireless data transmission (edge/cloud)". Fraunhofer HHI contributes to the demonstrator by implementing a Sidelink that runs on a Software-Defined-Radio (SDR) platform and integrating the front-end modules (FEM) provided by Infineon AG (IFAG). The aim is to have an ongoing Sidelink communication at millimetre-wave frequency range with the SDR platform provided by Fraunhofer HHI and the FEMs by IFAG. In the following, the Sidelink implementation is described and then the integration of the IFAG FEMs.

4.3.1 Sidelink Implementation

Within the project, Fraunhofer HHI is developing a Sidelink implementation according to 3GPP Release 14 and beyond. Regarding the LTE Sidelink implementation according to 3GPP Release 14, the development is finished and already tested on a SDR platform. While the LTE Sidelink according to Release 14 mainly targets basic safety use cases, the 5G NR-V2X Sidelink according to Release 16 paves a path for autonomous driving.

Since the project addresses Automotive Intelligence for/at Connected Shared Mobility, Fraunhofer HHI was focused on the implementation of the 5G NR-V2X Sidelink according to Release 16. Therefore, important technical foundations for the implementation were laid and specific work has already been carried out on the software platform.

Within the project, most of the physical (PHY) layer aspects were implemented including: Physical Sidelink Broadcast Channel (PSBCH); Physical Sidelink Shared Channel (PSSCH); Physical Sidelink Control Channel (PSCCH); Sidelink Primary/Secondary Synchronization Signal (S-PSS/S-SSS) and Physical Sidelink Feedback Channel (PSFCH).

Besides the PHY layer implementation, an implementation of the medium access (MAC) layer started. The MAC layer procedures are essential for an efficient selection of communication resources and avoidance of conflicts in multi-user environments. This includes an interface between PHY and MAC layers to serve as a foundation for MAC layer development. This interface facilitates configuration on PHY layer parameters by mechanisms implemented at MAC and, subsequently, higher layer protocols

The implemented parts of the 5G NR-V2X Sidelink are tested with a software simulator (RFSim) in a point-to-point data transmission between two user terminals scenario, before starting with over-the-air (OTA) tests.

A selection of suitable hardware for the SDR platform was carried out with a view to the millimetre-wave FEM provided by IFAG. The following components were selected: Intel NUC computing unit for baseband signal processing and USRP B210 for up/down-conversion to the intermediate frequency (IF) of 5.8 GHz.

With the components mentioned previously, a hardware-in-the-loop setup was realized with a channel emulator (Keysight Propsim64) that allows the manipulation of the RF signals according to various wireless channel conditions in different scenarios. Table 6Figure 6 shows the block diagram of the test setup.

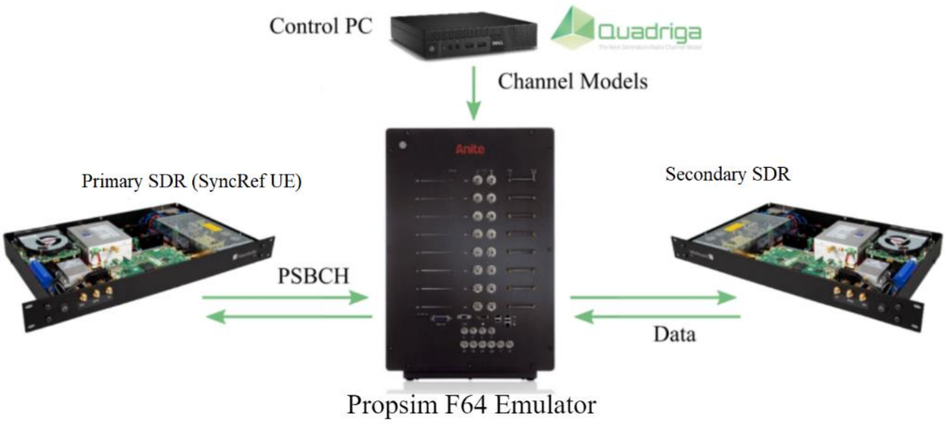


FIGURE 6 BLOCK DIAGRAM OF TEST SETUP WITH CHANNEL EMULATOR

For testing the Sidelink implementation, the behaviour of the Packet Error Rate (PER) with increasing Signal-to-Noise Ratio (SNR) was evaluated for two channel models, taken from the 3GPP specification, involving frequency-selective fading and additive white Gaussian noise as impairments (3GPP 5GNR 1x1 TDLA30-5 and IS 95 1Tap). Figure 7 visualizes the PER over the SNR for the channel emulator setup.

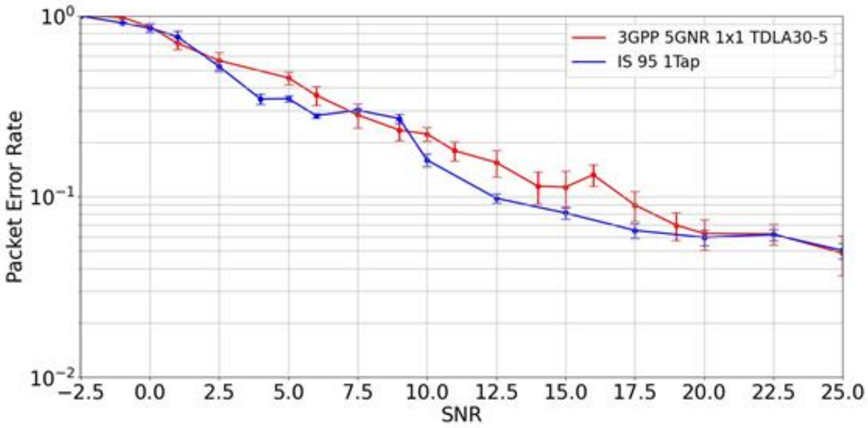


FIGURE 7 PER OVER SNR FOR SETUP WITH CHANNEL EMULATOR

Lastly, the Sidelink implementation was tested with an OTA setup at 5.8 GHz for various distances. The frequency of 5.8 GHz was chosen with regards to the SCD5.2 demonstrator's intermediate frequency. For the OTA tests, the PER was evaluated over the distance. Figure 8 visualizes the PER over the distance for the OTA trials.

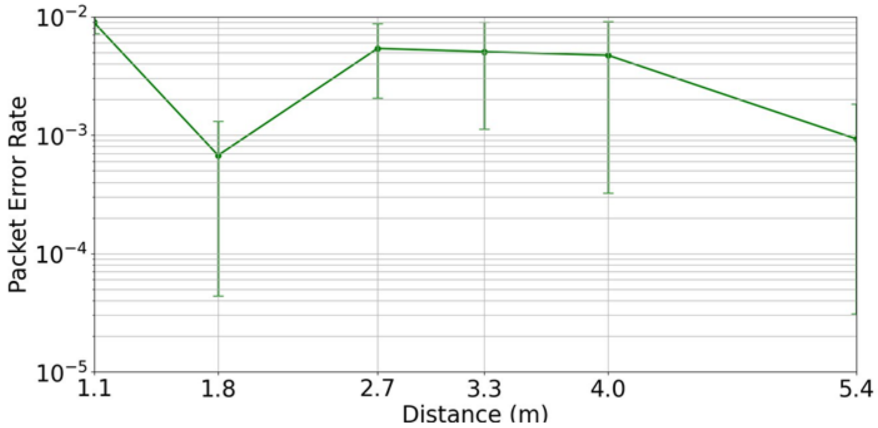


FIGURE 8 PER OVER DISTANCE FOR OTA SETUP

4.3.2 Integration of IFAG FEM

For realization of the demonstrator SCD5.2, the FEMs provided by IFAG have to be integrated into the SDR platform that is running the Sidelink implementation. Prior to that, the FEMs have to be tested in the lab in a controlled environment with controlled transmission signals.

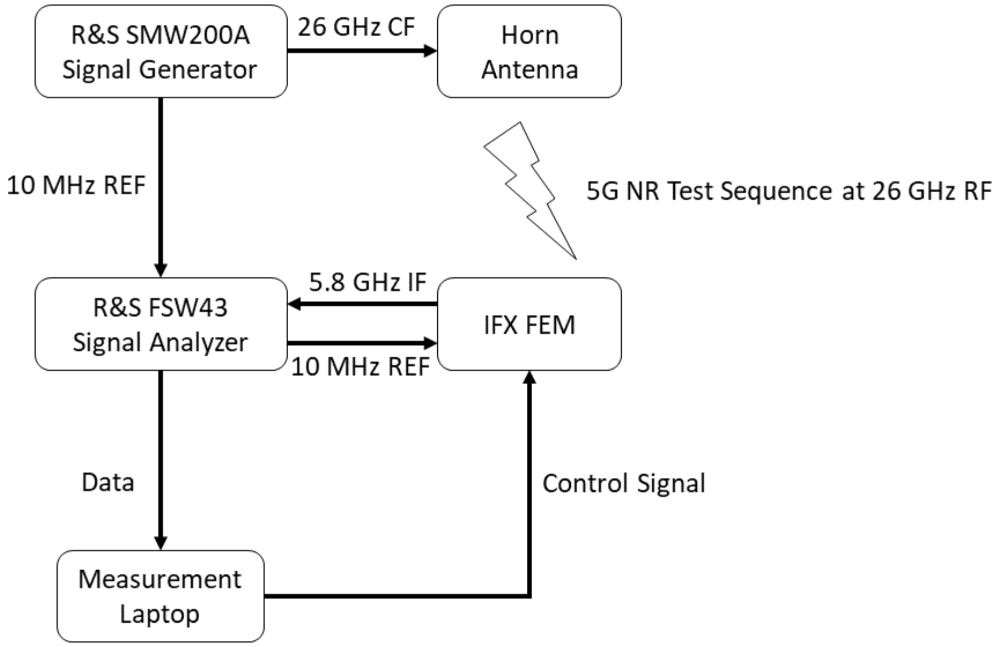
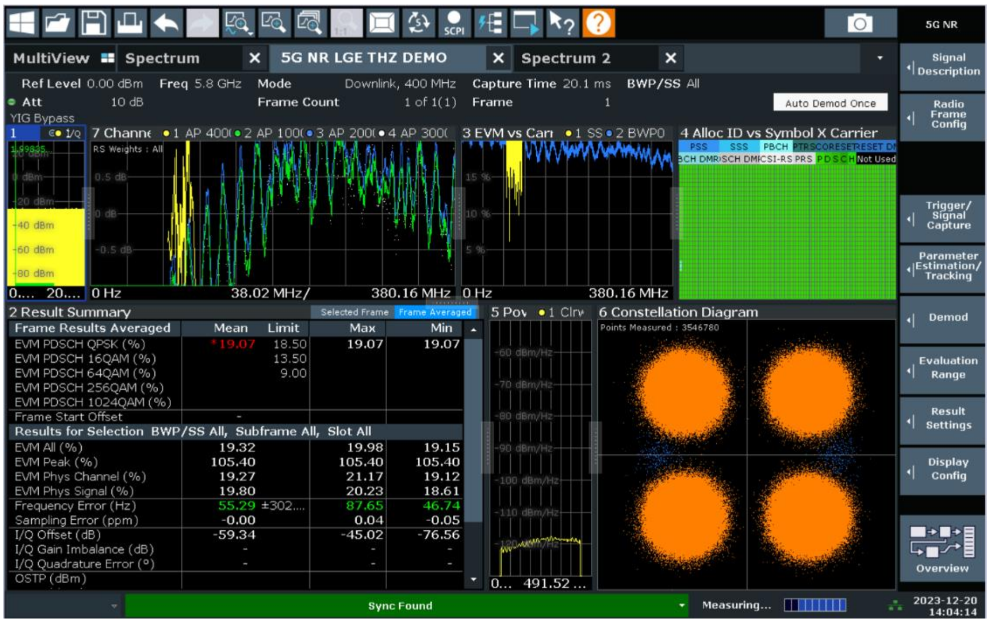


FIGURE 9 BLOCK DIAGRAM OF LAB TEST SETUP WITH IFAG FEM

Therefore, Fraunhofer HHI has tested the FEMs with a vector signal generator (VSG) and a vector signal analyser (VSA). As VSG, a R&S®SMW200A was used, that generated a 5G NR test signal. The test signal is generated at a frequency of 26 GHz, which will be the carrier frequency of the demonstrator. As a transmit antenna, a horn antenna with a gain of approx. 20 dBi was used. At the receiver side, a R&S®FSW43 was used as a vector signal analyser. As a receiving antenna an IFAG FEM was used, that down-converted the signal to an IF of 5.8 GHz. The VSA analyses the received IF signal and calculates typical parameters such as Error-Vector-Magnitude (EVM) and frequency error. The data is stored on a measurement laptop which also configures the IFAG FEM. The whole measurement is automatized. Figure 9 visualizes the block diagram of the lab test setup.



Ref Level 0.00 dBm Freq 5.8 GHz Mode Downlink, 400 MHz Capture Time 20.1 ms BWP/SS All
Att 10 dB Frame Count 1 of 1(1) Frame 1
YIG Bypass
Auto Demod Once

2 Result Summary (Selected Frame / Frame Averaged)

Frame Results Averaged	Mean	Limit	Max	Min
EVM PDSCH QPSK (%)	*19.07	18.50	19.07	19.07
EVM PDSCH 16QAM (%)		13.50		
EVM PDSCH 64QAM (%)		9.00		
EVM PDSCH 256QAM (%)				
EVM PDSCH 1024QAM (%)				
Frame Start Offset	-			
Results for Selection BWP/SS All, Subframe All, Slot All				
EVM All (%)	19.32		19.98	19.15
EVM Peak (%)	105.40		105.40	105.40
EVM Phys Channel (%)	19.27		21.17	19.12
EVM Phys Signal (%)	19.80		20.23	18.61
Frequency Error (Hz)	55.29	±302....	87.65	46.74
Sampling Error (ppm)	-0.00		0.04	-0.05
I/Q Offset (dB)	-59.34		-45.02	-76.56
I/Q Gain Imbalance (dB)	-		-	-
I/Q Quadrature Error (°)	-		-	-
OSTP (dBm)				

FIGURE 10 OUTPUT OF 5G NR TEST WITH VSA AND VSG

The figure reports that the EVM for Quadrature Phase-Shift Keying (QPSK) is only a few percentage (approx. 0.6%) over the limit. This can be adjusted for future test by supervision of IFAG. More interestingly, the frequency error is 55.3 Hz, which is around 33 Hz below the limit. Figure 10 shows the output of the 5G NR test software.

Future tests will include higher order modulations, such as Quadrature Amplitude Modulation (16QAM, 64QAM etc.). Within the next months, the IFAG FEM will be tested with the SDR platform running the Sidelink implementation.

4.4 TUD Contribution

4.4.1 Consistent and Cloud-ready Architecture

Modern cloud computing (CC) environments can support use cases that demand computation at nearly arbitrary scale, and have gained widespread popularity. These characteristics make CC attractive for use in the domains of autonomous driving, as well as Multi-Access Edge Computing (MEC) as defined by ETSI. A clear trend in the semiconductor industry is moving from monolithic building blocks for processing units, to Systems on Chip (SoCs), Chiplets, or disaggregated units linked by interconnects. The same is true in the datacentre, where custom silicon has replaced of-the-shelf switches for high performance applications (cf. Jupiter Evolving[1]).

The provisioning of cloud systems often makes use of the elasticity of the cloud computing, i.e., growing with current demands. In critical applications, over-provisioning is typically used because bottlenecks tend to lead to locking behaviours. Using faster machines tends to yield diminishing returns (cf.Figure 11).

The microservice paradigm approaches this with the decoupling. Single components can be replicated and connected according to the application's needs and current demand. This scaling out can be achieved for example by the Kubernetes Horizontal Pod Autoscaler. Reserving hardware, even virtualised, is not free though. Overprovisioning is costly, and just-in-time provisioning should be

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[1] Poutievski, Leon, et al. "Jupiter evolving: transforming google's datacenter network via optical circuit switches and software-defined networking." *Proceedings of the ACM SIGCOMM 2022 Conference*. 2022.

preferred. Uncertainty Quantification is the approach chosen in this project to navigate the decision-making problem of when and how much resources to request for a use case.
The expectation for a modern testbed is the utilisation of modern CNCF-like components. Thus, the best practices of cloud computing[2] were followed, which have already been put in production at scale[3]. The testbed is based on standardised tools, i.e., all components are to be containerised if not already done so by the developers or vendors. The consequence is a set of loosely coupled microservices, each with specific tasks, but clear boundaries and interfaces. Configuration of these components is done in config files, not separate setting dialogues. This allows for versioning and a clear mapping for every experimentation from configuration to results (or rather, to data and logs).

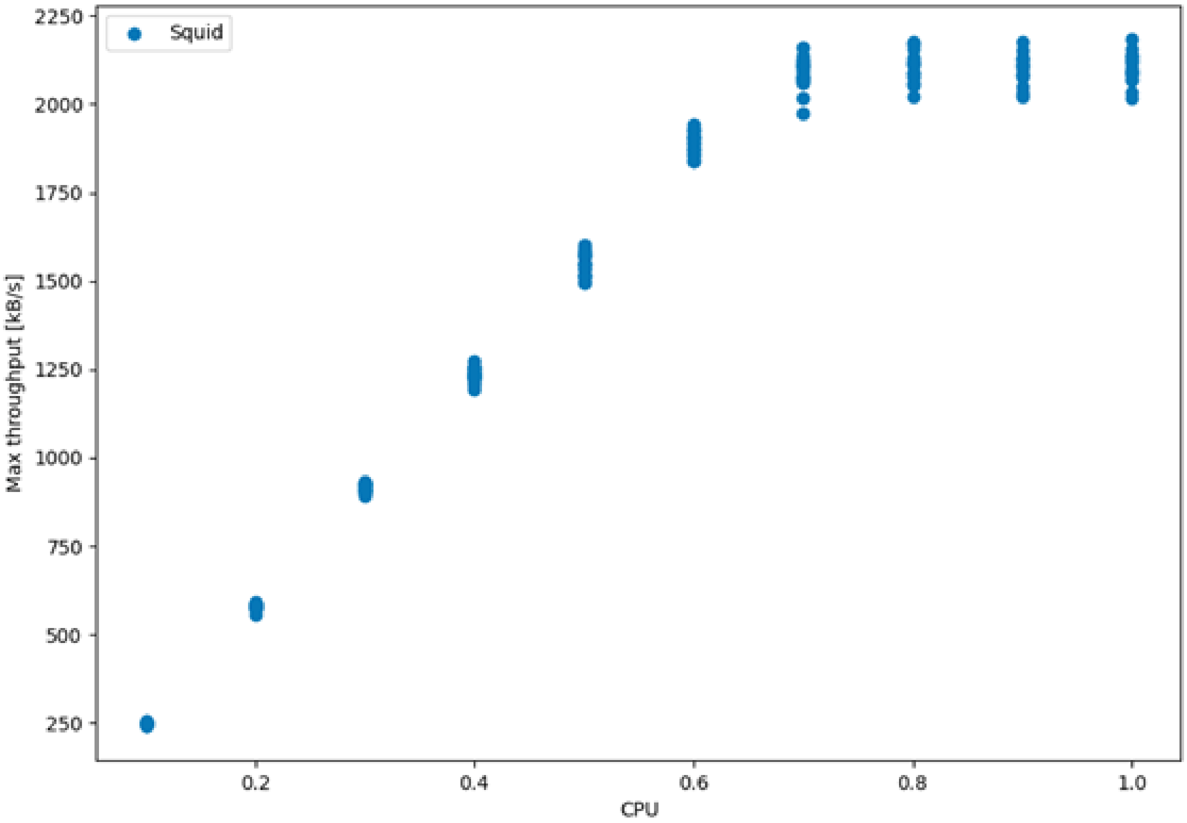

FIGURE 11 INCREASED CPU UTILISATION (X-AXIS) DOES NOT RESULT IN HIGHER PERFORMANCE MEASURES (Y-AXIS). SATURATION OCCURS IN APPLICATIONS, AND THEIR VARIANCE BALLOONS

MEC allows the support of (edge) devices (User Equipment in 3GPP terminology, UE) that find themselves in need of additional resources, be it storage or computation. Typically, servers are located at the base stations of a cellular network, where they run the mobile operator's tasks, such as functionality of the core or radio access networks. Increasingly, these capabilities are offered to customers. Applications that are designed to run on mobile user devices can be packaged to be split into subtasks, which form a Directed Acyclic Graph (DAG) of co-dependencies to prohibit race-conditions. These tasks may be distributed to various available nodes, and these typically have non-homogeneous computational capabilities.

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[2] https://12factor.net

[3] Brendan Burns, Brian Grant, David Oppenheimer, Eric Brewer, and John Wilkes. Borg, Omega, and Kubernetes. Communications of the ACM, 59(5), April 2016. doi: 10.1145/2890784. URL https://dl.acm.org/doi/10.1145/ 2890784

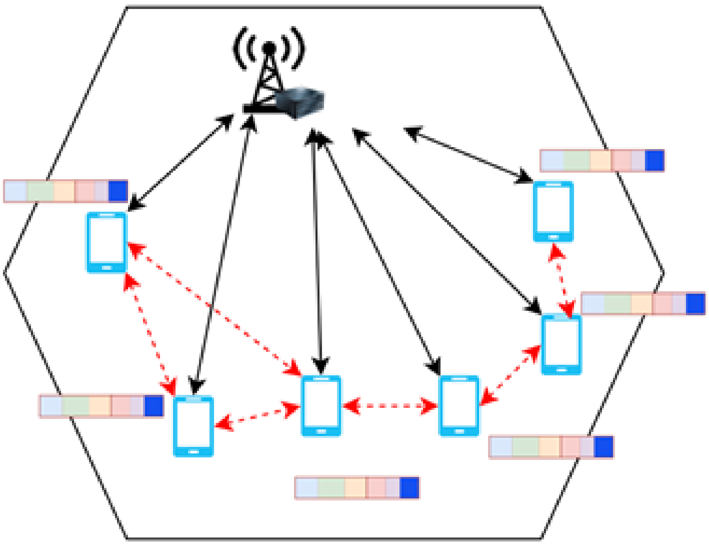

FIGURE 12 DEVICE-ASSISTED MEC

4.4.2 Setup and Application Description

Similar to modern developments in industry, the testbed uses Kubernetes as the foundation and final hardware abstraction. It serves to establish a structure for the deployment of workers, with the ultimate goal to launch containerized applications, hide the complexity of their networking stacks, service discovery, and observability. The Istio service mesh supports Kubernetes with envoy proxies in deployed pods, to gather metrics efficiently and easily. Load simulation is provided by the tools Locust and Fortio. They use arbitrary functions to define the characteristics of stress shaping, and we use configuration files to define these and their numerical expressions. Observation of the experimentation and the testbed as a whole is achieved using Prometheus and (on demand) the OpenTelemetry-compliant Jaeger tooling, which allow for both high-level and trace-level visibility. Storage of time series (for demand reporting, metrics scraping, end-to-end service latencies, etc.) is covered by InfluxDB. Confer Figure 13 for the architecture.

End to end latencies are recorded for any experiment. However, latencies are not plain numbers, but rather distributions, with long tails. Analytical approaches have in the past been subsumed by measurement (cf. The Tail at Scale[4]). Given the large number of data available, sufficient granularity is available to motivate this. The various percentiles of interest, i.e. 50th percentile (mean), 99th percentile, and 99.9th percentile is all routinely stored in the database. The large spread on the right side in Figure 11 is explained by this phenomenon.

Optimal provisioning is of course strongly dependent on the load characteristic and an open topic in research. The state-of-the-art solutions use *reactive* autoscalers that use reported service level metrics, such as the end-to-end latency of a service. The computation offloading problem is a Mixed-Integer Nonlinear Programming (MINLP) problem.

We set up the testbed as the platform for scaling experiments, as well as running optimisations for computation offloading under SLA constraints. We reason the performance impact of the abstraction introduced by the testbed is negligible, and in real world deployment, workloads are encapsulated by default as well as by policy.

The computation offloading problem is a Mixed-Integer Nonlinear Programming (MINLP) problem. Various constraints (confer the publication in the project[5]) address, among others, the mobility of users during their application's execution time and the prohibition of race conditions.

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[4] Jeffrey Dean and Luiz André Barroso. The tail at scale. Communications of the ACM, 56(2), February 2013. doi: 10.1145/2408776.2408794. URL https://dl.acm.org/doi/ 10.1145/2408776.2408794

[5] V. Latzko, O. Lhamo, M. Mehrabi, C. Vielhaus, and F. H. P. Fitzek, "Energy-aware and fair multi-user multi-task computation offloading," in 2023 International Conference on Computing, Networking and Communications (ICNC), 2023, pp. 231–236

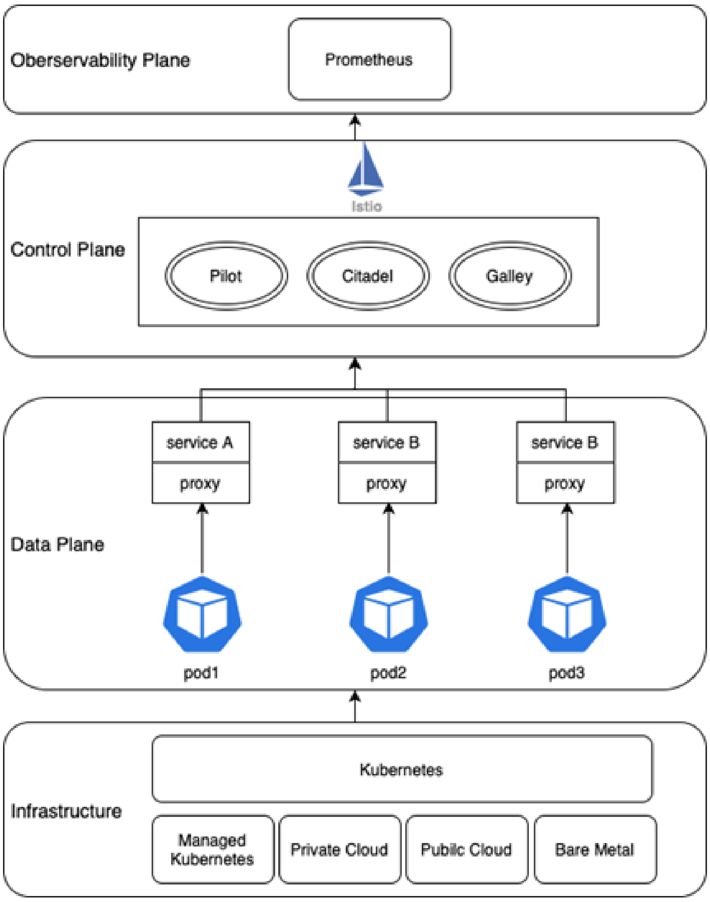

FIGURE 13 THE TESTBED ARCHITECTURE

We set up the testbed as the platform for scaling experiments, as well as running optimizations for computation offloading under SLA constraints. We reason the performance impact of the abstraction introduced by the testbed is negligible, and in real world deployment, workloads are encapsulated by default as well as by policy.

4.4.3 Containerised Solution and Optimisations

We formulate a MINLP-optimisation problem with suitable constraints. Since this is a NP-hard problem, we solve it using a hybrid Genetic-PSO Algorithm[6]. Evolutionary algorithms have proven robust to the noisy nature of the problem and were demonstrated[5]. Candidate solutions are iteratively mutated and shifted in the search space using Particle Swarm Optimisation. Details are supplied in an upcoming publication. We compare the scenarios for their total effort based on the fitness-values, All local (all tasks are executed on their UEs), All server (all tasks are completely offloaded to the edge), Computation cooperation (UEs can act as helper nodes, executing incoming tasks), Communication cooperation (UEs can act as relays, transmitting tasks to the edge for execution on the MEC), Accelerated cooperation (full flexibility with acceleration consideration on some fraction of the UEs), and finally Accelerated MEC (full flexibility, but only the base station is equipped with an accelerator). We average the scores for all experiments over 50 runs. For higher computational load of tasks, increased margin of our approach follows. The accelerated scheme beats all baselines. The same holds for increased data sizes, where more energy needs to be utilised for eventual offloading. This additionally increases the scores of all methods, as expected.

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[6] J. H. Holland, Adaptation in natural and artificial systems: an introductory analysis with applications to biology, control, and artificial intelligence. MIT press, 1992

We finally analyse a situation where telecommunications providers are looking to differentiate their offerings. We inspect the impact of added dedicated accelerators to the edge servers. To compare with a more conservative and more general-purpose upgrade case, we also model a doubling in CPU capabilities. When we sweep the computational complexity, we see a clear ranking, cf. Table 2. Deploying accelerators should be preferred, as it clearly has larger impact. Larger accelerator deployments are also clearly a path that should be explored in this situation.

TABLE 2 FITNESS METRIC FOR INCREASING COMPLEXITY OF WORKLOAD, FOR DIFFERENT CAPABILITIES OF THE MEC

Complexity	**8**	**18**	**26**	**37**	**62**	**71**	**80**
MEC	0.13	0.25	0.33	0.4	0.57	0.65	0.78
MEC double CPU	0.12	0.21	0.26	0.31	0.48	0.52	0.59
MEC accelerator	0.13	0.18	0.23	0.26	0.35	0.39	0.42

4.4.4 Conclusions

The Cloud systems' elasticity is testable in the testbed, which we demonstrated in the first section and tests. Our setup uses CNCF-compliant and industry-standard components. Full observability and transparency are achieved with monitoring and time series database, provided by Prometheus and InfluxDB. The bane of over-provisioning, all too common in critical applications to avoid bottlenecks, is addressed in later works. The foundations for resource allocation decisions under quantified uncertainty are laid, the controller interface is implemented.

MEC enables support for edge devices needing additional resources, like storage or computation. With the semiconductor industry's move towards SoCs and disaggregated units, our offloading framework distributes subtasks of a DAG to prevent race-conditions, which can be distributed to nodes with varying computational capabilities. We show significant improvements when exploiting the dedicated capabilities of the heterogeneous substrate.

4.5 IMA Contribution

The rapid evolution of automotive technology, combined with increasing demands for connectivity and seamless user experiences, is driving the need for advanced car access systems. On the other hand the fast advancement cyber-security threats requires solutions that will remain robust and secured against malicious threats while offering the advanced functionality, connectivity, OTA updates etc.

Traditional physical key fobs are giving way to digital solutions that offer greater flexibility and security. The motivation behind developing such systems focuses on enhancing user convenience—allowing car access and identity verification through digital keys managed via smartphones and other devices. Furthermore, as vehicles become more interconnected and function as part of larger smart environments, digital key systems must therefore incorporate advanced technologies like encrypted NFC, BLE with UWB, and secure cloud communications to protect against unauthorized access and cyber threats, while enabling interoperability with standardizes third party systems and solutions.

4.5.1 System architecture description

IMA is investing in the development of a secure, digital car access system that incorporates various modern technologies to ensure both convenience and safety. The system is built around a secure architecture that integrates NFC, BLE and UWB for robust, multi-layer communication and authentication mechanisms.

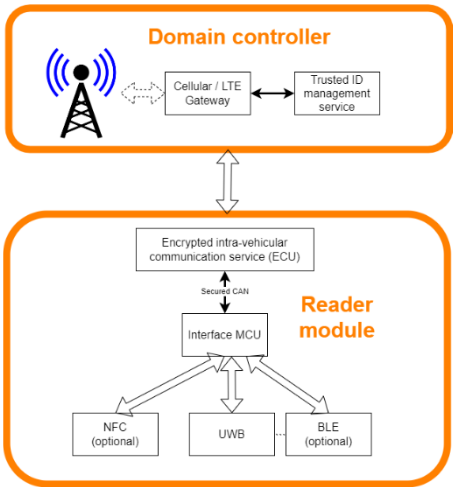

FIGURE 14 IMA CAS USE CASE SYSTEM ARCHITECTURE

Depicted schematics on Figure 14 follow up on development in WP2-WP4. The main focus is put on the reader module, also called sensor node or outer anchor, which is pivotal to the system functionality. Key system components are:

1. **Domain Controller:**
    - The central unit responsible for overseeing communications between various components managing the access rights and controlling the processes such as lock/unlock, keys update etc.
    - ECU can directly include a Cellular/LTE Gateway to facilitate external communications with a cloud-based Trusted ID management service. Typically, the LTE connection can be also shared from different unit, which is not relevant for this use case.
    - The power management can power up the ECU operation based on specified external trigger
2. **Reader Module:**
    - This module acts as the interface between the vehicle and the external devices or credentials (like digital key stored in a phone's secure element, app or dedicated HW).
    - The Interface MCU (Microcontroller Unit) operates the communication via selected implemented interface. The MCU can contain specific cryptographic credentials stored in dedicated secured storage, it can also trigger a power up operation of a domain controller.
    - Considered interfaces for wireless communication:
        - **NFC (Near Field Communication)**: This is used for close-range communication, allowing for secure access when a device is in immediate proximity to the vehicle. The functionality with a smart phone in this case is similar to Apple Pay or Google Wallet. The NFC interface is considered mainly for the driver side door handle.
        - **UWB (Ultra-Wide Band)**: This technology is used for accurate, medium to short-range distance measurement or ranging in order to reliably determine

the position of the user device (e.g. phone). The ranging is triggered only after a first successful key credentials validation. This interface is considered for the front door handles and possible multiple external ranging modules can be used based on OEM's requirements.

- **BLE (Bluetooth Low Energy)**: BLE provides the long-range functionality of device discovery and initial communication. For that reason it is not strictly necessary for the door-handle unit and can be implemented as a stand-alone module. It is intended to provide a balance between range and energy efficiency, useful for mobile device connectivity. In successful scenarios it will trigger the UWB ranging process.

Integrated system module as a technology demonstrator currently contains all 3 wireless technologies with NFC and BLE integrated in the door handle and UWB implemented and tested as a separate module. That is caused by a dimension and EMC constraints of the current door handle model structural design when there is not enough space for specific UWB patch antenna together with the NFC. The UWB has been tested in a single small antenna package (PCB antenna, however a module antenna is also available) and in a MIMO antenna configuration with multiple multiplexed antennas for evaluation of the angular measurement with a single UWB transceiver. This decision is based on WP4 results with MIMO antenna configuration.

4.5.2 IMA application and system context description

IMA, serving as a research and development centre for a leading European automotive Tier 1 supplier, focuses on pioneering technical solutions for next-generation car access components and door handles. Our current technological demonstrator integrates NFC and BLE within the vehicle door handle, while UWB technology has been separately implemented due to spatial and EMC constraints in the existing door handle design.

Individual SW and HW components are not intended to be delivered as a final product but to provide a basis for robust, scalable technical framework that can be adapted by automotive manufacturer for future applications.

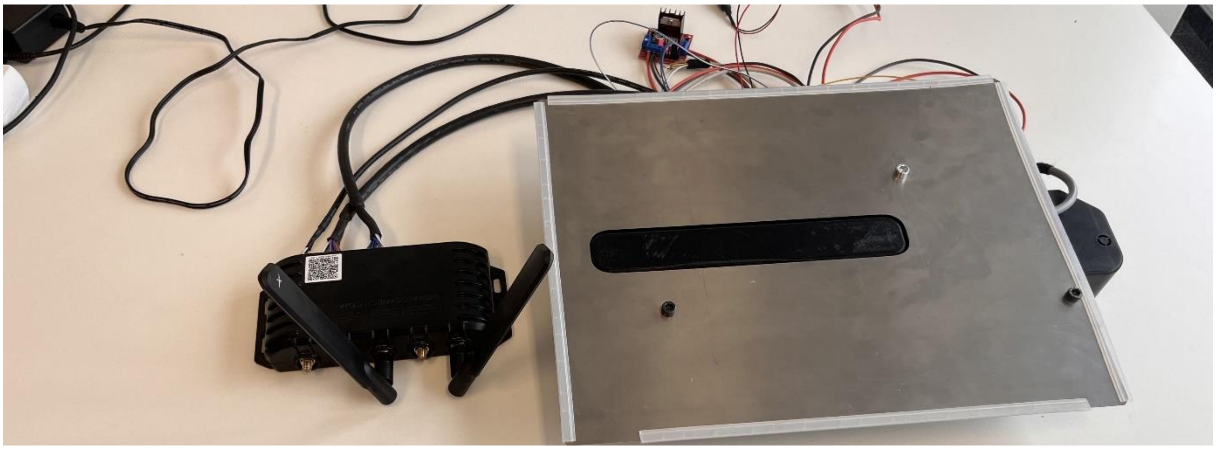

FIGURE 15 IMA READER MODULE WITH NFC AND BLE INTEGRATED INSIDE THE DOORHANDLE AND ADDITIONAL UWB INTERFACE

4.5.3 Conclusions and next steps

The UWB was tested as a single antenna a MIMO antenna setup, the more complex MIMO version was integrated and used as part of the system since it can be used in both modes as a basic single antenna for distance measurement only and for angular measurement also which lower the complexity of maintaining and testing different demonstrators with different HW combinations. For selected doorhandle demo the MIMO configuration does not fit inside the form factor, however for the different available doorhandles the implementation of such an antenna configuration is considered feasible. At this stage multiple tests and functional validation need to be performed of individual integrated building blocks. Since the main focus is on usage with mobile phones detailed tests with iPhone 15 with the new Apple U2 module (UWB transceiver from Apple) are planned.

4.6 NXPN Contribution

4.6.1 Electrical and Electronic architecture trends

Enable the new Advanced Driving Assistance Systems (ADASs) in vehicles, the automotive industry is researching new Electrical and Electronic (E/E) architecture concepts. With the shift towards level 4 and level 5 automated driving, the vehicle E/E system shall perform perception, planning, and control functions, as well as communicate with other road users or the road infrastructure. Figure 16 E/E Architecture Trends shows an example of the new trends where zonalization and consolidation of the computing task are driving the evolution of the vehicle architecture.

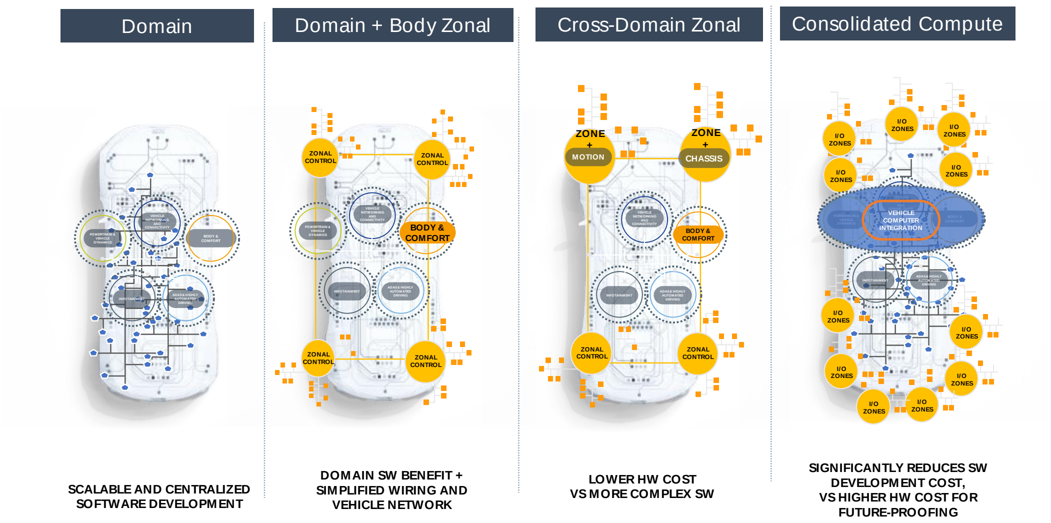

FIGURE 16 E/E ARCHITECTURE TRENDS

The domain-based functions are grouped progressively into zonal controllers, and while some applications still require isolation for performance, safety, or security requirements, in the future full consolidation of the electronic functions into a central vehicle computer is expected. In this extreme scenario (right-most E/E architecture in the figure), sensors and actuators data are collected in I/O aggregators units placed in their proximity. While reducing the system complexity, zonalization and consolidation introduce new safety and security concerns. Mixed-critical applications are sharing hardware resources, such as communication links or vehicle processors, potentially interfering with each other. This means that safety-critical, real-time applications could be influenced by the execution of non-critical applications, possibly not achieving their original safety or performance requirements. Isolation and safety & security mechanisms shall be designed into the new E/E architectures from the beginning, as they are going to be key elements for the commercialization of future vehicle and self-driving systems. In the rest of this Section, we describe the NXPN contributions to the Supply-Chain Demonstrator 5.1 (SCD5.1), related to the zone communication and in-vehicle network in the integrated V2X connectivity platform.

4.6.2 In-Vehicle Network hardware setup

As contributions to the SCD5.1, we present our proposed solution for a heterogeneous communication system that uses redundant Ethernet links and a CAN-XL based safety channel. By using two different communication protocols, it is possible to take advantage of diverse safety and security mechanisms based on the different technologies. Cyberattacks would need to be able to interfere with both channels to corrupt the communication data if sufficient detection mechanisms are present on each channel. Figure 17 shows a block diagram of the setup, where two NXP S32G2-based development boards (S32G-RDB1 and S32G2-RDB2) are connected by using Automotive safe and secure Ethernet switches (SJA1110) and redundant Ethernet links. The two Ethernet links are 100BASE-T1, and the IEEE Std. 802.1CB protocol is used for frame replication and elimination.

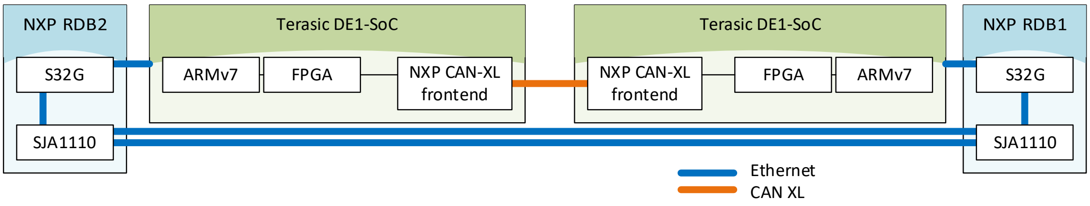

FIGURE 17 IN-VEHICLE NETWORK COMMUNICATION SETUP BLOCK DIAGRAM

The Ethernet configuration details are shown in Figure 18, where the MAC and IP addresses, as well as the switch ports used, are shown. Additionally, the Ethernet interfaces on the Linux-based A53 processors are using the IEEE Std. 802.1AE Media Access Control Security (MACsec) configuration to transmit authenticated messages over the communication links.

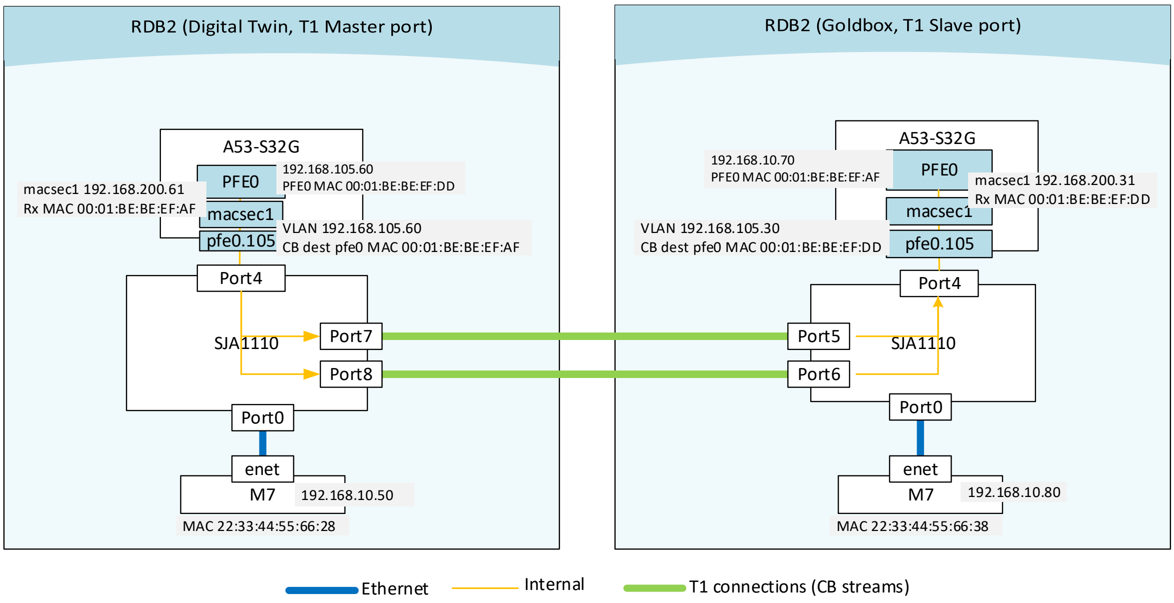

FIGURE 18 HARDWARE SETUP - ETHERNET CONFIGURATION

On the CAN-XL side, as shown in Figure 19, Ethernet messages are tunneled via the CAN-XL bus in a transparent way: the application is communicating on Ethernet interfaces that are then tunneled in the ARMv7 processor of the DE1-SOC development board. From an application perspective, this allows for the use of various application-layer Ethernet-based protocols, such as SOME/IP, DDS, ROS, while being able to use safety and security hardware mechanisms of the CAN-XL technology.

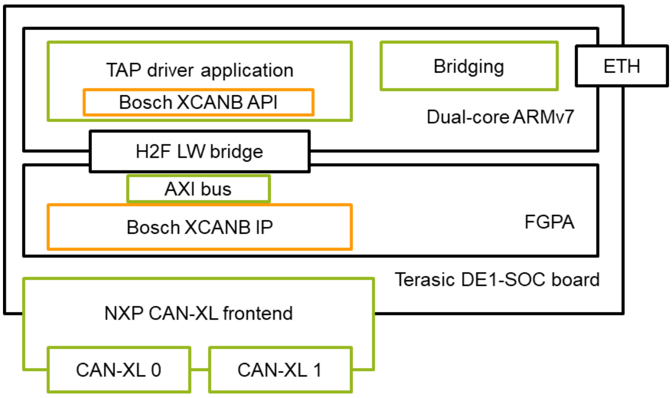

FIGURE 19 ETHERNET TUNNELING THROUGH CAN-XL STACK

To demonstrate the use of the hardware setup, we integrate a realistic self-driving application using the redundant communication system: the CARLA automotive simulator ([7]) simulates both an environment and a vehicle driving on the road, with its sensors and actuators; the Autoware.AI open-source self-driving software ([8]) is connected to the simulator through the redundant communication system and controls the vehicle.

4.6.3 Use case application description

The CARLA Simulator is an open-source simulation platform designed for the development and testing of autonomous driving systems. It provides a realistic, 3D virtual environment, where developers can emulate real-world driving scenarios. The CARLA Simulator includes different landscapes, maps, weather conditions, and sensors. These features enable developers to validate autonomous driving algorithms and systems for various conditions in a virtual environment without on-road testing. Autoware.AI is an open-source software platform designed to support several aspects of autonomous-driving software. Autoware.AI platform simplifies the process of building self-driving systems, by providing a software stack for sensing, localization, perception, planning, and control features. This framework enables developers to create, evaluate, and optimize autonomous vehicle software for both simulation environments and on-road applications. In the co-simulation used for this work, the default autonomous driving features of Autoware.AI are used.

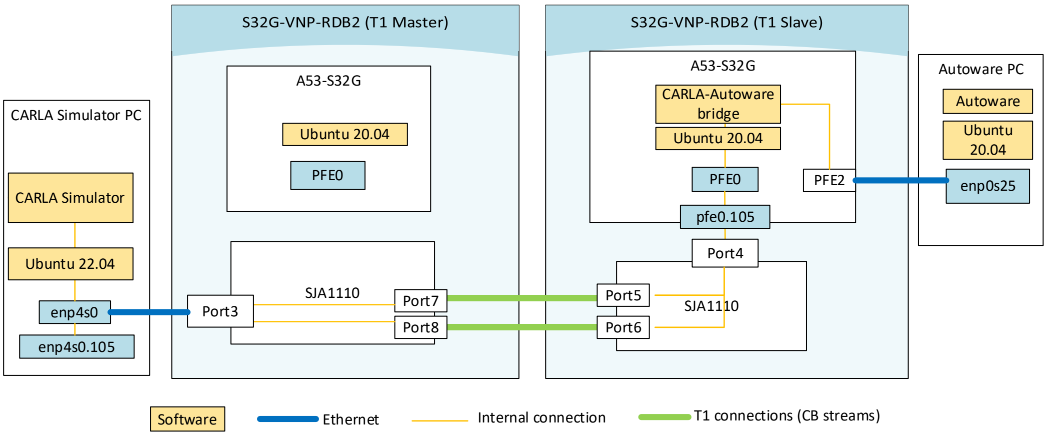

FIGURE 20 USE CASE APPLICATION SETUP

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[7] https://carla.org

[8] https://github.com/autowarefoundation/autoware/tree/autoware-ai

Error! Reference source not found. shows the block diagram of the complete use case scenario, in which two additional PCs are connected to the communication setup to run the CARLA simulator and the Autoware.AI self-driving application. Table 3 describes the hardware specifications of the two additional PCs.

TABLE 3 ADDITIONAL HARDWARE SPECIFICATIONS

	CARLA Simulator PC	Autoware PC
Processor	Intel(R) Xeon(R) CPU E5-1620 v3 @ 3.50GHz	12th Gen Intel(R) Core(TM) i7-12700H
GPU	GA107M [GeForce RTX 3050 Ti Mobile] – 4GB	GP104 [GeForce GTX 1080] -8GB
RAM	16GB	16GB

The CARLA – Autoware Bridge, running in the communication setup, is a vital component, which provides communication and data exchange between the CARLA simulator and the Autoware.AI platform. This communication and exchange play a key role in the translation of data, commands, and information between the two applications. From a system-level perspective, this use case shows that it is possible to run part of the applications, especially if related to the communication system, in the processors of the zone or edge controllers to offload the main vehicle processor.

The data exchanged between the simulator and the self-driving application mainly consists of: (i) the sensor data from the camera sensor, the LiDAR sensor, the Global Navigation Satellite System (GNSS) module, and the Inertial Measurement Unit (IMU), and (ii) the command data for controlling the vehicle, e.g., to accelerate, brake, and/or steer.

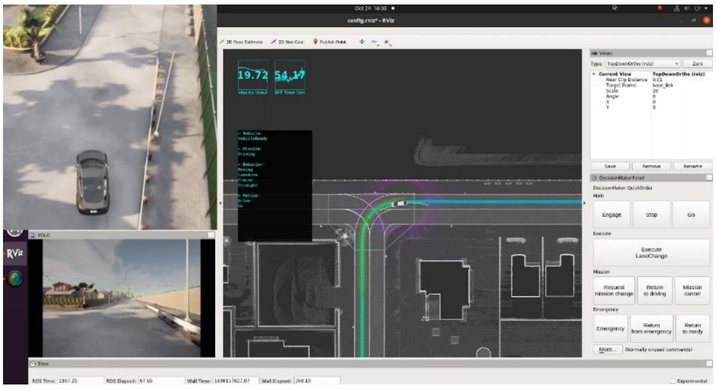
Table 4 shows the total transmit and receive rates of the data passing through the Ethernet network.

TABLE 4 DATA RATE BETWEEN CARLA SIMULATOR AND CARLA-AUTOWARE BRIDGE

All Sensor Configuration	Carla Sim. Transmit Rate	Carla Sim. Receive Rate
Front Camera (400x300), Lidar (64 channel, 320000 points), GNSS, IMU	17.1 Mbps	400 Kbps

4.6.4 Conclusions

The realistic use case is used to demonstrate the integration of the redundant communication setup. It is possible to disconnect one of the redundant links, simulating a malfunction of the link, and maintaining the control of the self-driving vehicle. Figure 21 shows an overview of the use case application: the simulated environment is shown in the top-left side of the figure, with the aerial view of the vehicle. The camera data generated by the simulator and transmitted over the Ethernet network is shown in the bottom left. On the right, the Autoware.AI RViz interface shows the trajectory and control data that is transmitted to the CARLA simulator over the Ethernet network. The use of standardized solutions (IEEE Std. 802.1CB for redundant links, IEEE Std. 802.1AE Media Access Control Security for message authentication) makes the solution compatible with other devices and easy to integrate in a complex system architecture.



Type: TopDownOrtho (rviz)
Current View TopDownOrtho (rviz)
Near Clip Distance 0.01
Target Frame base_link
Scale 10
Angle 0
X 0
Y 0

FIGURE 21 USE CASE OVERVIEW

In the final part of the project, NXPN will add the safety channel based on the CAN-XL link as an alternative path for the application in case a malfunction or a cyberattack is detected in the Ethernet subsystem. The final integration results will be reported in the last deliverable, D5.13.

4.7 TTTAUTO Contribution

In modern ADAS systems architectures, there's a trend of transitioning functionalities from hardware to software and the architecture from a distributed to a centralized model. This allows for modularization within a unified hardware platform that can be used cooperatively and managed centrally. This shift has increased the demand for a more scalable and adaptable integrated platform to cater to the intricate real-time requirements of, for instance, ADAS subsystems, and to facilitate a mixed-criticality paradigm.

4.7.1 Middleware Architecture and Communication channels

The application of the mixed-criticality paradigm in the automotive sector necessitates the integration of multiple software functions with different levels of criticality onto a single hardware platform. This demands the achievement of safety-critical temporal and spatial isolation in a composable way, while maintaining real-time capabilities. To effectively address this challenge, new communication methods need to be implemented and abstracted from the programmer to lessen the complexity at the application layer. The different communication channels utilized during the development and integration are depicted in orange in Figure 22.

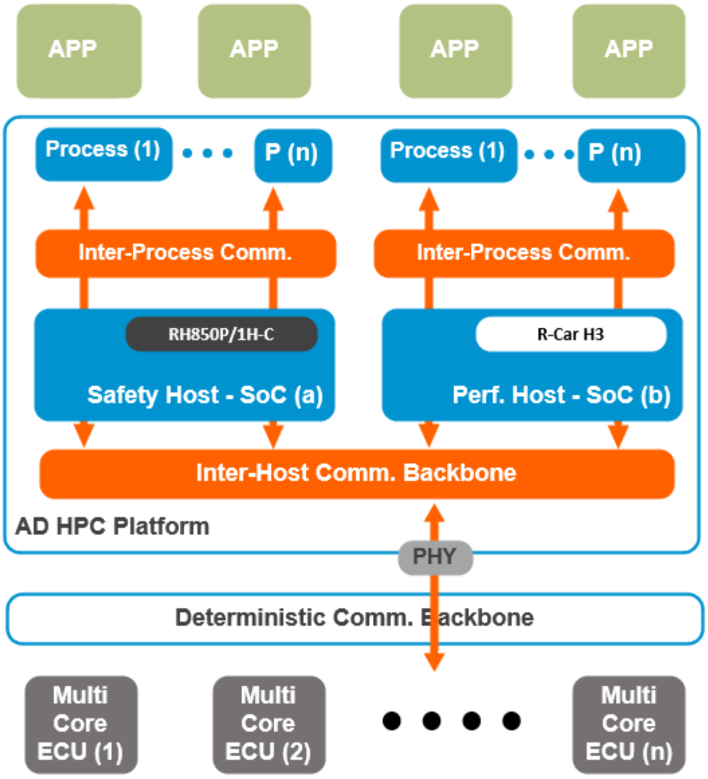


FIGURE 22: COMMUNICATION CHANNELS HANDLED BY THE MIDDLEWARE SOFTWARE CONCEPTS.

The development of modules and SW layers in WP 4 had to be integrated in the initial validation and test scenarios. The applications and use case specifications have been provided so far by the output enabler supply chain (SC1) in the case of the robot-taxi scenario. Nevertheless, additional SC5 contained demonstrations and integration efforts are ongoing and the benchmarking results will be shown in reports of WP6.

4.7.2 Use case application description.

The integration efforts so far have been concentrated on cross supply chain integration into SC1. There the communication platform developed in SC5 has been deployed into the robot-taxi scenario. Given the application requirements to communicate with the in-car edge controller module and the cloud services for energy and CO^2 efficient route planning, the interfaces and data handling modules have been adapted and configured. The initial integration and testing setup is depicted in Figure 23. The AD computing platform hosting the communication middleware framework comprises a Renesas RH850P/1H-C ASIL D MCU with lockstep cores running at 240 MHz and two Renesas R-Car H3 ASIL B SoCs with four Cortex A57, four Cortex A53, one Cortex R7, one IMP-X5, and one IMG PowerVR GX6650 GPU. The framework is compatible with AUTOSAR Classic RTE, AUTOSAR Adaptive on POSIX-based hosts and supports the OMG DDS standard. In addition to that the computing platform an off-the-shelf 5G/LTE telecommunication module was integrated to re has been to enable the up/down link for interfacing the cloud service APIs. These services provide the application data in form of JSON packages which are sent and updated based on the current state of the route planning algorithm. Apart from the above-mentioned ECUs and devices additional debug equipment is utilized to enable a testing of communication channels in this initial configuration.

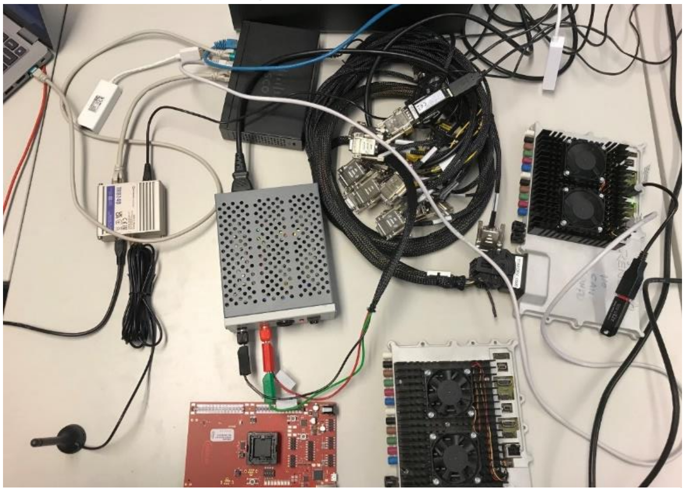


FIGURE 23: HARDWARE SETUP FOR INTEGRATION TESTS.

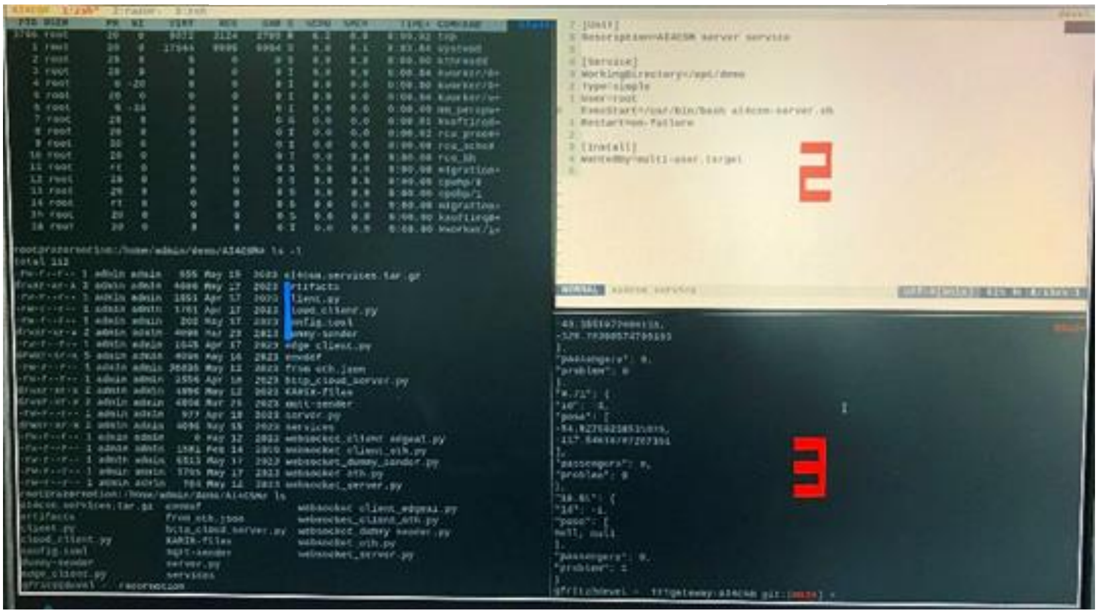


FIGURE 24: TESTING AND DEBUGGING OF THE APPLICATION LAYER.

Figure 24 depicts one intermediate test scenario, where on the left-hand side **(1)** the communication framework is monitored on the ADAS computing platform, specifically on one of the performance cores of the ECU. The second screen shows the service configuration of one of the channels towards the cloud services **(2)**. Finally, on the bottom right the data stream received is monitored for debugging purposes **(3)**.

During the integration application specific timing requirements, related to message passing between processes, with respect to communication latency have been considered. The most complex set of timing requirements come from the edge controller responsible for the movements of the robot-taxi. Since the tasks in the processing chain have been implemented on different hosts, the communication needs must be included in the end-to-end latency considerations w.r.t. communication methods. These methods have been adapted during the integration meetings between VIF and TTTAUTO in WP5.

4.7.3 Conclusions.

Achieving temporal and spatial isolation in the foreseen ADAS application scenario presents various challenges for the communication and computation platform. The integration performed so far identified two focus point, when combining the hardware and software modules in the scenario. The complexity of integration when fusing multiple software functions of different criticality levels into diverse hardware platforms. Although the design has been performed carefully and thoroughly, the efforts to achieve a modular, composable system with guaranteed temporal and spatial isolation remains difficult. The initial integration setup will be further extended over the next month to stress the real-world scenarios in the project. However, a platform for testing and validation is available for performing the activities in WP6. Benchmarking sub-components against the specified requirements will be supported by additional experiments performed in the next project month. Considering the hardware availability during the duration of the project, the demonstrator platform may vary in the final demonstration scenarios. Nevertheless, the methods and tools developed during the course of the project will be compatible with potential platform alternatives.

5 Conclusion

5.1 Contribution to overall picture

Deliverable 5.12 (D5.12) targets the realization of the supply chain demonstrators SCD5.1 and SCD5.2 on a conceptual and technical way.

The contributing partners have presented their project outcomes to date with a special regard their contribution to the final demonstrators and their integration.

Table 5 lists the contribution to the overall picture and summarizes the outcome of deliverable 5.12 (D5.12).

TABLE 5 CONTRIBUTION TO OVERALL PICTURE

Partner/Topic	**Description**
AIT	AIT is collaborating closely with SC5 lead TTTAUTO define a concept for integrating FER prediction technology into the V2X communication system protype. Our work is focused on tackling the reliability aspect of the prototype.
IFAG	Bring up and Integration Workshop done together with HHI. First Point 2 Point link established.
FHG	FHG (HHI) has laid the foundation for the mm-wave communication link that is part of SCD5.2, by implementing the Sidelink. Integration Workshop with IFAG.

TUD	As part of this task, TUD evaluated the integration of the softwarised testbed setup. Secondly, an optimiser-framework was developed that uses state of the art particle momentum for solving a MINLP-problem in a strongly heterogeneous computation substrate under SLA-constraints.
IMA	Within the V2X topic IMA focuses on short-medium range secured communication with a user device for a user authentication and car access/usage management. The OTA updates and online functionality is in this case present only in readiness and compatibility of the system since the technology being used for development is using own LTE connectivity for the ECU. However, for the future production applications the shared connectivity of multiple car sub-systems is considered as a generic solution. IMA mostly worked with short and medium range communication via BLE and NFC complemented by UWB based ranging service.
NXPN	As part of this task, NXPN demonstrated the use of the integrated communication platform with a realistic self-driving application connected to an automotive simulator. The redundant communication system is tested to prove its robustness. The standardized elements that form the in-vehicle network communication subsystem are described in this document.
TTTAUTO	As part of this task, TTTAUTO showcased the utilization of the communication layer and methods derived from the middleware architectural design of WP2. The concepts have been prepared and integrated into a realistic ADAS scenario defined in SC1. The communication between the edge controller and the cloud services was initially tested and the integration setup is described in this document.

5.2 Relation to the state-of-the-art and progress beyond it

TABLE 6 RELATION TO THE STATE-OF-THE-ART AND PROGRESS BEYOND IT

Partner/Topic	**Description**
AIT	End-to-end approach and methodology definition for estimating FER in autonomous driving. A detailed and systematic approach to obtain high-quality and representative dataset for DNN training. We introduced a pragmatic approach to the challenge on-the-fly FER predictions by identifying appropriate FER classes which promotes usability and efficiency.
IFAG	The Frontend Module is compliant to 5G 3GPP standard for the 28GHz band and can be configured individually without constrains.
FHG	Beyond SOTA is the 5G NR-V2X Sidelink implementation according to 3GPP Release 16 running on a SDR platform. Currently no manufacturer is offering a solution. SOTA are the 5G NR transmission tests with IFAG FEM.
TUD	Optimised Computation Offloading for strongly-heterogeneous computational tasks, of which a fraction can be placed on dedicated accelerators has not been analysed. We have shown an energy-optimising framework that respects application level constraints. Automated Scaling experimentation-as-code in a testbed with statistically evaluated stopping criteria is not in the literature body.
IMA	The Car Connectivity Consortium is working on standardizing an approach of car access rights being managed with Digital key as a SW based entity via mobile phones mainly. Since almost all OEMs world-wide are participating on this activity it will probably become a standard for future products, however the standardization nor any wide adoption is there yet. Any solutions in this direction however must consider interoperability and compatibility with existing and upcoming standards in order to stay relevant.
NXPN	NXPN combines in this integrated setup different State-of-the-Art technologies and protocols to improve the safety and security of the in-vehicle network subsystem.

TTTAUTO	TTTAUTO extended the existing middleware communication concepts using different SoA technologies to guarantee temporal and spatial isolation on a composable manner.

5.3 Impacts to other WPs, Tasks and SCs

TABLE 7 IMPACTS TO OTHER WPS, TASKS AND SCS

Partner/Topic	Description
AIT	SC8 – standardization for reliable communication
IFAG	None
FHG	None
TUD	The results obtained with the work presented in this document will be a starting point for the remaining work of Task 5.5, which will be reported in D5.13. Moreover, the results of this work contributed to Task 4.4.
IMA	Activity of IMA is strictly linked to all previous WPs, mainly to WP4 activity T4.4.
NXPN	The results described in this document show the integration steps taken until now. Consolidated integration results will be reported in D5.13. In parallel, the work contributes to Task 4.4.
TTTAUTO	The results described in this document describes the integration steps taken until M36 of the project. The final integration results will be summarized and reported in D5.13. In parallel, the work contributes to Task 4.4.

5.4 Contribution to demonstration

TABLE 8 CONTRIBUTION TO DEMONSTRATION

Partner/Topic	Description
AIT	A trained Deep Neural Network able to predict FER classes for an urban driving scenario, which can be integrated into *SCD5.1: Proof-of-concept communication platform* building blocks.
IFAG	FEM Hardware deployed and ready to use
FHG	Sidelink running on SDR platform
TUD	TUD is contributing to SCD5.2
IMA	IMA is not directly contributing to the SC5 demonstrator.
NXPN	The in-vehicle network safe and secure communication, part of SCD5.1, is described in this document.
TTTAUTO	The communication platform, as part of SCD5.1, utilized during the initial integration efforts in SC1 is described in Chapter 4 of this document.

5.5 Other conclusions and lessons learned

TABLE 9 OTHER CONCLUSIONS AND LESSONS LEARNED

Partner/Topic	Description
AIT	The process of creating a usable and high-quality dataset is very involving in terms of: (1) time required for real-world driving and (2) in terms of domain knowledge to build physical models and (3) effort to establish_Hardware-in-the-Loop setup.
IFAG	Perform HW bring up and characterization should be done in an earlier state

FHG	Inter-carrier spacing, referencing of setup, EVM and frequency error are crucial KPIs for mm-Wave communication
TUD	None
IMA	None
NXPN	None
TTTAUTO	None

6 References

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List of figures

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