RESERVE

D5.9 v1.0

Report on Validation of ICT Concepts using live 5G Network, Gateway and Pan-European Infrastructure, V2

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Abstract:

The focus of the RESERVE project is to enable scenarios with up to 100% RES generation by using the new functionality which the 5th generation mobile communication network will provide.

This deliverable provides an analysis of the power network and ICT communication protocols performance tests conducted on various versions of 5G mobile network. The comparison between the communication protocols and 5G test systems is evaluated in this deliverable.

The VILLASframework which was developed by RWTH as part of RESERVE project has reached a mature level and is released as a stable version with examples, documentation and workshop material.

The Pan-European simulation infrastructure is used to conduct co-simulations between RWTH and POLITO to validate SfA scenario. Further the simulation infrastructure is extended with three external partners in Europe as part of H2020 Transnational Access (TA) exchanges.

Keyword list:

5G, LTE, VILLASframework, voltage control, frequency control, power network simulators

Executive Summary

ICT tests have been conducted on four different test systems in order to validate the behaviour of the 5G mobile network for RESERVE use cases. The four test systems are: Ethernet test system as a baseline, 5G-ready with remote core network, Enterprise 5G-ready with core network in a box and 5G-prototype network which has New Radio (NR) - the most advanced mobile radio access. In all of the tests, VILLASnode gateway software is utilised as a test data generator and analysing tool for power system automation protocols.

The tests results have shown that the functional requirements, performance requirements and security requirements for the voltage and frequency control scenarios defined in RESERVE can be achieved by the 5G mobile network system.

The VILLASframework software stack developed as part of RESERVE project has reached a mature level. Several improvements to its stability, maintainability and performance have been incorporated. The first stable version 1.0 has been released and is now available alongside with examples, workshop material and documentation for external users.

The pan-European simulation infrastructure was used in distributed co-simulations between POLITO and RWTH. During this test the SfA scenario was validated. As part of two H2020 Transnational Access (TA) exchanges, researchers from RWTH extended the pan-European simulation infrastructure by adding three project external partners to the network of laboratories: TU Delft, DTU Denmark and SINTEF Trondheim, Norway.

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1. Introduction

1.1 Objectives and outline of the deliverable

RESERVE has specified new voltage and frequency techniques in Work Packages 2 and 3, where 5G-based ICT will be used. The requirements for the use of 5G-based ICT are mentioned in D2.5 and D3.7 for frequency and voltage control, respectively. The ICT test cases this deliverable covers are defined in D5.8. Some of the tests were conducted in year 2 and are described in D4.6.

ICT tests have been conducted on various test beds including Ethernet, 5G-ready, 5G-prototype, which are briefly described in Chapter 2.2, and also on the new test system Enterprise 5G-ready, which is in detail described in Chapter 2.2.1.

This deliverable covers the results of all the tests which were planned and mentioned in D4.6 and D5.8. The results include the 5G-ready, 5G-prototype and Enterprise 5G-ready test systems.

The deliverable also covers detailed description of the VILLAS framework and Pan-European simulation infrastructure.

1.2 How to read this document

This deliverable is closely linked to D4.5, D4.6 and D5.8.

Deliverable 4.5 describes the 5G and ICT components used in the tests and test lab set up.

Deliverable 5.8 describes the 5G and ICT test cases and lab setup. The test cases and lab setup that are described in D5.8 were used to perform the tests and their results are reported in this deliverable.

Deliverable 4.6 describes the test results performed in lab on various test systems in year 2.

Deliverable 2.5 and 3.7 describe the 5G and ICT requirements for voltage and frequency control scenarios of RESERVE.

Figure 1.1 illustrates the relationship between this document and existing deliverables in RESERVE.

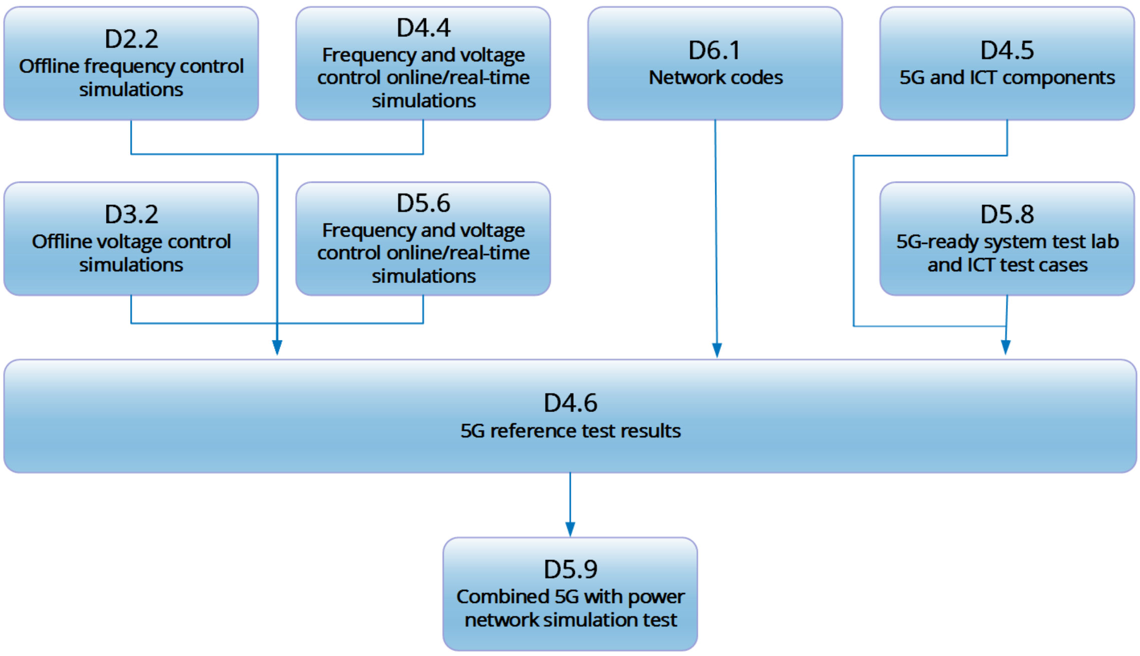

Figure 1.1 Relations between D5.9 and other deliverables

1.3 Structure of the deliverable

In Chapter 2, the power network protocols that are most relevant for frequency and voltage control scenarios and were used in performance tests are described. Furthermore, a brief description of the test systems which are used in the experiments are given; and finally, the results and evaluation of the performance tests are presented. In Chapter 3, development progress of VILLAS framework is explained. Chapter 4 explains the validation and testing of the Pan-European simulation infrastructure which was conducted in three different use cases. Finally, conclusions of the work done in this deliverable are described in Chapter 5.

2. ICT performance measurements

2.1 Architecture of the protocols used in the experiments

2.1.1 IEC 61850-9-2 Sampled Values (SV)

IEC 61850-9-2, also called Sampled Values (SV) protocol [1], is used to transmit high speed streams of data set samples encoded in multicast Ethernet frames. The protocol uses a Publish-Subscribe model in which a publisher transmits unacknowledged data to subscribers. The Sampled Values protocol does not support any mechanism to retransmit lost messages thus it is an unreliable protocol.

Since the SV protocol is a layer-2 Ethernet protocol, in order to transmit over mobile network or internet we have configured Point-to-Point tunnelling for performance testing purposes. The ethernet frames are then encapsulated in to the tunnel and then transmitted over IP layer.

2.1.2 Message Queue Telemetry Transport (MQTT)

Message Queue Telemetry Transport [2] is widely used for light weight messaging. The design principles of MQTT are quite simple and based on a Publish-Subscribe mechanism. It does not have any queue in spite of the name. It is specially designed for resource constrained devices communicating over wireless network. MQTT works on top of TCP (Transmission Control Protocol), which is a connection-oriented protocol where the sender waits for acknowledgment message and retransmits the packet if it does not receive any acknowledgement.

MQTT offers 3 QoS levels:

- QoS 0 - at most once, guarantees best-effort delivery and often called fire-and-forget.
- QoS 1 - at least once, guarantees the message is delivered at least one time to the receiver. It is possible that a message is sent multiple times.
- QoS 2 - exactly once, guarantees each message is only delivered once to the receiver and is the safest and slowest QoS level.

2.1.3 Advanced Message Queuing Protocol (AMQP)

Advanced Message Queuing Protocol [3] was designed to be more reliable and interoperable protocol. It provides a wide range of features related to messaging, including reliable queuing, topic-based publish-subscribe messaging, flexible routing, transactions and security. AMQP works on top of TCP, which is a connection-oriented protocol.

2.1.4 User Datagram Protocol (UDP)

UDP [4] is a simple, transaction-oriented protocol and does not provide assurance for data delivery or protection against duplicate delivery. Unlike TCP, which is a connection-oriented protocol, UDP is unreliable.

2.1.5 IEC61850-8-2 lab performance test

D4.6 states that a “future test could validate if a 5G communication medium can support the Extensible Messaging Presence Protocol (XMPP) [5] technology suite, with XML Encoding Rule (XER) payloads [6]. XMPP protocol could be used for analysis and action in either the voltage or frequency control use cases.”

The reason for identifying the XMPP technology suite was due to the fact that a new IEC standard, IEC 61850-8-2:2018 [6] specifies a method of exchanging data through client / server services, with the principle mapping of objects and services of the ACSI (Abstract Communication Service Interface defined in IEC 61850-7-2) to XML messages. The mapping description includes:

- The usage of the XMPP protocol itself, describing in detail which features are really used and how they are used by the mapping,
- The achievement of end-to-end secured communications,
- The description of the XML payloads corresponding to each XML schema and XML message examples.

This IEC 61850-8-2:2018 standard is an effort to adapt the IEC 61850 protocol suite to smart grid communication. In recent years, the IEC 61850-8-1 MMS protocol, instead of DNP3 and IEC 60870-5-101/104, has been largely applied to substation automation systems in which communication networks are based on ethernet local area networks. However, the growing demand for smart grid applications involving large scale connections of devices and dynamically changing network topologies requires a more internet / web-based solution. MMS-based SCSM (specific communication service mapping) was not originally designed to address these issues. Therefore, a solution that supports web scalability and cybersecurity must be used in such an application and IEC 61850-80-2 proposes XMPP as that solution.

There are a number of XMPP technological server solutions available such as ejabberd [7], Openfire [8] and IoT Gateway [9] and the team within RE-SERVE have evaluated them, however given that IEC 61850-80-2 specifies that there must be support for a MMS XER payload over a XMPP transport, the actual testing of IEC61850-8-2 was not feasible in the RE-SERVE lab because there is no open implementation of the IEC61850-8-2 standard available to use and to develop software for a IEC61850-8-2 compliant XMPP client would have taken time to design, develop and test and given the size of this software development project it was not possible to complete this work in the RESERVE project timeframe.

2.2 Test systems used for the experiments

ICT performance measurement experiments were performed on the following test systems:

- Ethernet test system
- 5G-ready test system with remote core network
- 5G-prototype test system
- Enterprise 5G-ready test system

The Ethernet test system is used to conduct tests to obtain a baseline for pure protocol characteristics without the influence of a radio system.

5G-ready test system uses 4G radio access and connects to the mobile core network in Ericsson Aachen.

5G-prototype test system was the state-of-the-art non 3GPP standardised prototype version of Ericsson used internally for testing purposes and it uses 5G New Radio (NR) access [10] and not connected to the mobile core network as everything required for prototyping was built in a single compact box. The 3GPP standardised New Radio (NR) was commercially launched in mid-2019 as a commercial product.

The main difference between 5G-ready and 5G-prototype test systems is that 5G-ready system relies on LTE radio access while 5G-prototype system uses New Radio (NR), the next generation radio access.

The difference between 5G-ready test system and Enterprise 5G-ready system is that 5G-ready test system is connected with the mobile core network in Aachen over a secured IP tunnel. While the Enterprise (Private) 5G-ready system is packed in a single box and does not require any connectivity with an external Mobile Core-network system. The solution consists of all the nodes required to run a fully functional mobile network including the core network nodes. Enterprise Core network setup is running on Ericsson Cloud Execution Environment that virtualises all the core network functions.

Enterprise 5G-ready test system architecture is not described in the earlier deliverables as it was not available at the time, however it was used for the experimental testing during the last year of the project. The first three test systems are explained in D4.6 while the new Enterprise 5G-ready test system is explained below in Chapter 2.2.1.

2.2.1 Enterprise 5G-ready test system architecture

The Enterprise 5G-ready infrastructure is a network in a box solution and its architecture is illustrated in Figure 2.1.1. It does not need any connectivity to external core network as the core network is configured in the box. It provides all the functionality of a mobile network but with a compact and fast deployment which is very suitable for industries and use cases where performance is a big factor.

The Enterprise 5G-ready solution is a system consisting of:

Evolved Packed Core (EPC), which provides access to external packet IP networks and perform several core network related functions (e.g. QoS, security, mobility and terminal context management),

User Data Consolidation (UDC), which provides management of subscription data

Enterprise Operations Support System (E-OSS) which provides local operations for enterprises,

Radio Units that are used for connecting to the User Equipment.

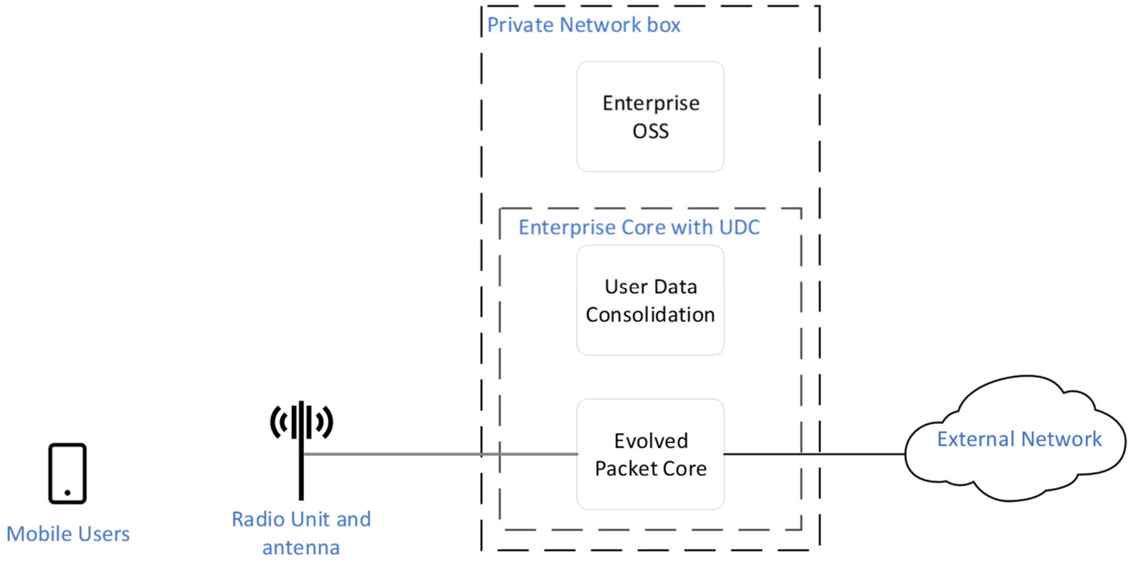

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Figure 2.1: Enterprise (Private) 5G-ready high-level architecture

2.3 Test setup and methodology

In each test system, VILLASnode (Deliverable 4.1) has been used as a power traffic generator and traffic measurement tool on a dedicated PC. As a measurement tool, VILLASnode allows for logging the latency of each individual message. Deliverable 4.5 and 5.8 contain a detailed description of the ICT components and test cases. A detailed description of the measurement PC is provided in the annex, A.1 of this deliverable.

Figure 2.2 provides a common overview of the test infrastructure. All three mobile test systems use a Radio Base Station (RBS) and a single User Equipment (UE) to establish a radio link. The term “UE” refers to any device that allows a user to connect to the base station. VILLASnode is connected to both endpoints of the radio link (RBS and UE) in order to close the measurement loop and to log the latency. Detailed description of test infrastructure is in Chapter 3 of Deliverable 4.6.

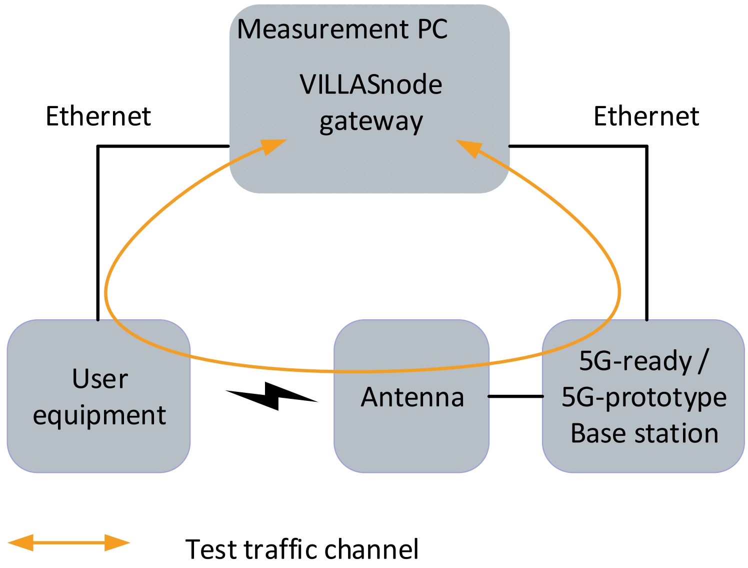


Figure 2.2: 5G system test infrastructure

All experiments have been conducted on the 5G-ready system, the 5G-prototype system, the Ethernet system and Enterprise 5G- ready system as described in the previous chapter, Chapter 0. The user plane latency experiments (test case 4.1.1 in D4.8) have been repeated for different transmission rates: 1, 10, 100, and 1000 messages per second. The number of data samples included in each message was increased to 10 and 100 values per message. Each value is 64 bits in size. For the reliability test case (test case 4.1.2 in D4.8), the results of the latency test have been reused to analyse the occurrence of packet loss. Deliverable 5.8 contains further descriptions of the applied test methodology.

VILLASnode has been used as a traffic generator (generating traffic in accordance to characteristics of power network measurement devices) and traffic measurement tool. To avoid side effects caused by the scheduler of the operating system, the VILLASnode software has been pinned exclusively to Central Processing Unit (CPU) cores.

Regarding the set-up of the general infrastructure and these experiments, the following constraints have been identified:

- No handover, device stationary and in fixed distance to one base station.
- In a full-scale deployment solution scenario, devices would have a range of distances to the nearest base station which will affect the signal strength and performance characteristics of the individual radio links to these devices.
- The hardware and software characteristics of the equipment and deployed software used in the lab can differ from the hardware and software used in a full-scale live infrastructure. For instance, the equipment may differ in processor, memory and discs performance, software versions, etc. In particular, the 5G-prototype would be replaced by a commercial solution.
- There was less interference on the radio interface in the test lab, and the devices had optical visibility to the antenna. In a real deployment, there will be obstacles in the environment of the air interface, including many reflected signals, each with a different time delay and phase, arrives at the receiver, etc.
- Packet loss in a real environment is certainly higher than in a test lab because we were not able to congest the networks.

2.4 ICT full performance test results and comparison for different 5G test systems

This chapter describes the results of the test experiments conducted on the Enterprise 5G-ready test system as well as the results from the 5G-ready, 5G-prototype test system infrastructure. The results described below are from the test cases where the messages contain 10 values. In annex A.2 of this deliverable, a description of how to read the latency plots is provided.

2.4.1 Performance results of test systems

2.4.1.1 Comparison between test systems for each protocol

2.4.1.1.1 AMQP protocol tests

For AMQP, tests were conducted on all test systems in both directions uplink and downlink. The results in Figure 2.3 show the mean latency on test systems. For 5G-ready and Enterprise 5G-ready mean latency tends to decrease as rate increases from 1 to 100 messages per second. 5G-prototype has shown much less mean latency than the other two test systems. It is to be noted that the overall mean latency on Enterprise 5G-ready test system is significantly higher than the other two test systems. The results showed that, using AMQP, latency requirement of less than 32 ms can be achieved on any of the three 5G test beds, and less than around 10 ms can be achieved on 5G-prototype test bed which is a suitable mobile network for the cases where a very fast communication is required.

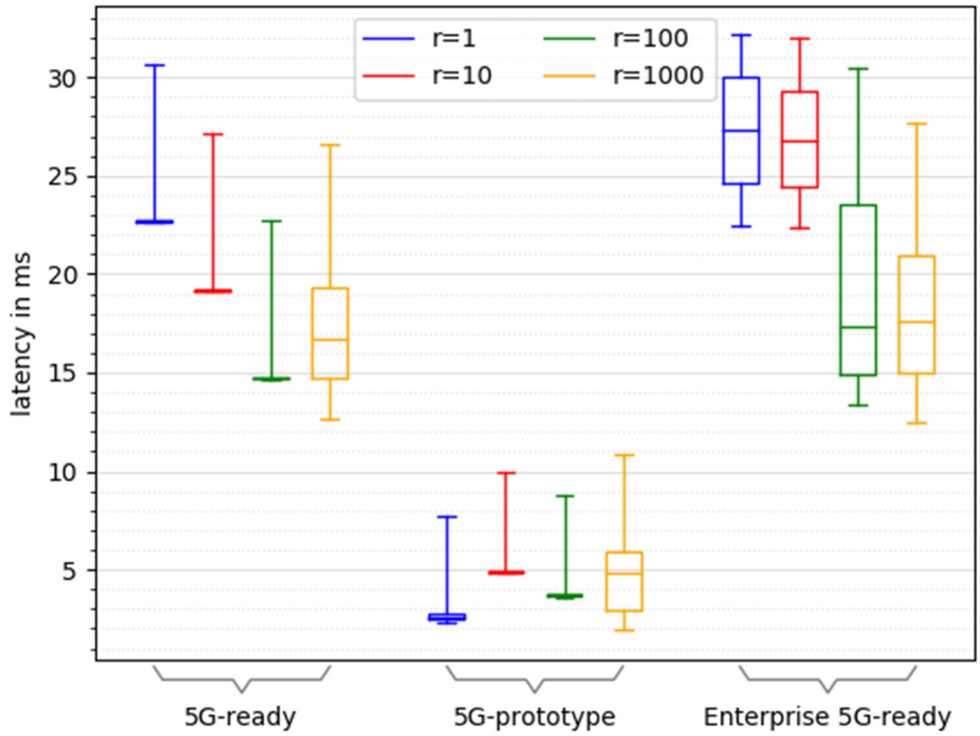


Figure 2.3: Uplink latency boxplot for AMQP

2.4.1.1.2 SV protocol tests

Sampled Values (SV) protocol tests were conducted only on 5G-ready and Enterprise 5G-ready test systems. They were not conducted on 5G-prototype test system due to some technical issues.

SV protocol results in Figure 2.4 have shown lower mean latency on 5G-ready network compared to the Enterprise 5G-ready network for the transmission rates of up to 100 messages per second. For transmission rate of 1000 messages per second we have observed that the mean latency is almost the same on both networks. No packet loss has been observed from the tests even though the protocol itself is a connectionless protocol. SV has shown larger range of outliers for transmission rates of 100 and 1000 messages per second.

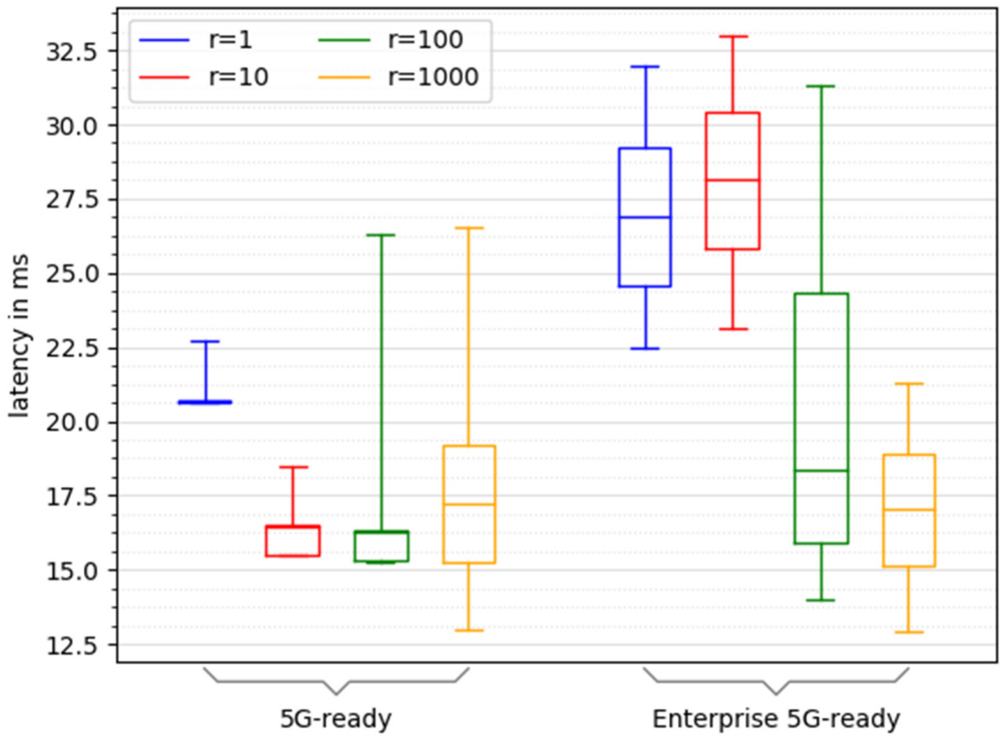


Figure 2.4: Uplink latency boxplot for SV protocol

2.4.1.1.3 UDP protocol tests

UDP protocol tests were conducted on Enterprise 5G-ready and 5G-prototype test systems and the results are shown in Figure 2.5. The difference between mean latency for transmission rates between 1 and 1000 messages per second is not much on both test systems. This behaviour is quite different from other protocols as with other tested protocols mean latency difference for different transmission rates is higher.

UDP has shown average latency of up to 5 ms for all the transmission rates on 5G-prototype test system. This result was expected because the radio link was 5G-NR which provides much lower latency than any other existing mobile network systems.

2.4.1.1.4 MQTT protocol tests

MQTT protocol tests were conducted on Enterprise 5G-ready and 5G-prototype test systems. They were not conducted on the 5G-ready test system due to some technical issues. The tests for the highest rate, the rate of 1000 messages per second, on the Enterprise 5G-ready system did not pass due to limitations of software that is generating message streams; therefore, it is excluded from the analysis. Figure 2.6 shows the test results. Similar to the other protocols it is observed that the mean latency of MQTT protocol is much lower for the 5G-prototype test system than it is for the Enterprise 5G-ready test system. For the 5G-prototype system, the latency has a lower mean value of around 5 ms while the maximum latency is 11 ms. For the Enterprise 5G-ready system, the results of latency measurements showed decreasing behaviour with increasing rate from 1 to 100 messages per second.

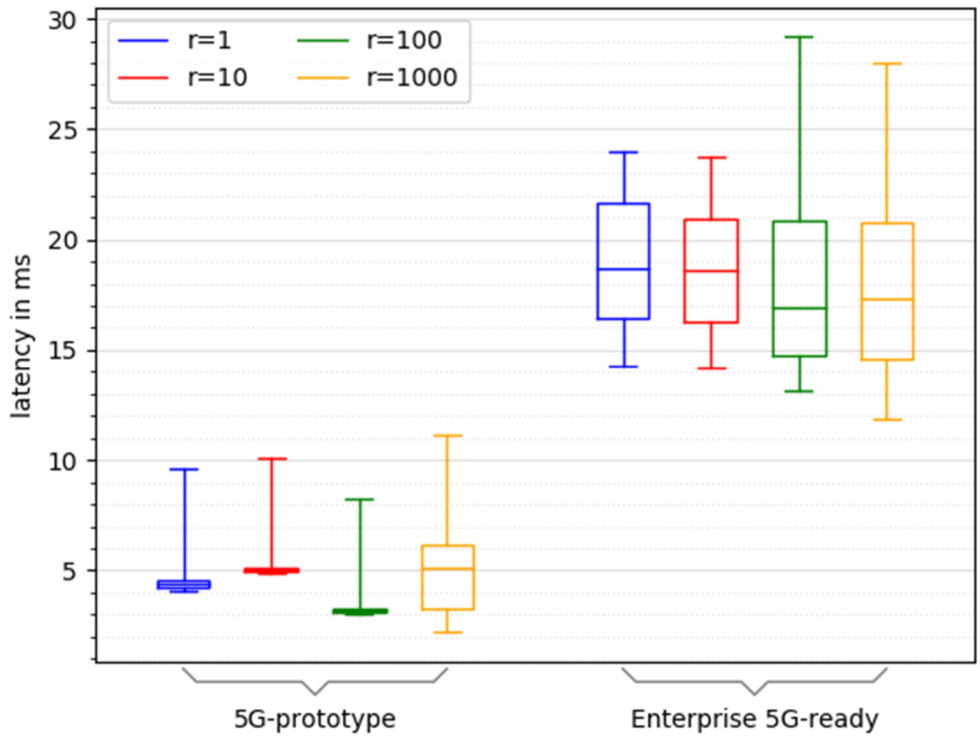


Figure 2.5: Uplink latency boxplot for UDP

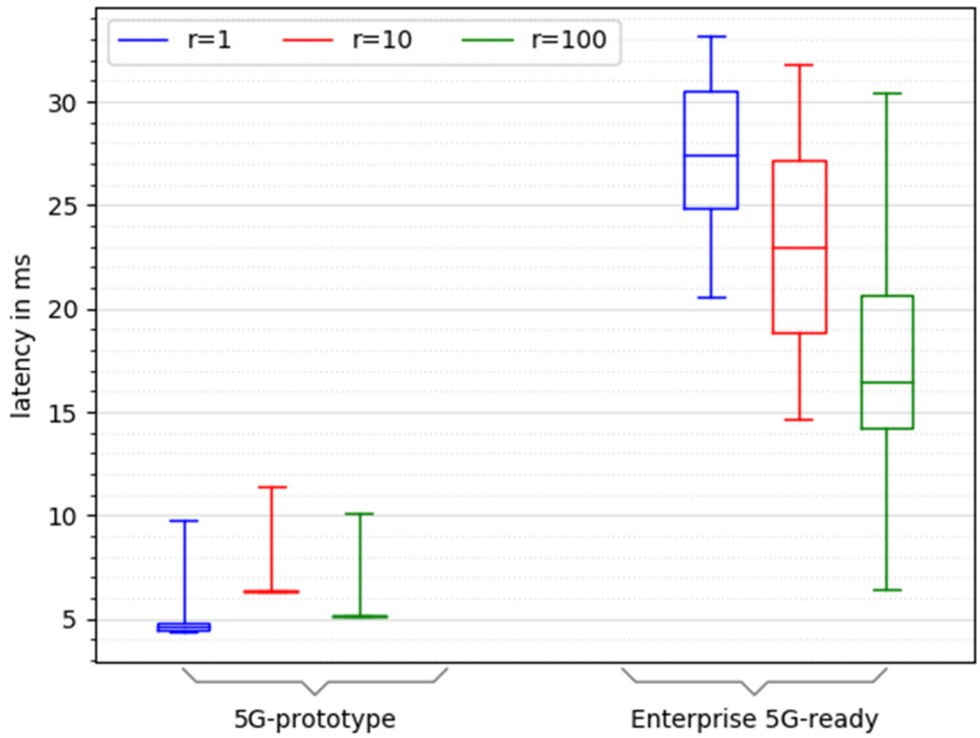


Figure 2.6: Uplink latency boxplot for MQTT protocol

2.4.1.2 Comparison between protocols for each test system

2.4.1.2.1 5G-ready test system

On the 5G-ready system, experiments with two different protocols were conducted. Figure 2.7 shows a box plot comparing the latencies of measured AMQP and SV uplink latencies for transmission rates of 10, 100, and 1000 messages per second.

The mean latency of the messages varies in the range between 15 ms and 25 ms. It is noteworthy that the mean latency tends to decrease with an increasing transmission rate. However, the variance of the latency is significantly higher for a transmission rate of 1000 messages per second compared to the lower rates due to retransmissions on the radio link.

SV being connectionless protocol has not shown better results in terms of latency compared to AMQP. AMQP being a reliable protocol has shown better results than SV, thus making it preferable to use over SV.

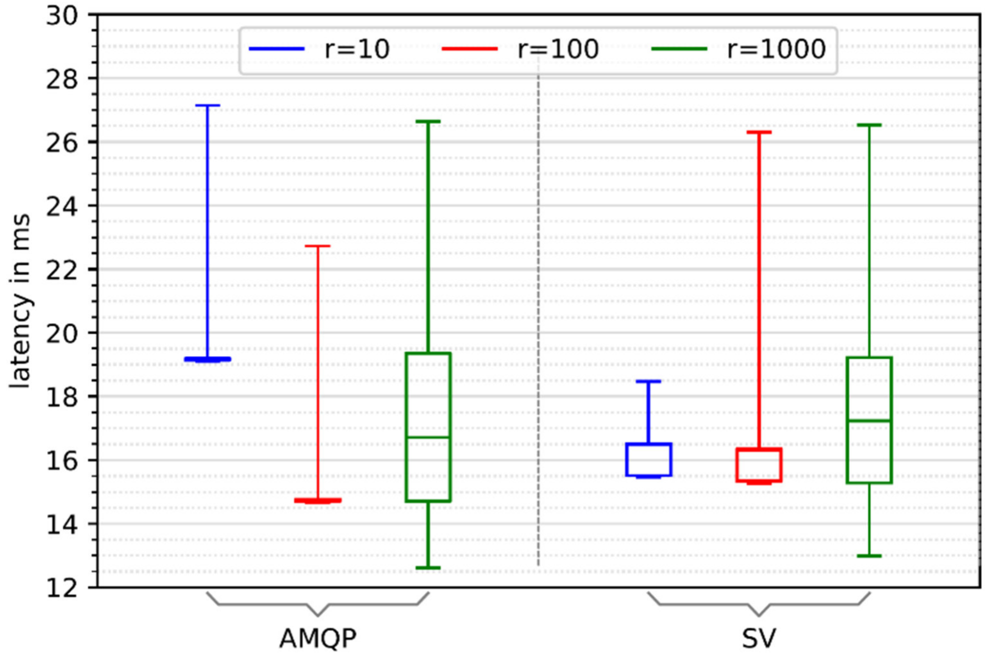


Figure 2.7: 5G-ready test system results

2.4.1.2.2 5G-prototype test system

On the 5G-prototype system, the experiments with three different protocols (AMQP, MQTT and UDP) have been conducted. The mean downlink latency for all protocols and rates varied in the range from 1.5 ms to 7 ms. The mean uplink latency was between 2.5 ms and 6.5 ms, which is shown in Figure 2.8.

The worst-case latency for all protocols is significantly lower than on the 5G-ready system. For instance, AMQP has caused latencies up to 380 ms on the 5G-ready system while it only caused a worst-case latency of 33 ms on the 5G-prototype system. Furthermore, the worst-case latency on the 5G-prototype system is similar to the worst-case latency on the Ethernet baseline system. Hence, these outliers seem to be caused by side-effects on the measurement computer and not by the radio network. Since the 5G-ready and the 5G-prototype experiments were conducted with different computers, this also explains the high difference in the worst-case latencies.

Furthermore, the experiments confirmed the behaviour of the protocols as described in the Chapter 2.1 after a connection outage, as the connection-oriented protocols do not recover automatically.

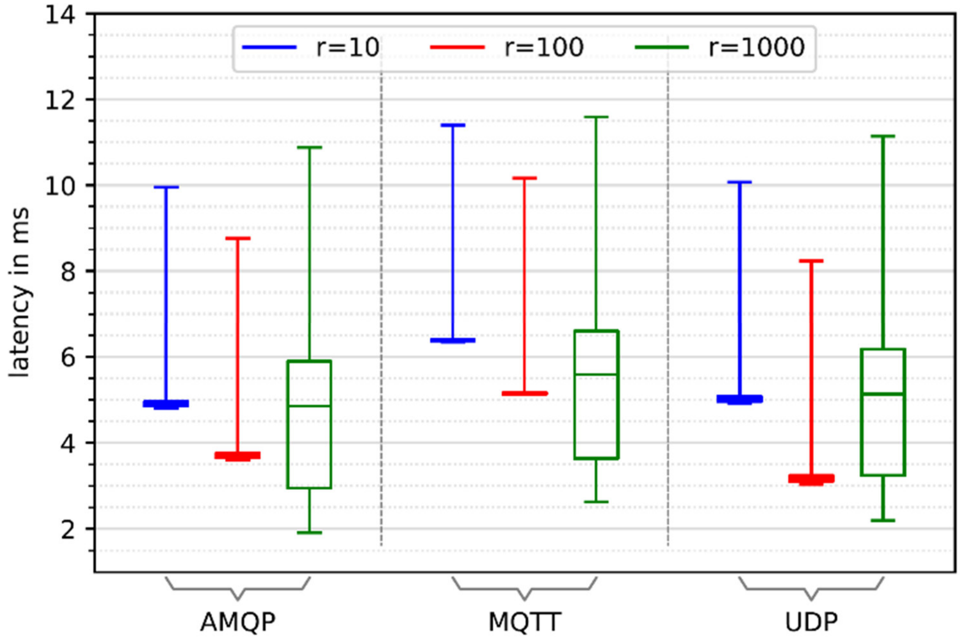


Figure 2.8: 5G-prototype test system results

2.4.1.2.3 Enterprise 5G-ready

On the Enterprise 5G-ready test system, all the protocol experiments were repeated. AMQP has shown the same behaviour and mean latency for different payloads (value = 1, 10 and 100). In Figure 2.9 it can be seen that the mean latency is 27 ms for rates of 1 and 10 messages per second while for rates of 100 and 1000 messages per second, it is 17 ms. It is noteworthy that UDP has shown minimum mean latency for all rates as compared with other protocols. SV being a connectionless protocol has not shown better mean latency than AMQP and MQTT, which are connection-oriented protocols. Since AMQP and MQTT are reliable protocols, the results showed that they can be preferred over SV protocol.

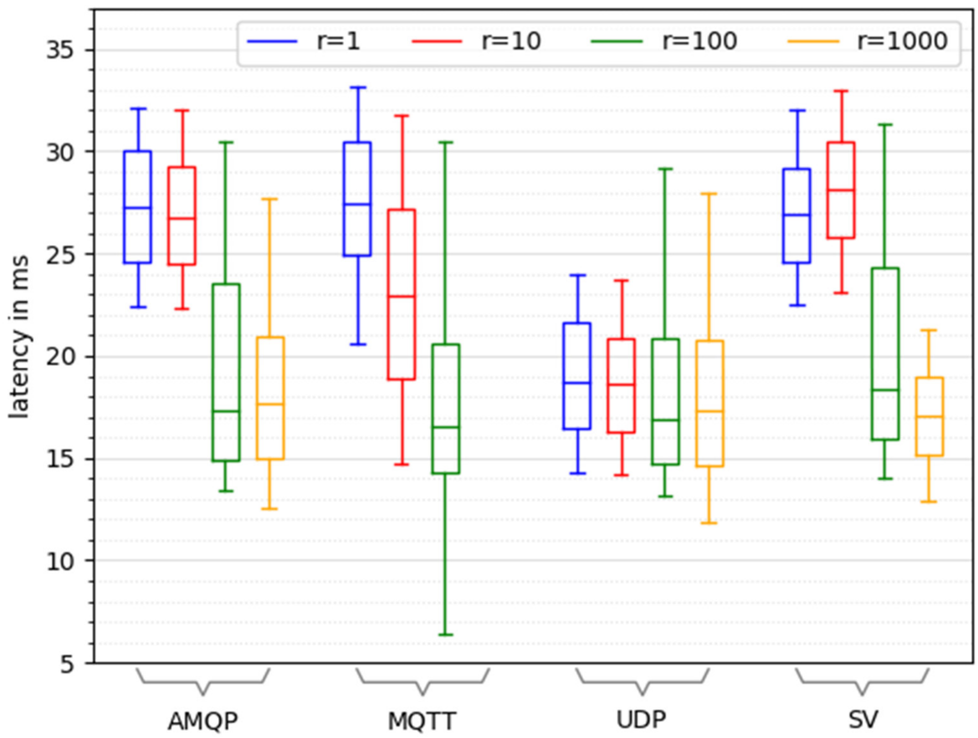


Figure 2.9: Enterprise 5G-ready test system results

2.4.1.3 Comparison of latency MQTT QoS levels

This test was conducted on the Enterprise 5G-ready test system. This particular test shows the behaviour of MQTT protocol for different QoS levels, which are described above in Chapter 2.1.2. In Figure 2.10, results have shown that for QoS level 1, the measured latency values increased dramatically for higher rate of 100 messages per second. Since QoS level 1 ensures that a message is at least once delivered, the sender could send each message multiple times. This could add load on the underlying buffers and combined with the increased transmission rate (rate of 100 messages per second) ultimately increases the latency. Of course, the reliability of message arrival is 100% ensured.

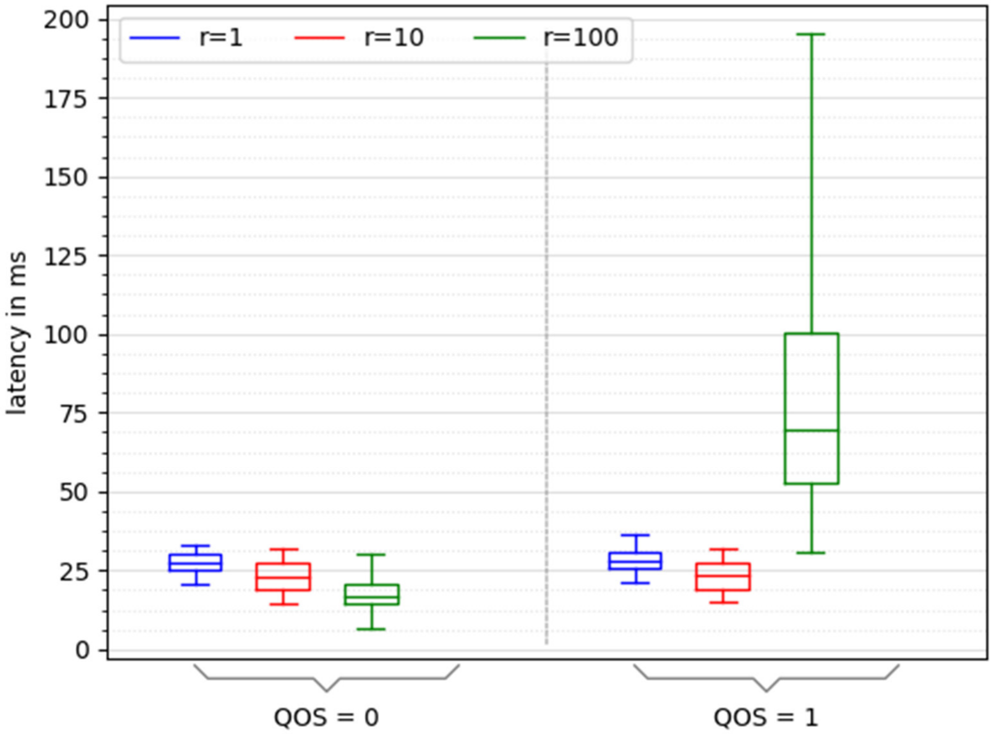


Figure 2.10: MQTT QoS 0 (fire-and-forget) and QoS 1 (at least once)

3. Progress of VILLASframework Development

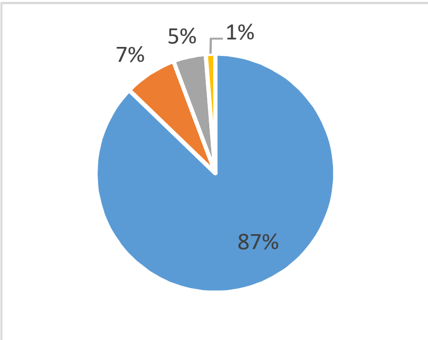
Since the initial demonstration of the laboratory infrastructure in deliverable D4.1 and D4.4 the development of the VILLASframework has progressed considerably. The main focus of the work on VILLASframework in the second half of the project was focused on improvements of stability, documentation, portability and maintainability of the code-base while using the framework to conduct distributed simulations as part of WP5. With these improvements, VILLASframework reaches its first milestone version 1.0 and is ready to be used in future projects and distributed co-simulation scenarios.

3.1 VILLASnode

In order to prepare the VILLASnode gateway for future developments, most of the source code has been rewritten in the C++ programming language which offered improved extensibility over the previous C implementation due to its object-oriented programming paradigm.

Table 3.1 Physical Source Lines of Code (SLOC).shows that the current code base consists of about 33,5 thousand lines of code (excluding, empty or duplicated lines and comments). The share of C code has been reduced to around 1475 lines.

Table 3.1 Physical Source Lines of Code (SLOC).



Language	*Source Lines*
C++	29287
Bash Scripts	2380
C	1475
Python	435
Total	**33577**

3.1.1 New Interfaces and Plugins

With the new C++ implementation, the extension of the gateway was greatly simplified. New interfaces (node-types), payload formats, and processing hooks can be added via a plugin system. Since the introduction of the gateway in D4.1 the following new interfaces have been added:

- IEC61850-8-1 (MMS)
- Real-time Transport Protocol (RTP / RTCP)
- Infiniband (ibverbs)
- Sub-process Execution
- Analog IO for Hardware-in-the-Loop interfacing (uldaq, cometdi)

The Real-time Transport Protocol (RTP / RTCP) has been originally introduced for audio/video multimedia streaming applications. The RTP specification (IETF RFC 3550) mentions in the abstract the possible application of the protocol for real-time simulation data. To our knowledge this protocol has not been employed for this use case. In an attempt to simplify the setup of distributed co-simulations, support for RTP/RTCP has been added to VILLASnode. This enables the gateway to adaptively alter the communication parameters during a running simulation to react changing quality of service on the communication medium. Furthermore, it such as sending rate or packet size can be automatically tuned without the need to manually specify them.

3.1.2 New processing hooks

In addition to the new interface types, support for new processing hooks has been added. These processing hooks allow for internal mangling of simulation data such as statistics collection, monitoring, filtering, or for the implementation of interface algorithms.

Previously, the signal processing required for the Geographically Distributed Real-time Simulation (GD-RTS) was performed on the real-time simulators themselves. Specifically, the transformation and reconstruction of instantaneous values in the time-domain to Dynamic Phasors in the time-frequency domain. This always required modifications to the existing simulation models which are undesirable. Therefore, two new processing hooks have been added to the gateway which take over tasks formerly performed by the simulators themselves.

3.1.2.1 Dynamic Phasor Hook Function

The Dynamic Phasor hook function is responsible for transforming time-domain instantaneous values of voltage and current on the sub-system boundaries to time-frequency domain Dynamic Phasors before exchanged with remote gateways. On the remote side, the phasors are used to reconstruct the time-domain signal which controls a voltage/current source in the simulation model.

3.1.2.2 Energy Based Metric (EBM) Hook Function

The EBM hook function allows the monitoring of the co-simulation interface and allows the user to quantify possible errors introduced by the co-simulation. Further details about this feature are described in Chapter 4.2.2.

3.1.3 Continuous Integration Tests (CI)

As the VILLASframework software becomes grows in complexity and code size, continuous testing of the components becomes critical. Especially as the VILLASnode component is getting used more and more by other projects and external users which contribute features and bug fixes.

From the beginning, the development of VILLASframework has been conducted in the open as an Open Source Project under the GPLv3 license. For management of the source code, the version control system Git is used. The code itself is hosted at RWTH Aachen, GitLab server[1]. Every change to the code which is committed to the Git repository is tested against a suite of test cases which are coordinated by GitLab's CI system and executed on a dedicated build server at RWTH Aachen's, OpenStack cloud infrastructure.

These test cases simulate the most come use cases of the software to avoid the introduction of unintended side-effects and regressions.

3.1.4 New Platforms and Architectures

With the introduction of the CI infrastructure, is became possible to build and test VILLASnode against a multiple different platforms and operating systems. For its version 1.0 milestone, VILLASnode can now be used on ARMv7 (32 bit), ARMv8 (64 bit), Intel x86_64 (64 Bit) architectures running the Fedora, Centos, Debian and Ubuntu Linux distributions as well as the macOS operating system.

3.1.5 Python API

Like the DPsim simulator which has also been developed in work-package 4, Python support has been added to VILLASnode. This API allows for the programmatic configuration and setup of to co-simulation scenarios by allowing for a single Python script which configures both simulation in DPsim and co-simulation interfacing in VILLASnode.

3.2 VILLASweb

Apart from the gateway, the web-interface *VILLASweb* has been overhauled in several aspects. Most of the work on the web-interface was done in preparation for storage and post-processing

[1] https://git.rwth-aachen.de

of simulation results. For this purpose, the JavaScript-based implementation of the web backend as well as the NoSQL MongoDB database posed a bottleneck for the storage and processing of large amounts of simulation data. Therefore, the backend has been ported to the Go programming language. The MongoDB database has been replaced by a combination of a relational

PostgreSQL database with the scalable Apache Cassandra wide column store. In the future, Cassandra will be used to the simulation data while PostgreSQL is responsible to store the relation of simulation entities as shown in Figure 3.1.

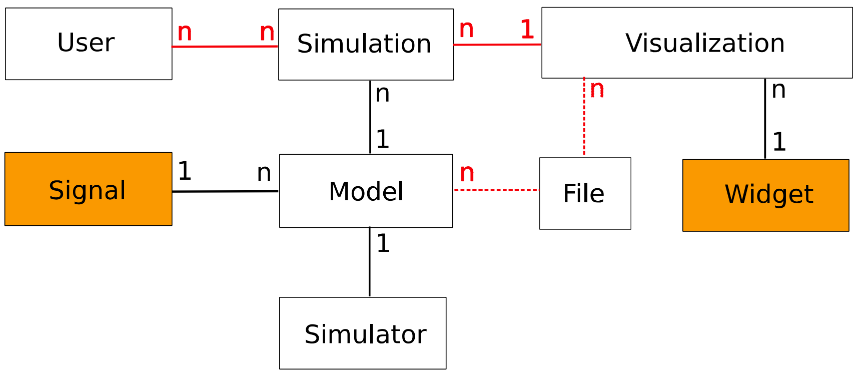


Figure 3.1: VILLASweb Database Structure

With the new Go-based backend, efforts where undertaken to document the programming interfaces (API) between the VILLASweb backend, frontend and the VILLASnode gateway to ease the implementation of new components in the future. These APIs are now specified by a document following the OpenAPI 2.0 specification which allows the generation of online documentation such as shown in Figure 3.2.

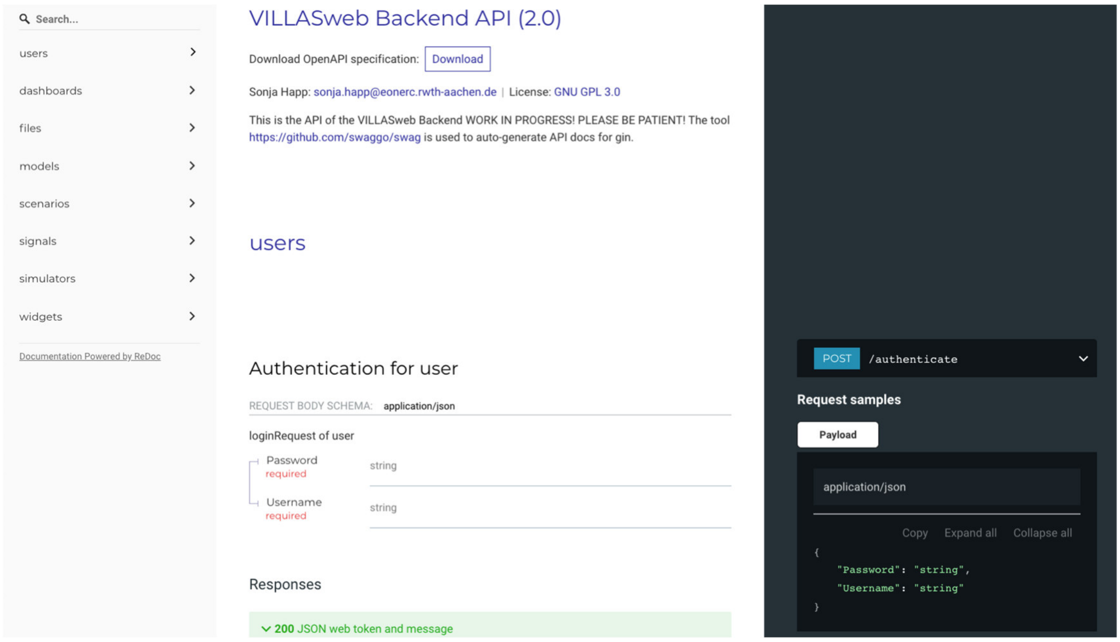


Figure 3.2: New API Documentation for VILLASframework.

While VILLASweb has been capable of continuously streaming live simulation data during the execution of a simulation, it has not been possible yet to capture short term transients which require the acquisition of a limited amount of data. This feature has been added by allowing the configuration of a triggering mechanism in the simulation gateway. VILLASnode and VILLASweb now support the configuration of a gate processing hook to capture interesting events with a high temporal resolution. Such events are then sent to the web interface for further inspection by the user.

4. Pan-European Infrastructure

After the definition and implementation of the pan-European simulation infrastructure in work-package WP4 during the first half of the project period, validation and testing of this infrastructure was conducted in three separate use cases in work-package WP5.

4.1 GD-RTS between RWTH Aachen and Politecnico di Torino

Within the RESERVE project, two project partners Politecnico di Torino (POLITO) and RWTH Aachen University (RWTH) own the necessary laboratory infrastructure to conduct geographically distributed real-time co-simulation (GD-RTS) as part of the pan-European simulation infrastructure. Both laboratories are equipped with OPAL-RT OP5600 real-time simulation targets. Firewall exceptions and Virtual Private Network (VPN) connections have been previously configured for the results presented in deliverable D4.4 and could be re-used for the first power system simulations.

From July to September 2019, a distributed co-simulation of a transmission / distribution system interconnection has been conducted. The goal of this distributed co-simulation was the validation of the concept and performance of the VILLASframework software and the testing of new frequency control schemes as defined in Scenario SfA.

As a transmission system, an IEEE benchmark model was chosen and simulated at RWTH details described in D2.6. The transmission system (TS) model consists of 9 busses with 230 kV and 18 kV voltage levels and three synchronous machines. The load connected to one of the busses has been replaced by a distribution network representing a portion of an Irish medium-voltage distribution system (DS). This model was provided by UCD and previously developed for the Dome solver. POLITO ported this model to MATLAB/Simulink for the simulation on their OPAL-RT real-time target. The distribution system is operated at 38kV and is composed of 6 busses. The connection between the TS and the DS is guaranteed by a transformer equipped with a On Load Tap Changer (OLTC). The DS comprises distributed energy resources (DERs), that include both distributed generators (wind and photovoltaic power plants) and storage systems. All the DERs are equipped with a phase-locked loop, which allows to synchronise the converter of the DERs to the DS, but also to estimate the frequency in the point of connection. The connected DERs can participate to the frequency regulation by supporting the traditional generators connected to the TS in case of frequency deviation. The case study considers temporary fault of one of the TS line (e.g., due to natural causes) which is cleared in 150 ms. Thus, the system can be re-operated, and the frequency deviation due to the fault can be recovered.

4.2 Transnational Access Exchanges

Due to the limited real-time simulation resources at other RESERVE project partners, RWTH researchers also partnered with European research institutions outside of the RESERVE project to further develop and expand the pan-European simulation infrastructure. These collaborations where conducted in the form of two Transnational Access (TA) researcher exchanges with the aim to extend the group of interconnected laboratories beyond the RESERVE project. During the TA exchanges, knowledge gained and developed in RESERVE has been transferred in form of workshops for other researchers at the visited institutions.

Figure 4.1 shows all laboratory interconnections based on the VILLASframework till today.

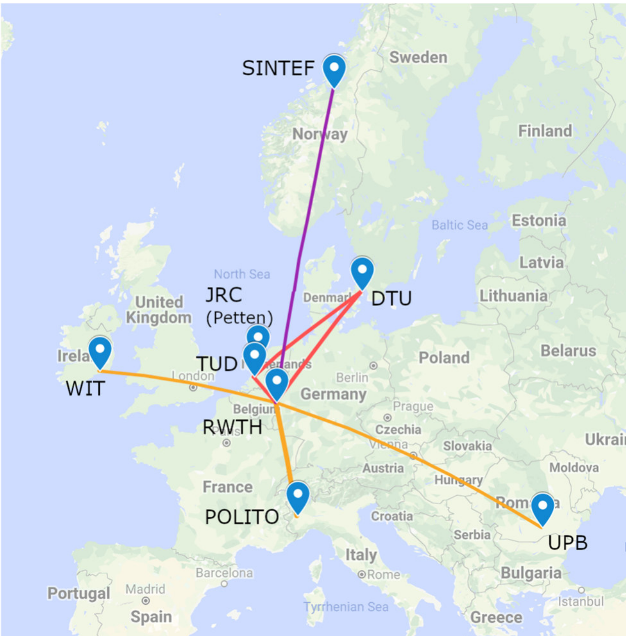


Figure 4.1: Current and past inter-connections in pan-European simulation infrastructure.

4.2.1 H2020 ERIGrid Transnational Access Exchange with TU Delft & DTU

In May 2019, two researchers from RWTH Aachen University visited the Intelligent Electrical Power Grids (IEPG) group of Prof. Peter Palensky at the Technical University Delft in the Netherlands. They were accompanied by a Master student from TU Delft as well as a post-doctoral researcher from the Technical University in Denmark. During the three week-long stay, they conducted distributed co-simulations between RWTH and TU Delft to further test and improve the reliability and stability of the GD-RTS interface algorithms based on Dynamic Phasors. Results of the work will be presented at the 45th IEEE Annual Conference of the Industrial Electronics Society (IECON) with a paper titled "*Improvements to the Co-simulation Interface for Geographically Distributed Real-time Simulation*".

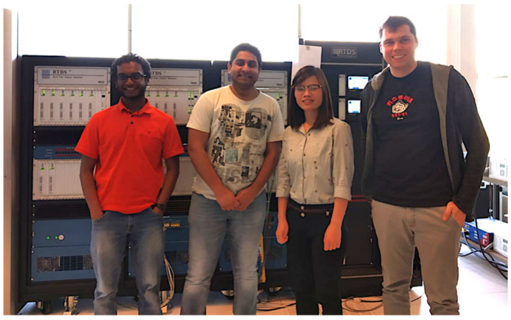


Figure 4.2: Group Picture at TU Delft, IEPG

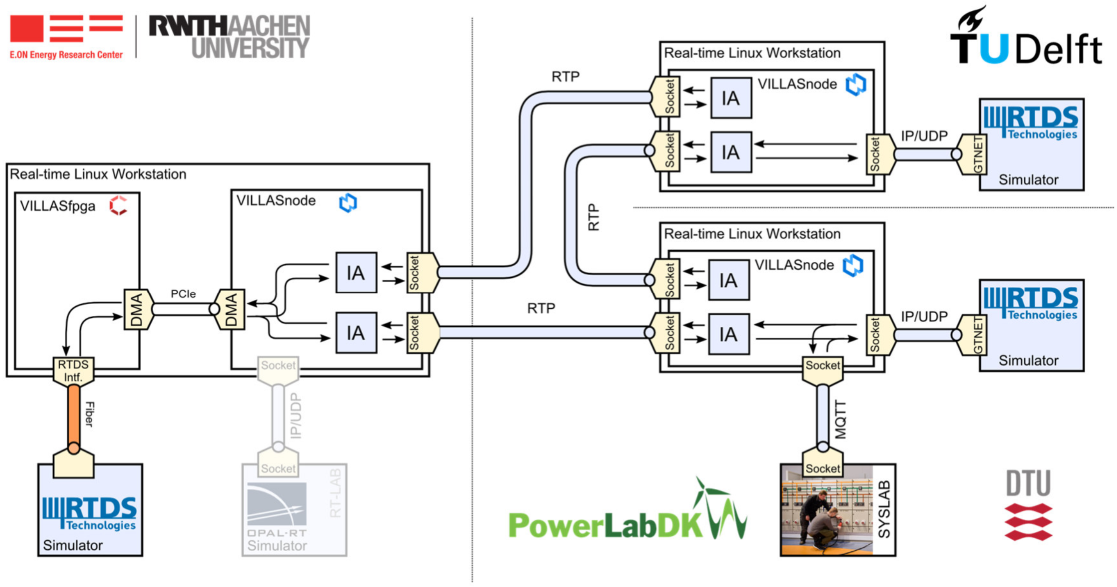
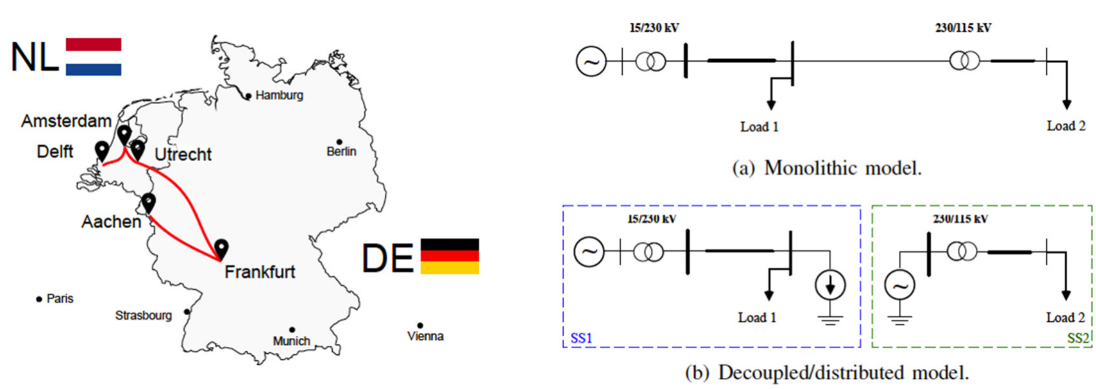


Figure 4.3: Topology of ERIGrid TA simulation.



(a) Internet routing between Aachen - Delft

Figure 4.4: Distributed Co-Simulation between RWTH Aachen and TU Delft.

4.2.2 H2020 MaRINET 2 Transnational Access Exchange with SINTEF

A second TA exchange was conducted in July 2019 together with researchers from SINTEF in Trondheim, Norway. In three week-long stay, the researchers worked on the implementation of an Energy-based Metric (EBM) to monitor and quantify the errors introduced by GD-RTS. Previously, it was necessary to compare the results of a distributed simulation against known-good reference results of a monolithic in order to quantify the errors. This requirement of a monolithic simulation challenges the usefulness of GD-RTS. Therefore, new methods to quantify the errors only by relying on the distributed simulation needed to be developed. The EBM tries to solve this problem by observing the law of energy conservation at the coupling point. Both ports of the co-simulation interface observe the amount of generated and consumed energy at their side of the simulation. If the exchanged energy at the coupling matches on both sides (both during short term transients and over the whole simulation duration), it provides a good indicator for the validity of the simulation results.

During this TA, the EBM observer has been implemented as a reusable component for VILLASframework. Results of this exchange will be summarized in a separate report and publication which are currently in progress of being finalised.

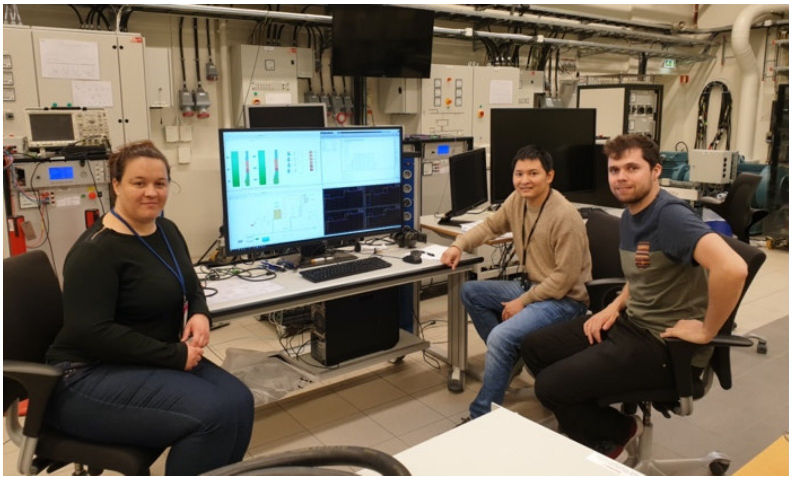


Figure 4.5: Group picture at SINTEF Smart Grid laboratory at NTNU Trondheim.

5. Conclusion

This deliverable has provided the results of the tests conducted on different test bed systems with 5G mobile network in order to validate the ICT concepts that are identified during the project. Combining the results of different scenarios, that were conducted throughout WP 4 and are reported in D4.6, and the results of the Enterprise 5G-ready test system included in Task 5.5, the latency performance of different 5G mobile network test systems for different protocols are compared and discussed in this deliverable.

The 5G-prototype system has shown significantly lower latency as compared to other 5G test systems. The 5G-prototype system resulted latency values less than 10 ms and the results proved that 5G NR radio access technology can be used in the scenarios considered in RESERVE. The 5G-ready and Enterprise 5G-ready systems have also shown promising results satisfying the latency requirements of most scenarios.

The results have shown that the protocols tested in the experiments achieve the latency required by voltage and frequency scenarios considered in RESERVE. Different protocols offer different reliability properties, i.e., AMQP and MQTT protocols, being connection-oriented protocols, are more reliable compared to the SV protocol and UDP. Hence, depending on the reliability requirement of the scenario, one protocol can be chosen over the other provided they satisfy the corresponding latency requirements.

The VILLASframework has reached its first milestone with version V1.0. It can now be further used in future projects for the co-simulation. Moreover, the Pan-European simulation infrastructure is extended with external project partners for validation and testing purposes.

6. References

[1] IEC 61850-9-2: "Specific Communication Service Mapping (SCSM)-Sampled Values over ISO/IEC 8802-3, 2004.A"

[2] ISO/IEC PRF 20922: "Information technology -- Message Queuing Telemetry Transport (MQTT) v3.1.1"

[3] ISO/IEC 19464:2014 "Information technology -- Advanced Message Queuing Protocol (AMQP) v1.0 specification"

[4] Postel, J. (1980). "User Datagram Protocol." RFC768.

[5] IEC 61850-8-2:2018, Communication networks and systems for power utility automation - Part 8-2: Specific communication service mapping (SCSM) - Mapping to Extensible Messaging Presence Protocol (XMPP), 2018. Available Online: https://webstore.iec.ch/publication/34345

[6] ITU-T X.693 | ISO/IEC 8825-4: "Information technology – ASN.1 encoding rules: XML Encoding Rules (XER)"

[7] https://www.process-one.net/en/ejabberd

[8] https://www.igniterealtime.org/projects/openfire/

[9] https://github.com/PeterWaher/IoTGateway

[10] TS 38.104, "Base station radio transmission and reception"

7. List of Figures

8. List of Abbreviations

3GPP	3rd Generation Partnership Project
4G	Fourth generation cellular network technology
5G	Fifth generation cellular network technology
AMQP	Advanced Message Queuing Protocol
ICT	Information and Communications Technology
LTE	Long-Term Evolution
MMS	Manufacturing Message Specification
MQTT	Message Queue Telemetry Transport
NR	New Radio
QoS	Quality of Service
RBS	Radio Base Station
SV	Sampled Values
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
XER	XML Encoding Rule
XMPP	Extensible Messaging Presence Protocol

Annex

A.1 Measurement PC - HW and SW configuration

The measurement PC used to run the experiments had the following configuration:

- CPU:
  - Intel Xeon CPU E5430 @ 2.66 GHz
  - 8 CPUs, 2 sockets, 4 cores per socket
- Operating System:
  - Linux 4.17.5-200.fc28.x86_64

VILLASnode software version:

- VILLASnode v0.6.2-6002d8f-Linux-x86_64-debug (built on May 15, 2018, 16:45:45)

MQTT/AMQP Broker:

- RabbitMQ Adapter 3.7.7

A.2 Reading the latency plots

In this report, grouped box-whisker plots are used to present the results of latency measurements. The plots either compare different protocols on one system or one protocol on different systems. For instance, in **Fehler! Verweisquelle konnte nicht gefunden werden.**, the uplink latencies on the 5G-ready test system are grouped by two different protocols: AMQP and SV as indicated on the x-axis. For both groups, different message transmissions rates (r=10, 100, 1000) per second are considered and indicated by a colour scheme.

A box in the box-whisker plot is determined by the first and third quartile and therefore contains 50% of all values. The line within the box represents the mean value. The lines above and below the box are called whiskers or antennas. In the scope of this document, the whiskers indicate the 98th and the 2nd percentile, i.e., two percent of the data are neglected as outliers.

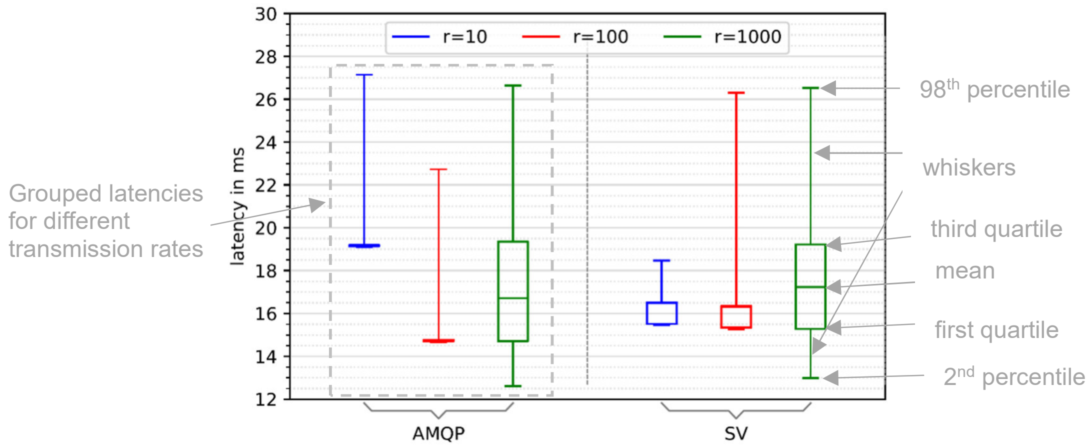


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Figure A2. 1 Exemplary box-whisker plot for uplink latency on 5G-ready system