Smart TSO-DSO interaction schemes, market architectures and ICT Solutions for the integration of ancillary services from demand side management and distributed generation

Lab-environment set-up and simulations

D4.4

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About SmartNet

The project SmartNet (http://smartnet-project.eu) aims at providing architectures for optimized interaction between TSOs and DSOs in managing the exchange of information for monitoring, acquiring and operating ancillary services (frequency control, frequency restoration, congestion management and voltage regulation) both at local and national level, taking into account the European context. Local needs for ancillary services in distribution systems should be able to co-exist with system needs for balancing and congestion management. Resources located in distribution systems, like demand side management and distributed generation, are supposed to participate to the provision of ancillary services both locally and for the entire power system in the context of competitive ancillary services markets.

Within SmartNet, answers are sought for to the following questions:

- Which ancillary services could be provided from distribution grid level to the whole power system?
- How should the coordination between TSOs and DSOs be organized to optimize the processes of procurement and activation of flexibility by system operators?
- How should the architectures of the real time markets (in particular the markets for frequency restoration and congestion management) be consequently revised?
- What information has to be exchanged between system operators and how should the communication (ICT) be organized to guarantee observability and control of distributed generation, flexible demand and storage systems?

The objective is to develop an ad hoc simulation platform able to model physical network, market and ICT in order to analyse three national cases (Italy, Denmark, Spain). Different TSO-DSO coordination schemes are compared with reference to three selected national cases (Italian, Danish, Spanish).

The simulation platform is then scaled up to a full replica lab, where the performance of real controller devices is tested.

In addition, three physical pilots are developed for the same national cases testing specific technological solutions regarding:

- monitoring of generators in distribution networks while enabling them to participate to frequency and voltage regulation,
- capability of flexible demand to provide ancillary services for the system (thermal inertia of indoor swimming pools, distributed storage of base stations for telecommunication).

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List of Abbreviations and Acronyms

Acronym	Meaning
3G, 4G, 5G	3rd, 4th, and 5th Generation mobile technologies
AC	Alternating Current
API	Application Programming Interface
AWS	Amazon Web Services
CDG	Certified Data Gateways
CET	Central European Time
CHIL	Controller Hardware-In-the-Loop
CHP	Combine Heat and Power
CIM	Common Information Model
CMP	Commercial Market Party
DAQ	Data Acquisition
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
DL	Downlink
DMS	Distribution Management System
DR	Demand Response
DSO	Distribution System Operator
FRR	Frequency Restoration Reserve
FRT	Fault Ride Through
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Groupe Spécial Mobile, Global System for Mobile Communications
GUI	Graphical User Interface
HIL	Hardware-In-the-Loop
HMI	Human-Machine-Interface
HTTP	Hypertext Transfer Protocol
HTTPS	HTTP Secure
HV	High Voltage
HVRS	High Voltage Regulation System
ICT	Information and Communication Technologies
IP	Internet Protocol
ISP	Internet Service Provider
LAMP	Linux, Apache, MySQL, and PHP
LMO	Local Market Operator

Acronym	Meaning
LTE	Long Term Evolution
LV	Low Voltage
LVRT	Low Voltage Ride Through
MMS	Manufacturing Message Specification
MO	Market Operator
MPP	Maximum Power Point
MSD	Italian Ancillary Service Market
MV	Medium Voltage
MVRS	Medium Voltage Regulation System
P	Active Power
PF	Power Factor
PHIL	Power Hardware-In-the-Loop
PPC	Power Plant Controller
PTF	Power Tracking Function
PTP	Precision Time Protocol
PV	Photovoltaic
Q	Reactive Power
R&D	Research and Development
RES	Renewable Energy Sources
REST	Representational State Transfer
RI	Research Infrastructure
RT	Real-Time
SCADA	Supervisory Control and Data Acquisition
SSH	Secure Shell
TCL	Thermal Controlled Loads
TCP	Transmission Control Protocol
TSO	Transmission System Operator
UDP	User Datagram Protocol
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VPP	Virtual Power Plant
XML	eXtensible Markup Language

Executive Summary

The continuous integration of large quantities of Renewable Energy Sources (RES) is challenging the whole European power system, both at the transmission and the distribution level. One commonly proposed solution to handle these challenges is ancillary services provided by connected units. For a secure operation of the network all units—including RES, flexible loads, and storage systems—should provide such services to the grid. On top of that, better coordination between the operation of transmission and distribution grids will be necessary for the future.

To tackle this problem, the SmartNet project proposes and evaluates five different coordination schemes between system operators using three benchmark scenarios from Denmark, Italy, and Spain. In the project, field tests in each of the benchmark countries are complemented with several laboratory validation tests, to cover scenarios that cannot be tested in field trials. This report presents the outcome of these laboratory tests.

At first, several possible validation cases were collected. These were based on use cases from the different field tests carried out in Denmark, Italy, and Spain. All possible validation cases were analyzed for their suitability for laboratory tests. Based on this analysis, three tests were executed, focusing on controller validation, analysis of communication impacts, and how well price-based control can integrate with the SmartNet coordination schemes. The laboratory tests focus on evaluating equipment that was developed for purpose of the pilots. This is done by combining the capabilities of AIT SmartEST laboratory with the SmartNet simulator. In other words, the laboratory validations were based on Hardware-In-the-Loop (HIL) setups, avoiding relying only on software simulations.

The work in this deliverable shows how laboratory tests can complement field trials. Although many aspects can be covered in field tests, there are still limitations, such as when the current regulatory framework is blocking. The results demonstrate important indications for the field tests and show some of the limitations with the current implementations of the coordination schemes. When combining the results from these laboratory tests with the simulation results and the results from the pilots, they all show the possibilities of the SmartNet approach and give important input for future work.

1 Introduction

1.1 Motivation and Objectives

The SmartNet projects compares different coordination schemes between Transmission System Operator (TSO) and Distribution System Operator (DSO) together with different real-time market architectures with the aim of finding out which of the solutions would deliver the best compromise between costs and benefits for the system [1]. Each coordination scheme presents different ways of organizing the relationships between system operators and is characterized by a specific set of roles (taken up by system operators and ancillary services providers) and a corresponding market design. A cost-benefit analysis is implemented to evaluate simulation cases on three benchmark countries—Italy, Denmark and Spain—in order to allow drawing conclusions on possible regulatory gaps both at European and national level. This simulation platform is then scaled up to a full replica lab where the performance of real controller devices will be tested, which is documented in this deliverable. At the same time, three demonstration projects (pilots) for testing specific technological solutions are implemented to enable monitoring, control and participation in ancillary services provision from flexible entities located at distribution level. For this purpose, one pilot is executed in each of the benchmark countries: Italy, Denmark, and Spain [1].

Although many different viewpoints and potential issues can be covered in the three pilots there are still certain aspects that cannot be covered or are only partially analyzed. The laboratory tests are dedicated to replicate and test some of the functionalities to be implemented within the pilots. Here, the focus of the lab tests is to anticipate some potential issues and troubles before they are implemented in a real scenario. In addition to that, laboratory tests can add further possibilities for testing new functions that cannot be tested in a pilot, such as situations where the current regulatory framework is blocking [2].

Having these goals in mind, the laboratory tests will focus on evaluating certain equipment that was conceived for purpose of the pilots. This is done by combining the capabilities of AIT SmartEST laboratory [3] with SmartNet simulator [4]. In other words, the laboratory validations will be based on HIL setups, avoiding relying only on software simulations. Furthermore, the use of the SmartNet simulator in a HIL setup also provides further possibilities for validation of the SmartNet simulator, especially considering real-time aspects. In the end, the following main goals were planned for this work:

- Analyze the interaction between selected equipment and elaborate suggestions on their utilization within the pilots
- Obtaining a validated simulation environment that can also be coupled with components or controllers running in real-time.
- Validation of additional hardware components that were not directly covered in the pilots
- Analysis of additional communication aspects, such as latency, packet drops, etc.

It should also be mentioned that it is not the direct intention of the laboratory tests to evaluate the different coordination schemes that were developed within the SmartNet project. Nevertheless, the findings from the laboratory tests may still provide some suggestions and guidelines for how the coordination schemes can be further optimized for field installations.

1.2 Organization of this Report

This deliverable is structured as follows: In Section 2 the proposed validation methodology is presented. Section 3 presents a collection of possible validation cases. These are based on different scenarios provided by the different SmartNet pilots. From the possible validation cases a selection is made which are then implemented in the laboratory. In Section 4 the implementation of the selected test cases is described in more detail and the results are presented. Finally, this section also provides a short discussion about the results from the experiments. The deliverable is concluded with Section 5.

2 Validation Methodology

2.1 General Approach

As described above, the laboratory tests are associated with the SmartNet pilots. One of the main goals with this work is to anticipate some potential issues and troubles before they are implemented in a real scenario (i.e., the pilots). Because of this, the scenarios developed in the pilots were used as main motivation for collecting possible laboratory validation cases. The validation methodology used in this work is described by the following steps:

1. Collecting validation cases: In the first phase different validation case were collected that may be used to validate different aspects. To find these validation cases the three pilots were analyzed and split up into multiple sub-cases. Sub-cases where the results will provide a benefit, either for the pilot or for the general outcome of the SmartNet project, were selected as possible validation cases.
2. Selection of test cases: Each of the selected validation cases from the first step is analyzed in more detail and an assessment is made whether the validation case can be implemented in the laboratory or not. At the end of this step, a rough description of the test and the main test objective should be available.
3. Test and experiment specification: Once test cases have been selected it needs to be specified how the test should be executed. This includes detailed specification of needed components and interfaces between the components. In this step it is also important to specify what the different test objectives are. The last part of this step is to specify the significant steps of an experiment, such as the information exchanged and in which order this must happen to create a successful test.
4. Experiment execution and collection of results: The last step is to execute the defined experiments and collect the measured results. After this step iterations with the previous steps may be needed in case the results are not descriptive enough.

2.2 Proof-of-Concept Validation According to the ERIGrid Method

In the H2020 ERIGrid project a formalized method for testing power system applications has been developed which is being used here in SmartNet in order to plan, specify, configure and execute several proof-of-concept laboratory validations. It refines the above outlined general validation methodology [5] (c.f., Section 2.1). An overview of the overall ERIGrid approach is depicted in Figure 1.

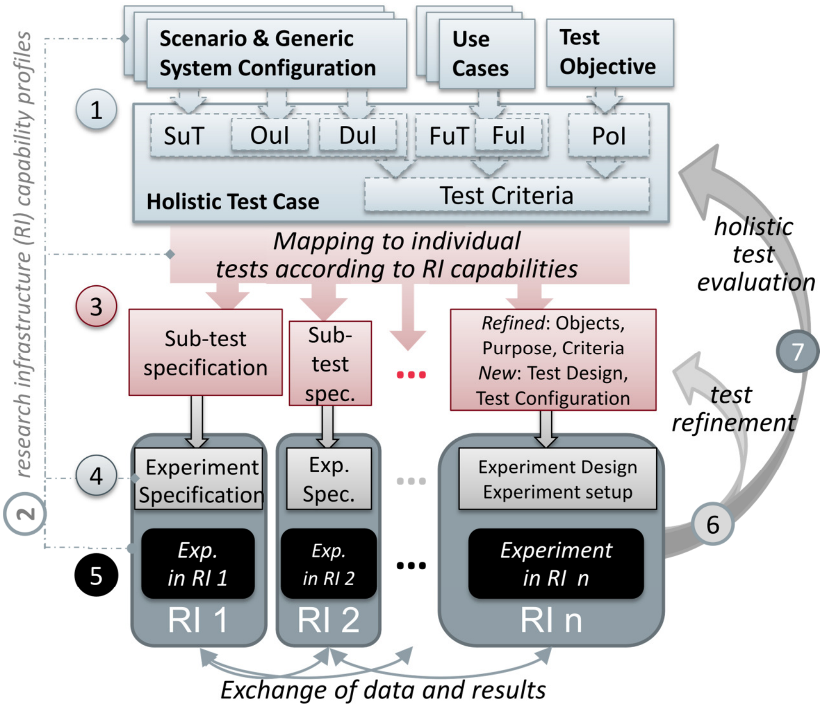

Figure 1: Overview of the ERIGrid validation approach for power systems [5]

The starting point of the ERIGrid validation methodology is the specification of a *holistic test case* (i.e., Step 1). This is derived from a scenario and corresponding system configuration as well as use cases within this setup. Thus, the test case aims to identify specific test criteria, relating to a test system configuration, relevant use cases and a specific test objective. In an independent step, the Research Infrastructure (RI)—i.e., laboratory environment in case of SmartNet—involved are profiled with regard to their testing capabilities (i.e., Step 2).

Depending on the complexity of the validation problem, a test case might be split-up into so-called sub-tests. The sub-tests concentrate on certain components or sub-systems in total reflecting the structure of the holistic test in such a way that the sub-test results may be assembled to offer quantitative feedback on the holistic test criteria. This decomposition is performed in the first part of the mapping step (i.e., Step 3), where the interfaces and dependencies between the sub-test cases as well as the resulting requirements must be specified as well. In a second part of the mapping step, the descriptions of the sub-test cases, given the RI profiles from Step 2, are employed to identify for each sub-test case the appropriate RIs capable of conducting the test. Once the RI and tests are known the experiments can be specified, e.g., the concrete setup and design (i.e., Step 4).

In context of carrying out the sub-tests (i.e., Step 5) it is necessary to analyze and to exchange data and results (i.e., Step 6) between the sub-tests, based on which cross-dependencies have been identified in Step 3. The results of all tests are analyzed and combined to obtain the criteria with which the holistic test is evaluated (i.e., Step 7). Possible methods for combining results might be up-scaling or aggregating results. Thus, the mapping between the tests has two purposes: *(i)* the re-use of results as an input to gen-

erate successive results, and *(ii)* the combination of results from different sub-tests to obtain results of the holistic test. To this end, dependencies between tests have to be considered beforehand.

The mapping step as well as the step of combining results of the sub-test might be an iterative approach. Before setting up and conducting the experiments, the process from holistic test to RI and back should be specified as precisely as possible to minimize the effort and costs.

3 Analysis and Selection of Test Cases

This section describes the validation cases collected during the first phase. Since the three pilots are in focus for finding possible validation cases, each pilot was analyzed in detail. In the following sections possible validation cases for each pilot are discussed. Based on these discussions, the most suitable validation cases are selected as actual test cases.

3.1 Validation Cases Related to the Italian Pilot

3.1.1 Pilot Overview

The Italian pilot project is managed and coordinated by TERNA and RSE. It aims to implement new features in order to promote the integration of ancillary services from Distributed Energy Resources (DER); the main goals are three:

- Observability of MV and LV sources in real-time. Different information should be aggregated at the interconnection point MV/HV (e.g., total load, P and Q at the connection point, forecast data). The information is provided from the DSO to the TSO;
- The voltage regulation and in particular the development of an architecture and the implementation of hierarchical systems for the reactive power regulation by generators connected to HV and MV grid;
- The power/frequency regulation (Frequency Restoration Reserve—FRR) with regard to generators connected to MV grid, still not available in the Italian market.

The pilot is conducted in the Ahrntal Valley (North Italy), where there is the availability of several Power Generating Modules of different size connected on all voltage levels. The distribution network involved is managed by the local DSO EDYNA, that provided a map of the users connected to the grid. The generators involved are:

- As regards HV project, 2 HV hydro generators of about 16 MW and 27 MW, connected directly to TSO's grid;
- The MV generation is composed by 33 generators of 43.5 MW total;
- 0.85 MW of photovoltaic generation in LV.

New devices, with two different ICT systems, are developed by SIEMENS and SELTA:

- HVRS (High Voltage Regulation System) that implements the algorithms to perform the functions of the reactive power information aggregation and to control the high voltage generation to achieve the voltage regulation. This device is realized only by Siemens.

- MVRS (Medium Voltage Regulation System) that implements the algorithms to perform the functions of the information aggregation and to control the medium voltage generation to achieve both the power/frequency and the voltage regulation.

Both devices are able to collect the data from the units connected to the substation where they are installed. As regards the HV grid, the power plants information is already available to the TSO. Regarding the MV and LV grid, MVRS provide for each primary substation facility technical data and real time data (updated every 20 s), divided by source, which are sent to the TSO to achieve high observability. An improved monitoring of the grid at MV and LV levels allows the TSO to better control the grid, to know the allocation of resources and so to ensure a more efficient safety of the grid system. The generation real time data is measured at some MV generators; where measurements are unavailable, data are calculated by the Real Time Estimation Algorithm, which is based on plant data, weather data, power plant measures and historical data. In order to evaluate the reliability of the obtained value, the Accuracy of the Estimate Index is an indicator derived by comparing the energy estimated with the energy measured through commercial metering. The aggregation of the load is obtained by difference between the measured generation and the technical data of the primary substation.

About the voltage regulation, an algorithm was implemented to fulfil the request sent by the TSO. The TSO defines the voltage or the reactive power set point for the substation, through an optimization algorithm, compatibly with the operating point. For the HV grid, the allocation of the reactive power among the generators is determined by the HVRS based on the operating point of each plant, so that the participation percentage of the capability is the same for all the plants. For the MV and LV grid, the MVRS has to manage the whole aggregation of DG connected to the primary substation. A specific function uses the data available (measures and estimates) to define a cumulative virtual capability seen from the interconnection point between DSO and TSO so that it is possible to manage the aggregation as virtual power plant.

Since currently in Italy the participation of DG in the Italian Ancillary Service Market (MSD) is not included in the market structure, an innovative functionality implemented on MVRS is the power/frequency regulation (FRR). Each generator that takes part in this regulation allocates a certain range of their active power capability, which can be used for either upwards or downward regulation. According to the grid and operating constraints, the MVRS calculates, in real time, the overall power regulation band of the aggregate subtended to the substation, that shall be made available for the TSO every 4 s. In response to the setpoint sent by the TSO, the allocation of the active power among the aggregated units is defined by the MVRS in order to optimize and speed up the satisfaction of the TSO's request.

3.1.2 Validation Case 1: Distribution Management System and Power Plant Controller

One of the participants of the Italian pilot, SELTA, provides a Supervisory Control and Data Acquisition (SCADA) system with an included Distribution Management System (DMS), which is installed at primary

substation level of the DSO. The DMS software is specifically developed for the Italian pilot. Furthermore, SELTA also provides a Power Plant Controller (PPC) specifically designed to manage different generation facilities, regardless of the primary energy source (e.g., solar, wind, hydro). Using these two components multiple DERs can be aggregated as a virtual power plant. This allows the included DERs to participate in the market and giving the possibility to ease the management of the distributed resources operating them in an aggregated way. Aggregation functionality and Volt/VAr regulation will be taken into account at primary substation level by the SCADA/DMS, according to load flow computation and state estimation. At the same time control functionality to the underlying DERs needs to be operated by the PPC and DER level.

The PPC from SELTA can be interfaced using both IEC 61850-7-4 and IEC 61850-7-420 data models. This will ensure manageability and controllability of the aggregated plant capabilities, taking care of all the actions needed to maintain a certain voltage profile at the interconnection point. From a logical point of view, the PPC implements several regulation functionalities that can be made available all at once, prioritizing their intervention according to a specific set of rules, or in a mutually exclusive way:

- Direct active power (P) setpoint
- Direct reactive power (Q) setpoint
- Direct power factor (PF or cos(ϕ)) setpoint
- Reactive power regulation function Q(V)
- Active power regulation function P(f)
- Power factor regulation function PF(P)
- Power Tracking Function (PTF)

Some of the above listed functions are already applicable with current regulation and without major impacts from the prosumer point of view, as long as they are within the capability limits of the generation plant; other functionalities, although technically feasible, suffer from a lack of rules in terms of market access and economic reward for service provisioning from DER side and need to be enabled by a framework revision.

In this validation case the SCADA/DMS and PPC will be tested in a laboratory environment to realistically assess which is the best scheme to provide flexibility and ancillary services from DERs to the grid stability. To do this, the SCADA/DMS and the PPC will be integrated in the laboratory using a HIL concept together with the SmartNet simulator, as seen in Figure 2.

In the HIL setup the SCADA/DMS and the PPC will be represented as real components. The market and aggregation layers required for the SmartNet approaches need to be represented as simulated components since these do not yet exist as real components. For the power system network, a part of it will be simulated and some parts of it can be can be represented by laboratory equipment (e.g., DERs, substation). The idea with the validation case is to integrate the SCADA/DMS into the market layer using an intermediate aggregator. The role of the aggregator is to create market bids based on the capabilities offered by the SCADA/DMS. In the other direction, a setpoint to the SCADA/DMS is created based on ac-

cepted bids from the market. Once the SCADA/DMS receives a setpoint, this is used to calculate a concrete setpoint for the PPC.

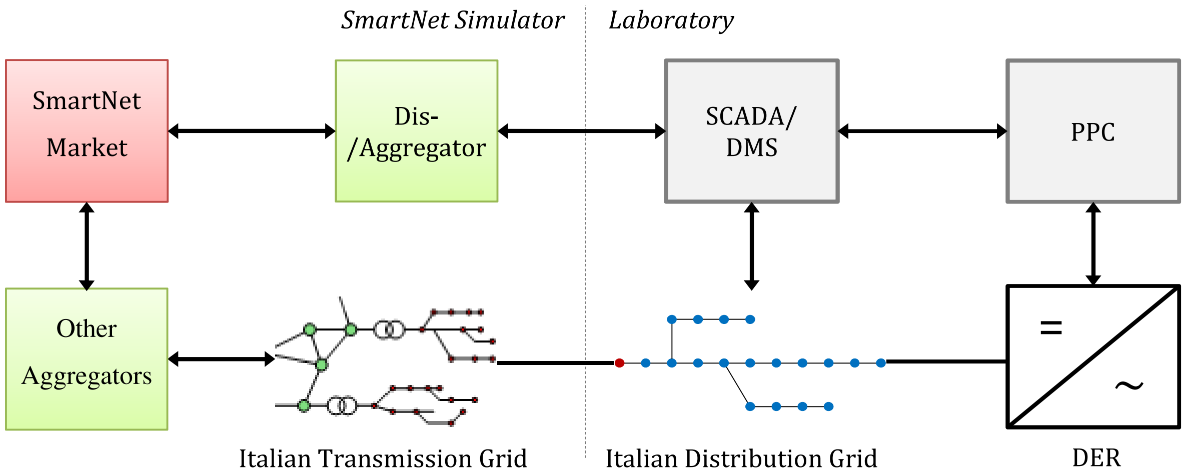

Figure 2: Conceptual setup of Validation Case 1: Distribution Management System and Power Plant Controller

The expected outcome for this validation case will focus on the following points:

- *Connection setup between SCADA/DMS, PPC, and DER:* The goal is to find any connection issues and resolve these before the same setup is used in the pilot.
- *Integration of the SCADA/DMS with SmartNet coordination schemes:* The SmartNet simulator offers the possibility to simulate the SmartNet coordination schemes without any regulatory restrictions or the like. This should be utilized for further investigations of the performance of the SCADA/DMS and the PPC.
- *Effectiveness of different PPC control schemes with different types of DERs:* In the pilot, the PPC is connected to hydro power plants. The laboratory tests provide an opportunity to test the PPC with other types of DER as well, such as a PV generator.

3.1.3 Validation Case 2: Communication Network Effects on the Interactions of the SCADA/DMS and the PPC

This validation case is a variant of Validation Case 1, but with the addition that a communication emulator is used to analyze the effects of different communication network parameters on the interaction of the SCADA/DMS and the PPC. As one part of the SmartNet project, ICT requirements for the different flexibility coordination schemes were discussed and evaluated on a theoretical basis. One of the main outcomes of this work was that modern telecommunication technologies, such as 4G or 5G, are more than capable of handling the proposed SmartNet solutions [4]. In this validation case a dedicated communication emulator from VTT will be used to emulate exactly this kind of communication technologies [7]. Using this possibility, it is the intention with this validation case to provide measurements that can be compared to theoretical analysis. A conceptual setup of the validation case is seen in Figure 3.

There are multiple possibilities where the emulator can be placed. Based on the Italian scenario, the most appropriate locations for the emulator would be either between the SCADA/DMS and the PPC or between the SCADA/DMS and the simulation of the power system. In the first case, the SCADA/DMS and the PPC are communicating frequently with each other and the physical distance between the two components is also far enough that emulated communication makes sense. For the second case, the SCADA/DMS needs to continuously collect measurements from the grid and thus emulated communication can also bring interesting results.

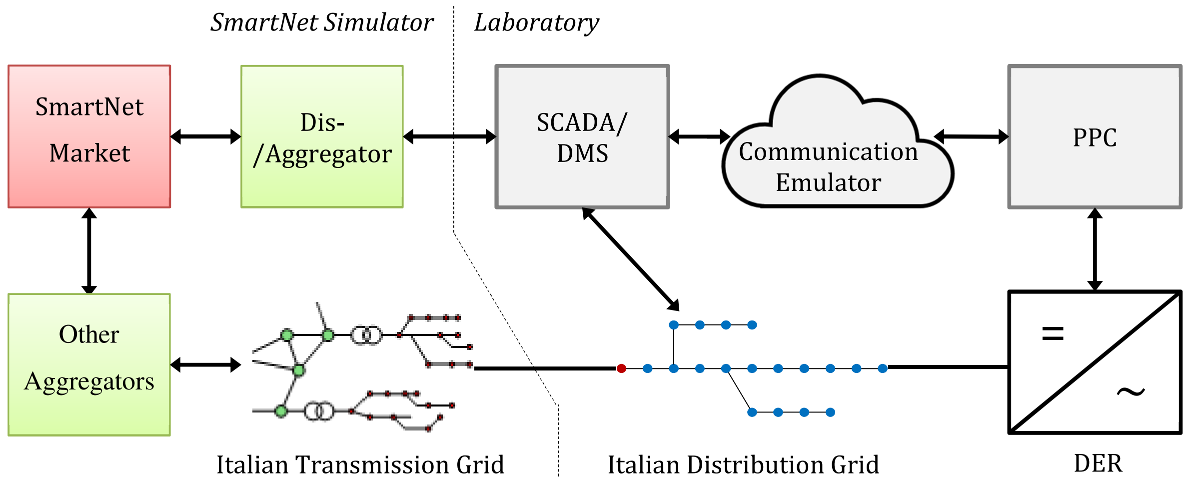

Figure 3: Conceptual setup of Validation Case 2: Communication Network Effects on the Interactions of the SCADA/DMS and the PPC.

Another result of the theoretical analysis of the ICT requirements was that pure problems with latency will probably not have any direct effects on the performance of the coordination schemes since the update cycle is too long. However, other communication network effects, such as packet loss or corrupted packets, will probably affect the performance in another way and should also be taken into account.

The expected outcome for this validation case will focus on the following points:

- *Communication effects on the performance of the Italian scenario:* The goal is to test how the SCADA/DMS and the PPC perform when different communication network effects are applied, such as delay, packet loss, corrupted packets etc.
- *Testing the SmartNet approach with different ICT technologies:* The communication emulator can emulate different ICT technologies, such as GPRS, 3G, etc. This can be used to test the performance of the SmartNet approach with these different technologies and can thus be used to validate some of the results from the theoretical analysis made previously in the project.

3.2 Validation Use Case Related to the Danish Pilot

3.2.1 Pilot Overview

The main purpose of SmartNet Danish Pilot is to implement and evaluate the concept of model-based control principles for activation of flexibility from swimming pools providing system balancing and grid congestion services at TSO and DSO levels. In 2017 in Denmark, it was seen that 44% of the electricity load was covered by the fluctuating and partly unpredictable wind power generation. This large penetration of the stochastic wind power often leads to balancing problems. The Pilot aims at assessing the potential of provision of ancillary services from an aggregation of Danish summer houses with swimming pools. Summer houses with swimming pools consume substantial amounts of electricity for heating the water and humidity control. The electricity demand from summer houses is particularly flexible. For example, swimming pools have a large thermal mass, thus, the load to heat pool water can be disconnected or shifted with little consequences on the comfort of the occupants. This makes them particularly well-suited to the provision of ancillary services. As a result, the Danish Pilot intends to assess and demonstrate, to which extent, the flexibility of summer houses can be exploited to provide both transmission and distribution grid levels with ancillary services. The pilot benefits from the use of price-based indirect mechanism to control the set-points of thermostats of swimming pools in rental summer houses, alleviating many of the issues arising in both transmission and distribution grids.

3.2.2 Validation Case 3: Effects of Integrating Price-Based Control with the SmartNet Coordination Schemes

The Danish pilot uses a priced based control, not only from market to aggregator, but also from the aggregator down to the heaters of the swimming pools. Since these price-based controllers are different than the controllers initially considered during the design of the coordination schemes, a laboratory test combining the price-based controllers with a simulation of the SmartNet coordination schemes provides an interesting validation case. Besides providing answers about the general setup of such a system, it might also be possible to validate how the coordination schemes perform in combination with price-based control. Of course, this is also studied in the Danish pilot, but a laboratory test brings more flexibility when it comes to testing scenarios that may not be comfortable for the residents of the Danish summer houses. Since the price-based controllers should be tested they need to be integrated into the laboratory environment. For this validation case two options were considered.

The first option consists of having a single (or more) controllers that are used to heat the swimming pools in the Danish pilot delivered and integrated physically into the laboratory environment. For this option, a HIL setup would be needed where the controller is the hardware, connected to a simulation of the remaining parts of the system, the market and aggregator/dis-aggregator by means of the SmartNet

simulator, and the swimming pool physics by means of a dedicated simulation. The setup for this option is seen in Figure 4.

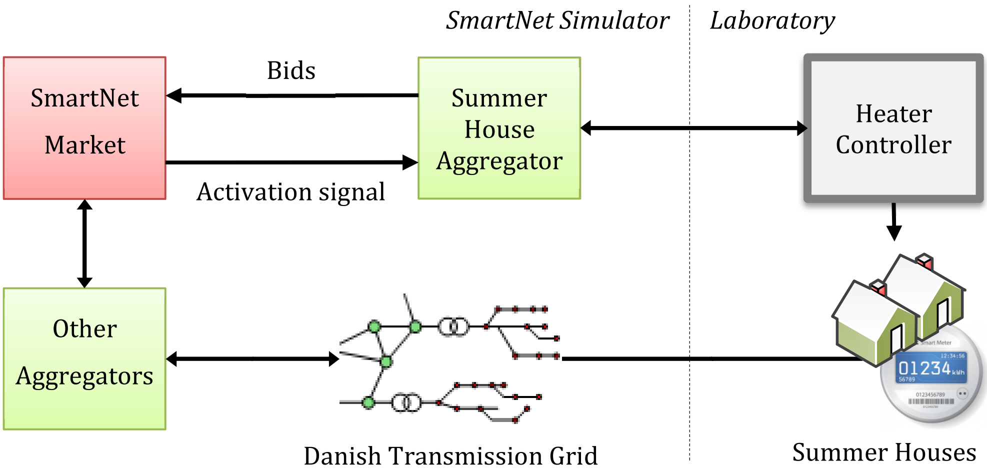

Figure 4: Conceptual setup for the first option of Validation Case 3: Price-Based Control in Combination with SmartNet Coordination Schemes

The second option consists of connecting the laboratory to the physical swimming pools located at the summer houses in Denmark. A simple possibility to achieve this kind of setup is to reuse as much as possible of the Danish system. This means that not only the local controllers for the swimming pool heaters, but also the aggregator, developed for the Danish pilot by Our New Energy (ONE). Furthermore, since real-time measurements of the active power consumption are available for the summer houses the reaction of the swimming pool heaters can be monitored and the measurements fed back to the network simulator. The concept for this option is seen in Figure 5.

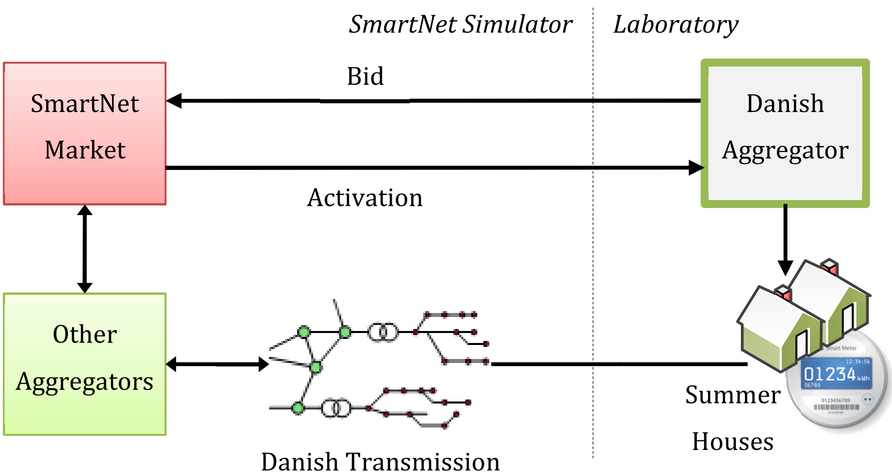

Figure 5: Conceptual setup for the second option of Validation Case 3: Price-Based Control in Combination with SmartNet Coordination Schemes

Both options have their advantages and disadvantages. In the first option, more detailed tests of the local swimming pool controllers are possible. The main disadvantage here is to provide the remaining laboratory setup. Since no swimming pool simulation model with enough detail was developed for the pilot, these would have to be designed and validated before they can be used in a HIL setup with the controllers. This problem would not be the case with the second option, since here the real swimming pools, used by real people, would be used. The main issue with this option is that the tests cannot be run in parallel with the Danish pilot. Since the aggregator for the Danish pilot can only connect to one market at the time (i.e., either the market used in the Danish pilot or the simulated market for the laboratory tests), this needs to be coordinated between the Danish pilot and the laboratory tests.

The expected outcome for this validation case will focus on the following points:

- *Connection setup between the Danish aggregator and the market operator:* The goal is to find any connection issues and resolve these before the same setup is used in the pilot.
- *Integration of price-based control with the SmartNet coordination schemes:* The SmartNet coordination schemes were originally not designed to work directly with price-based control schemes. Using the SmartNet simulator the integration between the price-based control and the SmartNet coordination schemes can be further tested.

3.3 Validation Use Case Related to the Spanish Pilot

3.3.1 Pilot Overview

The coordination scheme used in the Spanish pilot is called “Shared balancing responsibility model”. In this model, there are joint balancing responsibilities between the TSO and the DSO, according to a predefined schedule in the common border. The DSO organizes a local market to respect the schedule agreed with the TSO, while the TSO has no access to resources connected at the distribution grid. A new regulated function located at the control center of the DSO, called Local Market Operator (LMO), is proposed to facilitate that Commercial Market Parties (CMPs) become flexibility providers of aggregated DERs. This new function is designed to allocate flexibility among the different CMPs in a competitive manner.

The pilot combines technical and economic aspects aimed at providing a flexible response to the needs of both the TSO (balancing) and DSO (balancing and congestion management). It demonstrates the technical feasibility of using radio base stations to provide ancillary services for the DSO through demand side management. The base stations are equipped with backup batteries, which ensure the continuity of communications service in the (rare) event of a blackout in the distribution grid. By using the backup batteries, radio base stations can be disconnected from the grid on purpose when requested by the CMP. Therefore, a DSO-managed local market is created, where different CMPs offer the flexibility of the DER in their portfolio, so that the DSO can procure balancing services and congestion management for the distribution network.

The pilot involves five primary substations and 20 radio base stations in the city of Barcelona. The DSO (Endesa Distribución) is responsible for matching a scheduled active power profile at a virtual TSO-DSO interconnection point. This profile, which has a 24-hour horizon and a 15-minute resolution, is generated on a day-ahead basis and given as input data for the execution of balancing services the next day, based on historical data already archived by Endesa Distribución

Fundamentally, the Spanish pilot aims to implement balancing services and congestion management for the distribution network through direct bidirectional signals to the aggregator. This is pushed further downstream to the activation of backup capacities to reduce the consumption in selected grid regions of, in this case, the city of Barcelona.

3.3.2 Validation Case 4: Flexibility Provision for Base Station Backup Batteries

The validation case related to the Spanish pilot is similar to Validation Case 3 (i.e., the Danish validation case), with the main difference related to the actual component used for flexibility provision. In the Spanish pilot flexibility is provided by backup batteries for telecommunication base stations. For this validation case, one possibility would be to directly control the base stations in Spain. Another option would be to simulate the market and Spanish transmission grid with the SmartNet simulator and send the market results to the base station aggregator in Spain. The concept for second option is seen in Figure 6.

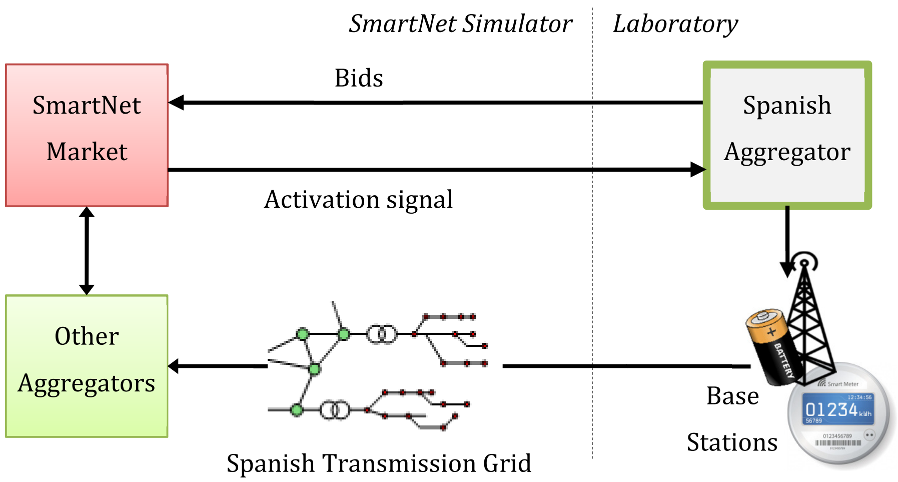

Figure 6: Conceptual setup of Validation Case 4: Flexibility Provision for Base Station Backup Batteries

The expected outcome for this validation case will focus on the following points:

- *Connection setup between the Spanish aggregator and the market operator:* The goal is to find any connection issues and resolve these before the same setup is used in the pilot.

3.4 Selected Test Cases

Based on the collected validation cases above the next step in the chosen methodology is to select the validation cases that are most suitable as test cases. In the end, from the presented validation cases above three were chosen as actual test cases:

- *Validation of DMS and PPC used in the Italian Pilot (Test Case 1)*: This test case is related to the Italian pilot (Validation Case 1). It shows how low-level components and DERs can be integrated with the SmartNet coordination schemes based on the Italian scenario used in the pilot. The main components under study are the SCADA/DMS and PPC from SELTA.
- *Validating the Impact of ICT on the Italian Scenario (Test Case 2)*: This is based on Validation Case 2 and can also be seen an extension of Test Case 1 by including some of the knowledge acquired during the ICT requirements analysis of the SmartNet project [6]. By adding a communication emulator between the SCADA/DMS and the PPC real communication problems can be tested. It can be validated if this affects the coordination schemes and how the components react to changing communication situations.
- *Price-Based Control in Combination with SmartNet Coordination Schemes (Test Case 3)*: This test case is based on the use case related to the Danish pilot (Validation Case 3). For this case two different options are possible, but in the end option 2 was chosen. It is distinguished by using the summer houses on-site in Denmark and connecting them to the SmartNet simulation through an interface over internet. Furthermore, it also shows how the price-based control of the Danish pilot interacts with the coordination schemes in the SmartNet simulator.

Mainly due to the similarity with Validation Case 3, Validation Case 4 was not used as a test case. Since the test case would have a test scenario similar to Test Case 3, it is not expected that this test case would bring any considerable new results compared to the amount of work needed to organize this test case. In this sense, it was decided not to further pursue the Validation Case 4. Nevertheless, the discussions regarding this validation case still contributed to the implementation of the other test cases, especially for the implementation of Test Case 3. In the following section, the selected test cases are described in more detail. As reference and overview descriptions of each test case—according to the ERIGrid method—are provided in Section 7.

4 Test Case Implementation and Results

The main part of this section presents the implementation of each selected test case from the previous section. Before that an overview of the validation environment is presented the give an overview of the different testing possibilities. Finally, the section is concluded with a discussion about the results and some lessons learned.

4.1 Overview of the SmartEST Laboratory

4.1.1 Description of the SmartEST lab infrastructure

The AIT SmartEST laboratory infrastructure offers an environment for testing, verification and R&D in the field of large scale distributed energy system integration and Smart Grids applications. The infrastructure accommodates DER components, such as inverters, storage systems, CHP units, voltage regulators/controllers, and other types of related electrical equipment. Powerful controllable AC and DC sources allow full-power testing capability up to 1 MVA (AC), including a high-performance PV Array (DC) Simulation and bidirectional source/sink for battery emulation. Additional equipment for simulating control and communication interfaces and the possibility of operating the equipment under defined (extreme) temperature/humidity conditions offer extended testing capabilities [3].

Advanced power system experiment and verification methods available at the lab include real-time (RT) Power Hardware-In-the-Loop (PHIL) simulation combining close-to-reality hardware system tests with the advantages of numerical simulation to allow for the integration of battery models into the laboratory analysis. By means of a controllable AC voltage source distribution network models can be coupled to the real components to develop, validate and evaluate control algorithms, system concepts and components for Smart Grid applications.

Figure 7 shows a simplified schematic of the AIT SmartEST lab. Designed as a pure low voltage (LV) (400 V) lab, all AC buses are rated for operation at voltages up to 480 V (line-to-line). The laboratory itself is supplied from the local 20 kV medium voltage (MV) grid via two independent MV/LV transformers. The following infrastructure is available in the SmartEST lab.

Electrical setup and components:

- Grid simulation (3 independent laboratory grids; 2 independent high bandwidth grid simulators—0-480 V, 800 kVA; 3-phase balanced or unbalanced operation; LVRT/FRT testing possibilities)
- Line impedance emulation (adjustable line impedances for various LV network topologies: meshed, radial or ring network configuration)
- Adjustable loads for active and reactive power (freely adjustable RLC loads up to 1 MW, 1 MVAr—capacitive and inductive behavior; individual control possibilities)

- Environmental simulation (test chamber for performance and accelerated lifetime testing)
- DC sources (6 independent dynamic PV array simulators: 1500 V, 1500 A, 960 kVA)
- DAQ and measurement (multiple high precision power analyzers with high acquisition rate; simultaneous sampling of asynchronous multi-domain data input)

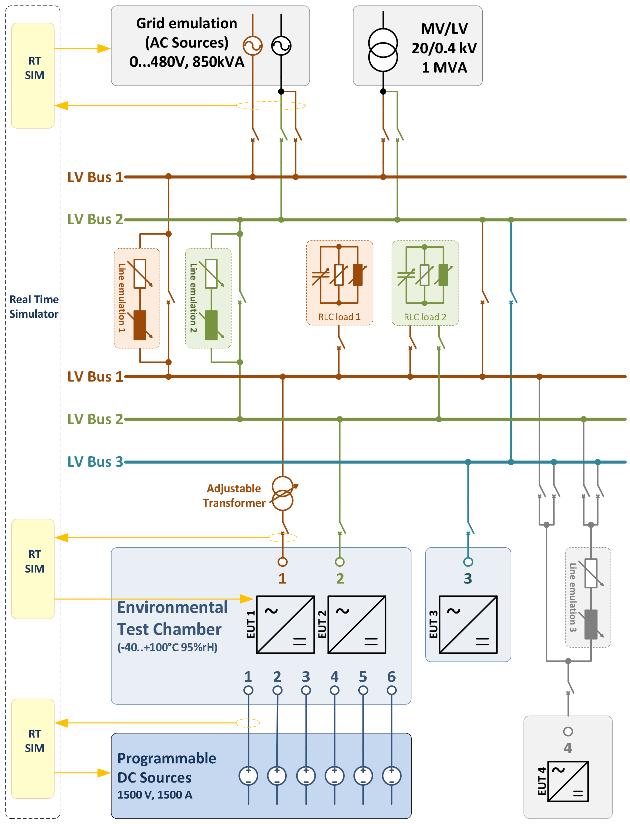

Figure 7: Simplified schematic of the SmartEST laboratory.

Simulation tools and components:

- Multicore Opal-RT Real-Time Simulator (i.e., eMegaSim)
- Typhoon HIL Real-Time HIL Simulator
- Mathworks xPC-Target Simulator
- PHIL and CHIL experiments at full power in a closed control loop
- General simulation tools: Matlab / Simulink, SimPowerSystems, PSpice / Cadence
- Network simulation tools: DigSILENT PowerFactory, NEPLAN, PSAT
- Communication network simulator: Omnet++
- Powerful simulation cluster for complex and large-scale system simulations (incl. co-simulation power system and information and communication/automation infrastructure)

ICT/Automation tools and components:

- SCADA and automations system (highly customizable laboratory automation system, remote control possibilities of laboratory components, visualization and monitoring)
- Distributed control approaches: IEC 61499 / 4DIAC
- Communication methods: IEC 61850, OPC/OPC-UA, Industrial Ethernet (Ethernet Powerlink, Modbus / TCP, etc.)
- Planning methods, interoperability and compatibility, integration: IEC 61970 / 61968 (CIM)
- Network information system
- Cyber-security assessment methods and tools for Smart Grid systems and components

4.1.2 Usage of SmartEST for the Laboratory Validation

SmartEST is mainly used to evaluate the SmartNet developments in the laboratory environment. Therefore, the laboratory infrastructure incl. the LV networks as well as loads (representing the consumer behavior), energy storage systems but also distributed generators (i.e., PV inverters) can be used in different scenarios. On top of that, the available laboratory ICT/automation and measurement system will be used for testing automation, control commands, and logging and measurements.

In order to validate the interaction of the hardware components with the SmartNet coordination schemes a general HIL setup will be necessary between the SmartEST laboratory and the SmartNet simulator (see Section 4.2 for more information). The SmartEST laboratory also includes real-time simulation systems that can be used to simulate certain parts (e.g., the distribution grid). However, due to the complexity of the SmartNet simulator, the replication of the same behavior within the real-time simulators in the SmartEST laboratory would go beyond the scope of the project.

4.2 Interfacing the SmartNet Simulator and the Laboratory

One of the main results of the SmartNet project is the simulator, capable of simulating and analyzing the different TSO-DSO coordination schemes developed in the project. Therefore, it also makes sense to use this simulator as much as possible also for the laboratory tests. As described in the section above, the SmartEST laboratory will be used to integrate real hardware components and controllers. This is done through a HIL setup where the components must be interfaced with the SmartNet simulator. Since this interface will be (almost) the same for all test cases this is described in this section.

4.2.1 Simulation Setup

The simulation platform (described in [4]) does not require any particular adaptation to interact with external software. The platform requires only two new functions for reading the data coming from external software and for writing back the simulation results. Instead, the main adaptation of the platform regards the scenario, not the simulation code. In fact, due to the high number of controllable devices, the speed of the simulation platform is too slow to be compatible with the laboratory environment. Since the

code was already optimized, the only way to a faster simulation process was to reduce the scenario size. Thanks to these modifications, the platform is able to simulate the evolution of the system faster than the real time evolution of the laboratory. In this way, when the laboratory sends new bids (every 60' minutes), the platform has already simulated the evolution of the system and it is ready to make a new simulation before new bids are received by the laboratory.

In order to interact with the laboratory, two functions were created. The first function pauses the simulation until the laboratory updates the input file. Reached the scheduled time, the laboratory writes in the input file the characteristics of the devices (e.g. maximum reactive power…) and their corresponding bid. When these data are updated, they are read by the function, which has also the role to convert them in the correct format to be inserted in the database. These devices, depending on their characteristics, are converted into one of the device formats already present in the platforms so that their evolution is computed automatically with no need of any adaptation.

The platform takes into account these new devices to compute the clearing of the market and the network evolution. The market clearing determines if the bids are accepted, while the physical evolution computes the automatic secondary regulation and the reactive power modulation. After the clearing of the market and the physical layer evolution, the second function reads the results of the devices evolution and writes the results to the file that will be read by the laboratory. The exchange of data with the laboratory and the simulation platform are represented in Figure 8.

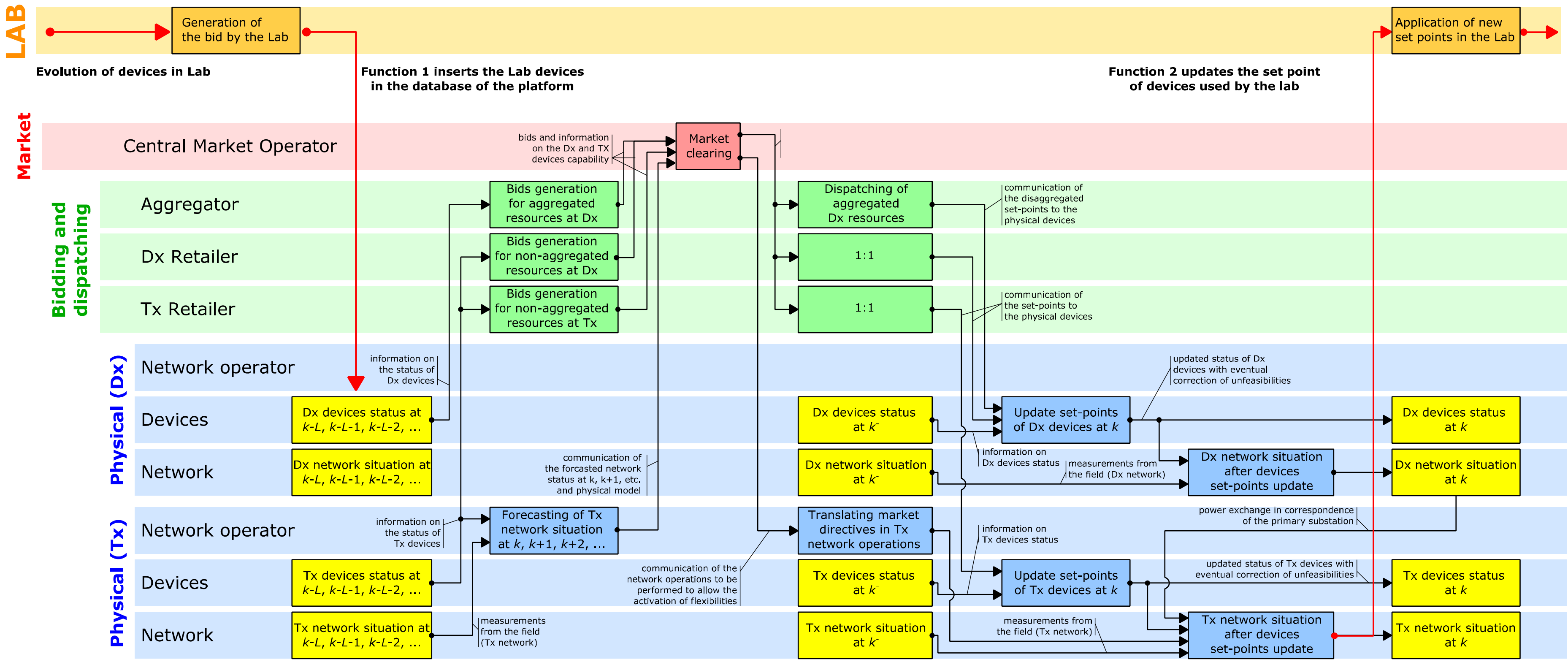

Figure 8: Overview of a simulation cycle and data exchange with the laboratory.

4.2.2 Interface between Simulation and Laboratory

In order to allow access to the SmartNet simulator for multiple parties simultaneously, the Amazon Web Services (AWS) were used. The simulator was deployed to an AWS server, which is more or less a Linux virtual machine running in the cloud. Therefore, it is also accessible from multiple sources and the synchronization with new updates is made easier. Consequently, an interface between the SmartEST laboratory and the simulator, running on the AWS server was needed. An overview of this interface is seen in Figure 9.

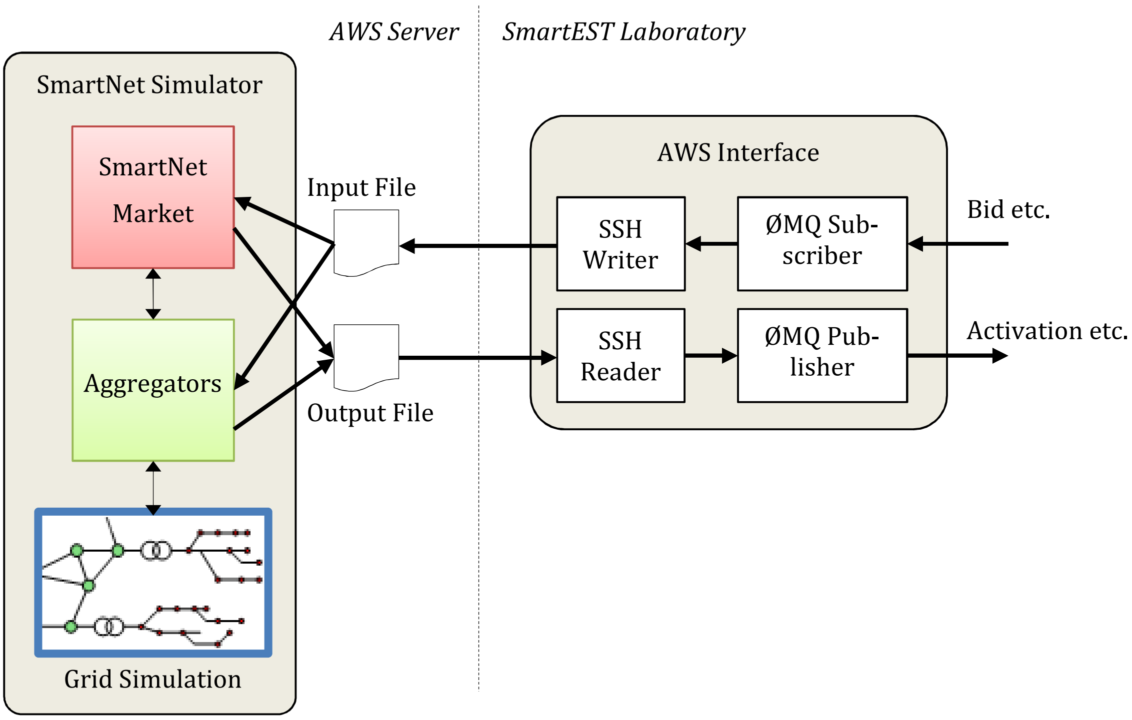

Figure 9: Interface between SmartNet simulator and SmartEST laboratory.

On the AWS server side, files are used for the interaction with the simulator, one for inputs such as bids or capability reports, and one file for simulation outputs, such as activation signals or setpoints. Depending on the scenario, either the market simulation part or the aggregation simulation part accesses the files. On the laboratory side, the files are read and written over a Secure Shell (SSH) channel. In order to provide a general interface towards the components in the laboratory ZeroMQ interfaces were used [9]. A ZeroMQ subscriber listens for incoming messages and forwards them to the AWS server via the SSH writer module. Conversely, the SSH reader module detects changes of the output file, which triggers it to publish these changes via the ZeroMQ publisher.

4.3 Test Case 1: Validation of DMS and PPC used in the Italian Pilot

4.3.1 Test Case Description

This test case is based on Validation Case 1, which is detailed in Section 3.1.2. The main components under study are the SCADA/DMS and PPC from SELTA. The test case is intended to show how low-level components and DERs can be integrated together with the SmartNet coordination scheme, based on the Italian scenario used in the pilot. An overview of this test case is seen in Figure 10.

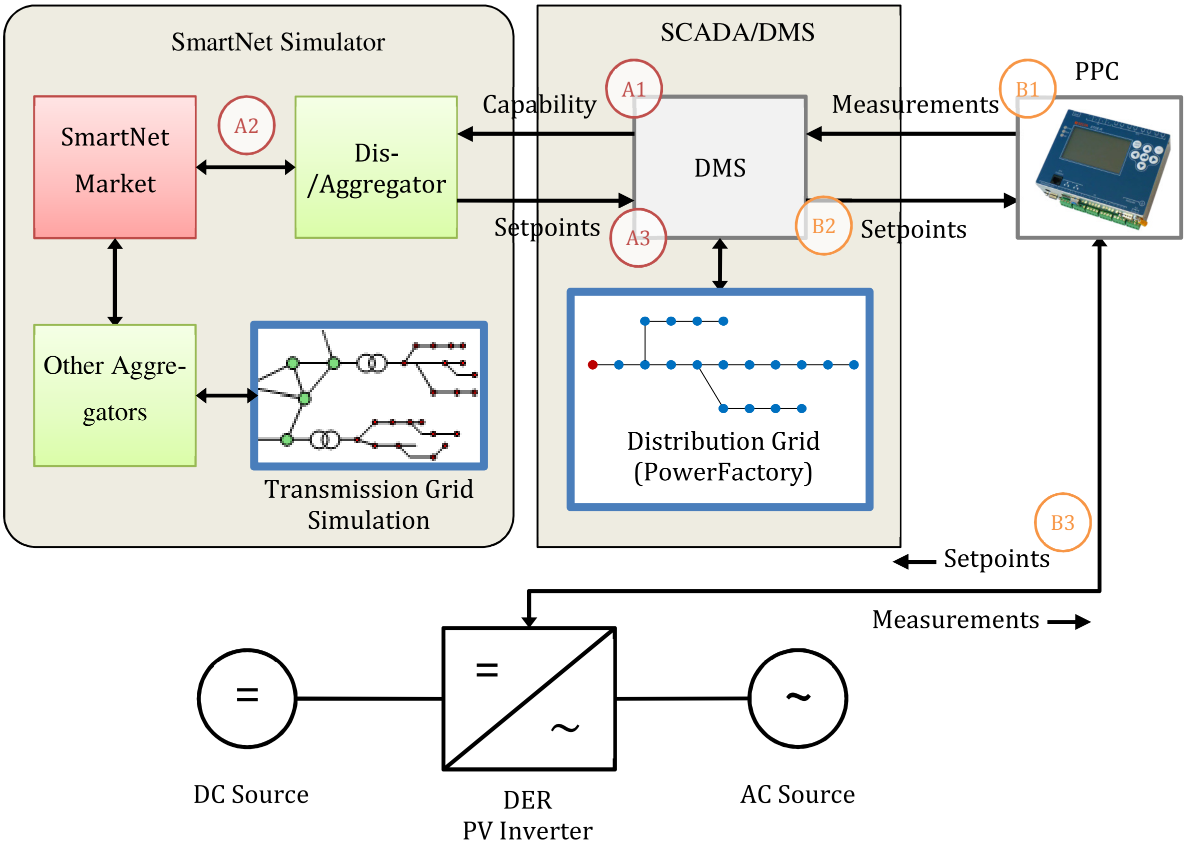

Figure 10: Overview of Test Case 1.

On the SmartNet simulator the Italian transmission grid is simulated together with other aggregators and the SmartNet market. In this test case the Italian scenario is used. For the integration of the SCADA/DMS from SELTA an additional aggregator is simulated. This has the responsibility of creating bids based on the current capability sent from the DMS. The bids are then used in the market clearing and if accepted the aggregator creates setpoints for the DMS. As explained in Section 4.2.2, the SmartNet simulator is running on the AWS.

The SCADA/DMS from SELTA is in this test case reduced to only the DMS. The SCADA system was used in the pilot for accessing measurements of remote components. However, in this test case this is not necessary since all components are available locally in the laboratory. The DMS is responsible for calculating

the optimal setpoints of the DERs based on the distribution system setpoints coming from the aggregator. To do this, the DMS uses load flow simulation of the distribution grid, made in PowerFactory. Because of this, the same simulations can also be used for evaluation purposes. The DMS is also connected to a PPC, which converts the setpoints of the DMS into proper setpoints for the PV inverter. At the same time, measurements are also collected by the PPC from the inverter and sent to the DMS, where they are incorporated into the distribution grid simulation.

The test case has two main sequences. The main sequence A is depicted with A1-A3 in Figure 10 and described below:

A1. The current capability (active and reactive power; increasing and decreasing) are calculated by the DMS and sent to aggregator on the SmartNet simulator.
A2. The aggregator uses the capability reports from the DMS to create bids. The bids are then submitted to the market. After the market clearing the activation signals are converted by the aggregator into setpoints for the DMS.
A3. When the DMS receives new setpoints from the aggregator these are used as the basis for calculating active and reactive power setpoints for the PPC.

Sequence B is executed in parallel with sequence A and is seen as steps B1-B3 in Figure 10. The steps are the following:

B1. The current active and reactive power measurements from the inverter are collected by the PPC and sent to the DMS.
B2. The DMS incorporates the DER measurements into the distribution grid simulation. Based on the optimal load flow simulation done with PowerFactory the DMS calculates new setpoints for the DER, which are forwarded to the PPC. This is done every 5 seconds.
B3. Once the PPC receives new active and reactive power setpoints from the DMS they are forwarded to the inverter, where they are implemented.

4.3.2 Validation Environment and Setup

4.3.2.1 Simulation Scenario and Setup

The Italian scenario, due to the high size of transmission network, cannot be simulated with the speed required by the laboratory. Thus, only the portion of the transmission network in the proximity of the distribution network simulated by the lab was selected. The scenario used for the laboratory simulation does not include only the transmission networks node and devices, but also a detailed description (i.e. including electrical and devices models) of distribution networks connected to that transmission node. By analyzing the transmission network near the node that correspond to the distribution network simulated by the laboratory, it was found out that with about 50 nodes it was possible to select a representative

portion of the transmission network. In fact, the considered distribution network is in the end of a transmission network line, which is almost independent from the rest of the system. Since the portion of the network is almost independent from the rest of the network, the simulations made by the market are realistic since all the important network components and devices that affect this section of the network are represented.

4.3.2.2 Description of the DMS and the PPC

The two main components that are analyzed in this test case come from SELTA and include the PPC and the DMS. A general overview of the setup and the interaction between the DMS and the PPC is seen in Figure 11.

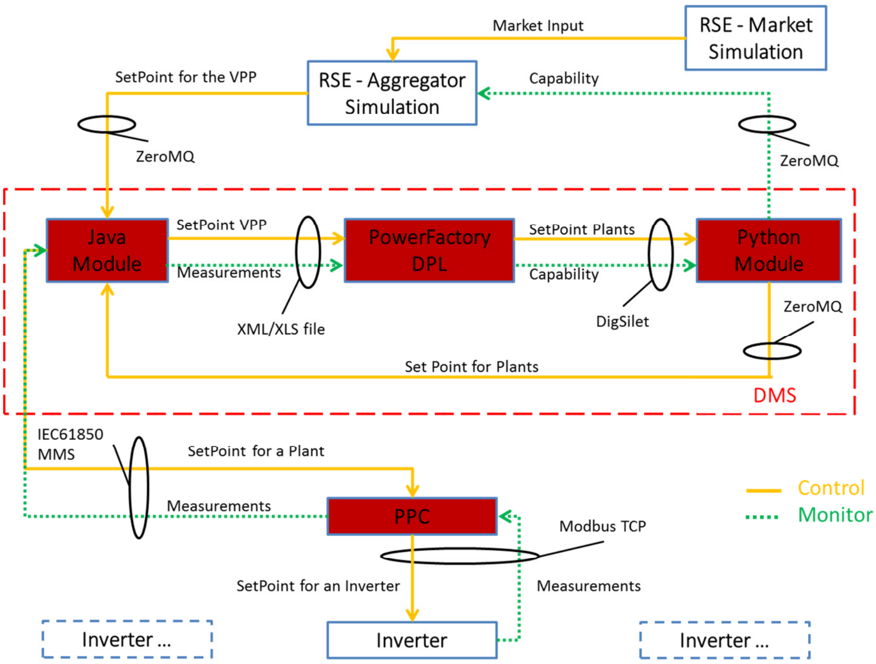

Figure 11: Overview of the setup and the interaction between the DMS and the PPC.

The PPC represents the physical device that allows the communication between the central control system and the inverters in the lab. Following the "monitor direction" (from inverter to PPC) the PPC acquires measurements and states from the inverter via Modbus TCP and collects these data thanks to a local automation (e.g. calculation for scaling and data type conversion). Then the data are sent to the DMS with IEC 61850 using a periodic report (based on the MMS[1] protocol). Moreover, the PPC is able to manage the set points coming from the IEC 61850 client in the DMS to control the operation of the inverters, connected via Modbus TCP. Finally, the set points are forwarded and applied by the energy resources

[1] MMS—Manufacturing Message Specification

connected to the inverters. The PPC provides the monitoring of its operation using the display or the web server page. A photo of the PPC is seen in Figure 10.

The main part of the functionality is contained in the DMS. A more detailed overview of the DMS functions is seen in Figure 12.

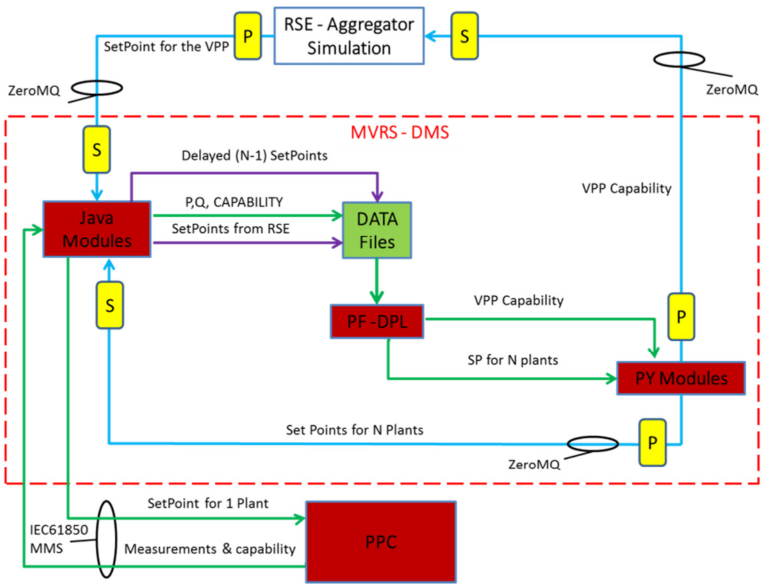

Figure 12: Overview of the different modules in the DMS and their interaction with each other.

The DMS is realized by the interaction of three fundamental modules:

- Java module: implementing the telecommunication protocol (IEC 61850).
- PowerFactory program: simulation platform for calculation and grid analysis.
- Python module: necessary for the real time operation of PowerFactory.

The role of the Java module is to receive measurements from the PPC via IEC 61850 MMS, to prepare and to write the received data (active power, reactive power and capability) to measurement files (represented as DATA Files in Figure 12) that can be read by PowerFactory. In order to consider the response of the simulated MV distribution grid, the set points generated by the DMS (except for PPC) are managed by this module, forwarding them to the DATA Files with a delay that corresponds to the fictitious time of real actuation.

The ZeroMQ library allows the Java module (subscriber) to acquire the set points requested by the Aggregator (publisher) for the Virtual Power Plant (VPP). Then they are written on the same DATA Files. Furthermore, this module manages the set points for the plants, coming from the Python module and directs them to the PPC, by sending the specific set point for each plant involved.

The task of PowerFactory within the DMS is to run the power flow calculation of the considered distribution MV grid. Every run takes about 5 seconds and it is based on the updated measures in the DATA Files. Moreover, it evaluates the capability of the whole VPP and tries to obtain the regulation requested

by the Aggregator, elaborating the set points for the available plants in order to solve an optimization problem.

The last module is the Python module. It mainly has two roles: the first one consists of managing the execution of PowerFactory through the provided Python interface program, and the second role consists of managing the set points and the capability of the VPP. The capability has to be separated from the other set points and is sent to different receivers. In fact, the Python module (publisher) sends the new set points to the Java module (subscriber) via ZeroMQ socket communication. In the same way, the VPP capability is send by Python module (publisher) to the Aggregator Simulation (subscriber).

Unlike the setup implemented for the Italian pilot, the setup for the laboratory tests includes a more compact and reduced system. In particular the SCADA has not been involved in the architecture. In fact, the communication protocols have been included in the Java module of the DMS and the HMI of PowerFactory replaces the typical view of the SCADA. Any change related to the configuration of the PPC has not been considered necessary. In fact, despite the nature of the energy resources is different (in the Italian Pilot only hydro power plants are considered), the PPC automatically adapts itself during the operation.

4.3.2.3 Laboratory Setup and Configuration

For this test case the SmartEST laboratory was used as seen in Figure 13. First, a PV inverter was used as a DER connected to the PPC. Secondly the SCADA/DMS was connected to the SmartNet simulator as described in Section 4.2.2.

As DER a standard PV inverter from Fronius was used, with a nominal power of 5 kW. Since this power was not high enough to affect the simulation in any remarkable way, the power measurement from the inverter was scaled by the DMS by a factor of 1000. The inverter was connected on the DC side to a programmable DC source that emulates a PV curve. On the AC side a normal grid connection was used. Furthermore, the power output of the inverter was measured by the laboratory measurement equipment.

The PPC is connected to the inverter through its Modbus TCP interface, which supports the SunSpec protocol. Through this interface measurements of the current active and reactive power output of the inverter can be requested. Also, the PPC can issue active and reactive power setpoint commands over the same interface.

To connect the SCADA/DMS to the SmartNet simulator it was possible to directly interface the ZeroMQ interfaces in the SCADA/DMS with the ZeroMQ interface in the SmartNet simulator. For more information about this interface see Section 4.2.2.

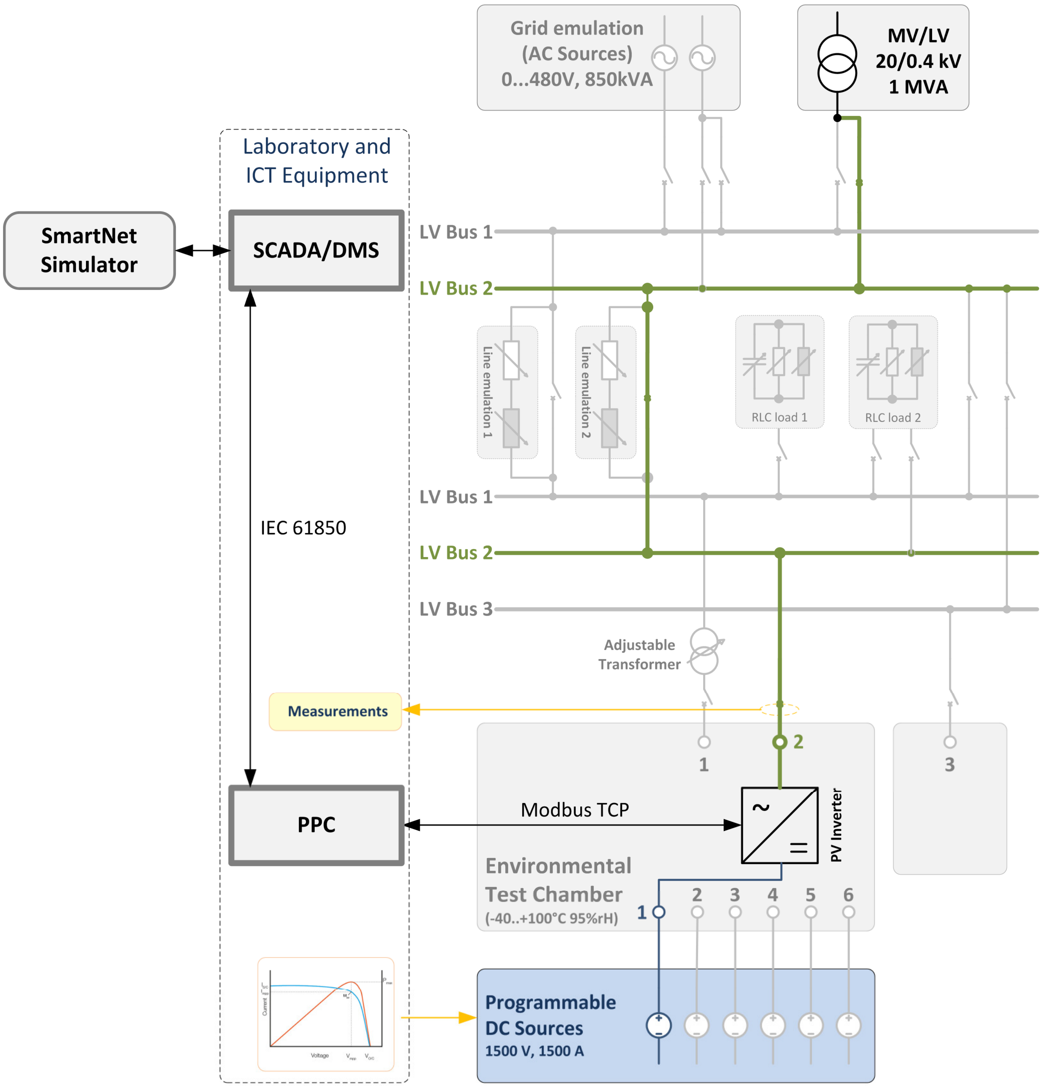

Figure 13: SmartEST laboratory setup for Test Case 1.

4.3.3 Performed Experiments and Results

Based on the test case description and the validation environment and setup two experiments were selected. They are motivated below:

- *Setup of the SCADA/DMS and the PPC:* Since both the SCADA/DMS and the PPC are also used in the pilot the laboratory tests were used to validate the setup of these two components to be able to fix any problems before the field tests. This includes sending/receiving measurements and sending/receiving control signals.
- *DMS and PPC in combination with the SmartNet Simulator:* Once a successful setup has been achieved between the SCADA/DMS and the PPC, tests can be executed to validate how these two components perform together with the SmartNet simulator.

4.3.3.1 Setup of the SCADA/DMS and the PPC

The setup was done in different steps:

- Connecting the PPC to the inverter.
- Connecting the DMS with the PPC.
- Connecting the DMS with the SmartNet simulator.

In the first step the PPC was connected to the inverter. The inverter provides a Modbus TCP interface using the SunSpec protocol. Through this interface measurements made by the inverter (active/reactive power, voltage, etc.) can be read and setpoints (e.g., active/reactive power setpoint, droop-curves) can be written. Before the setup was made the PPC had already been configured according to the inverter specifications. Due to this the setup was quite straightforward. Nevertheless, some problems were still encountered:

- Setpoints sent by the PPC were not applied correctly by the inverter. The cause for this was that the setpoints were (re-)sent by the PPC using an update interval that was too short for the inverter. This was solved by only sending the setpoints when the value changes.
- The current active and reactive power capabilities of the PV plant are not known by the inverter. If the inverter is not operating on the Maximum Power Point (MPP) (e.g., due to an external limitation) it cannot know the current maximum capability. For this to be known an external irradiance measurement would be need, which is seldom the case. In the pilot, the PPC was designed to control hydro power plants where the current capability is known by the power plant. For the laboratory tests, the current capability can be estimated instead.

After the successful integration of the PPC and the PV inverter, the DMS was added in a second step. Also in this case, the DMS had been preconfigured to make the setup easier. Furthermore, the communication between the DMS and the PPC had already been tested by SELTA. Therefore, this step of the setup was more related to the integration of the PV power plant into the DMS optimization algorithm. Some changes were necessary to the algorithm since the PV plant only allows for downward regulation. If the PV is operating on its MPP it can only reduce the active power generation. This is related to second bullet point in the list above.

The last step of the setup was to connect the DMS with the SmartNet simulator. This step also required some adaptions to the simulator for a successful connection. After this step it was also evident that the PV inverter power measurements needed to be scaled-up to higher power ratings for inclusion into the SmartNet simulation.

4.3.3.2 DMS and PPC in Combination with SmartNet Simulator

Once the setup was finished the DMS and the PPC were tested together with a simulated Italian scenario in the SmartNet simulator. As already said, this required the PV to be scaled up from 5 kW to 5 MW.

However, also when scaled-up, the standard Italian scenario, used in the experiment, was still too static for any noticeable changes on the DER side, see Figure 14. As seen, the only noticeable change happens after around 150 s when the simulation starts. After that the PV setpoint never changes.

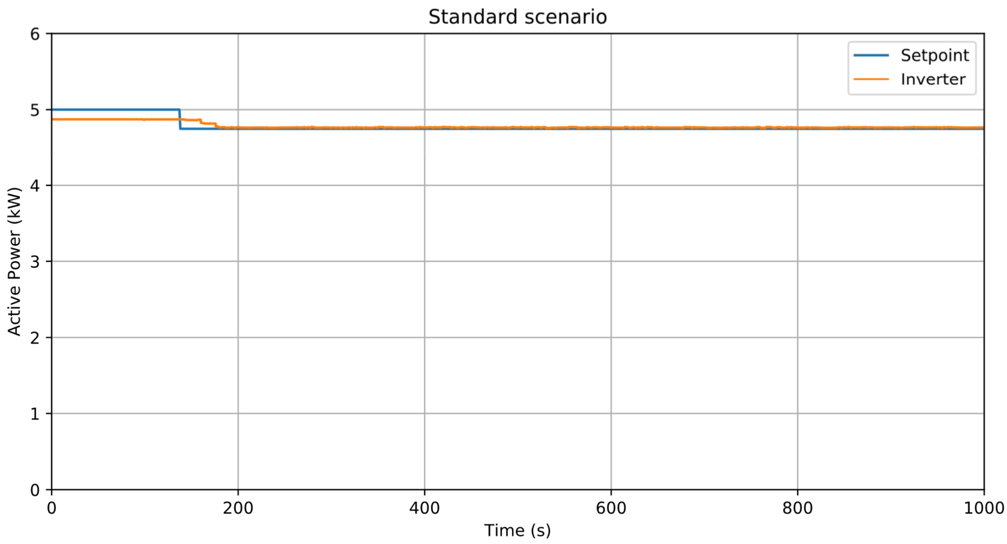

Figure 14: Setpoints and measurements from the PV inverter for a simulation of the standard Italian scenario.

To show that the whole integration works, the scenario was modified. The network unbalance was increased in order to force the participation of the distributed resources in the grid (e.g., the PV plant). This change activates more secondary regulation, which causes changes in the active power setpoint for the PV inverter. The results from this test are provided in Figure 15.

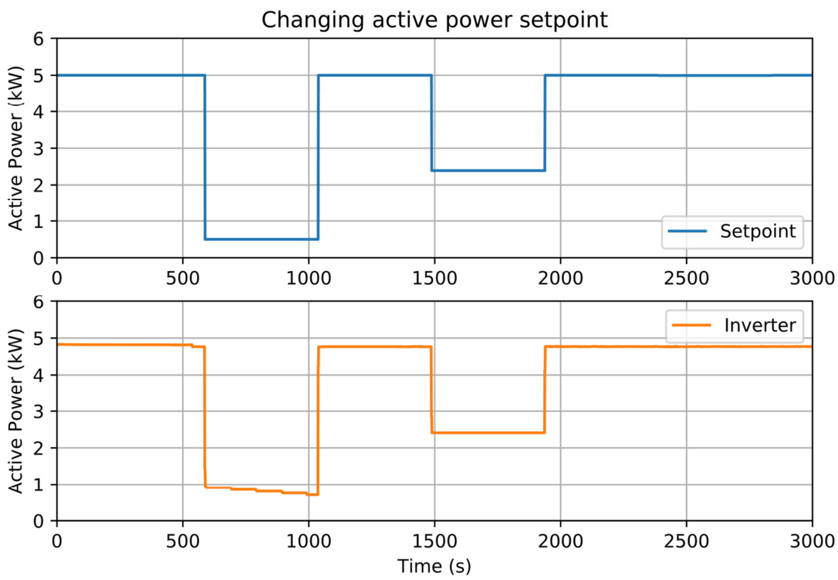

Figure 15: Results from a simulation with an adapted scenario (forced change in active power setpoint).

The upper plot in the figure shows the setpoints sent from the aggregator in the SmartNet simulator (see Figure 10). For comparison, the lower plot shows the measured active power output of the PV in-

verter. The small mismatches, especially between 500 s until shortly after 1000 s, are due to the internal optimization algorithm of the DMS (see Section 4.3.2.2).

In conclusion, the initial Italian scenario needed adaption in order to measure any interesting results from the PV inverter. In retrospect, this is also a logical outcome since the analysis done in the SmartNet simulator is focused on the transmission grid and the PV inverter is connected at the distribution grid level. Nevertheless, the tests still produced valuable results for the SmartNet project:

- Several technical issues regarding the coupling between the DMS and the PPC were discovered and solved during the setup of this test case. As a result, these detected issues could be avoided in the Italian pilot.
- The laboratory test also showed the importance of testing the solutions with different equipment. The PPC is designed to interface with any type of DER. But, the algorithms developed in the SmartNet project were developed with hydro power plants in mind. Therefore, several issues were detected when the PPC was connected to a PV inverter, such as the incapability of upward regulation of active power.

4.4 Test Case 2: Validating the Impact of ICT on the Italian Scenario

4.4.1 Test Case Description

This case is a variant of Test Case 1, see Section 4.3, but with the addition that a communication emulator is used to analyze how a non-ideal communication network affects the interactions between the SCADA/DMS and the PPC. As part of the SmartNet project, ICT requirements for the different coordination schemes were discussed and evaluated on a theoretical basis [6], [8]. One of the main outcomes of this work was that modern telecommunication technologies, such as 4G or 5G, are more than capable of handling the SmartNet solutions [8]. In this validation case, a dedicated communication emulator will be used to emulate exactly this kind of communication technologies [7]. Using this possibility, the intention with this validation case is to provide measurements that can be compared to the theoretical analysis.

Another result of the theoretical analysis of the ICT requirements was that the latency of a communication link is not the most critical for the performance of the coordination schemes, since the update cycle of the algorithm is too long. However, other communication network effects, such as packet loss or corrupted packages, will also affect the performance and thus should be taken into account [6].

Since this test case is an extension of Test Case 1, the setup is very similar. Compared to the setup of Test Case 1 in Figure 10, the only difference is that the communication emulator is connected between the SCADA/DMS and the PPC.

As with Test Case 1, the Italian scenario is used in the SmartNet simulator and the test case has two main sequences, see Section 4.3.1 for a description of these.

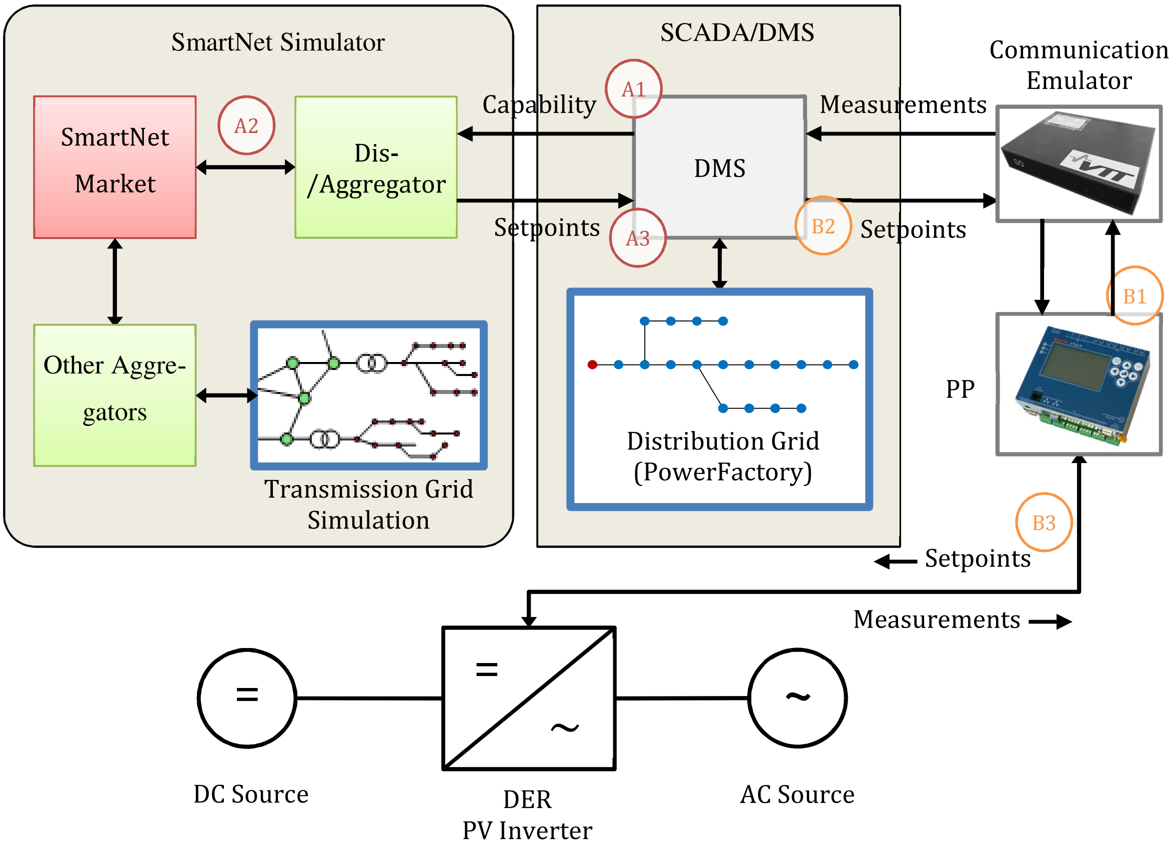

Figure 16: Overview of Test Case 2

4.4.2 Validation Environment and Setup

4.4.2.1 Simulation Scenario and Setup

This test case uses the same simulation scenario and setup as Test Case 1. More details are found in Section 4.3.2.1.

4.4.2.2 Communication Emulator

The communication emulator gives an opportunity to mimic the behavior of different types of fixed and wireless communication technologies in different radio conditions. The emulated communication link helps to detect possible bottlenecks in a system and to assess communication link's impacts on the system performance - how well used devices can tolerate changes in a communication link and how well they can fulfil the discovered ICT requirements studied previously in SmartNet [6], [8]. Testing components in different conditions gives better understanding about their performance margins. It is also feasible to test new technologies before they are deployed in the lab or operating environment.

The emulator is an Ethernet switch with added functionality to emulate slower and less reliable (than Ethernet) communication paths for the selected packet flows. The flow selection is based on source and destination addresses and port numbers (for UDP and TCP). Throttling and downgrading the flow is activated by attaching a profile to the flow. A profile consists of segments and for each segment, one or more of the following parameters can be defined [7]:

- Bandwidth up and down [Kbps] sets the emulated bit rate. The two values (up/down) are needed for a communication path where the bit rate is different depending on direction of the flow. In such case, the user must indicate the flow direction manually because the emulation device cannot know the direction.
- Delay control adds a delay to the flow. The delay for each packet is computed from three parameters: base delay [ms] ± variation [ms] and correlation [%].
- Packet loss setting causes random drops for packets. The loss probability for each packet is computed from two parameters: loss [%] and correlation [%].
- Packet duplication setting duplicates random packets. The duplication probability is given as a percentage value.
- Packet corruption setting adds random errors to packets. The corruption probability is given as a percentage value.
- Packet reorder setting causes random reordering to some packets in the flow. The reordering probability is given as a percentage value. For the reordering to work, the profile must also specify a non-zero delay.

The profiles, or selected segments of profiles, can be run indefinitely with a repeat option. The Graphical User Interface (GUI) implemented to manage the network emulator is presented in Figure 17. The picture shows multiple data flows with source and destination addresses and an example of a delay profile.

In the lab setup, the communication emulator is a Lanner industrial computer with 4 Ethernet ports. It is running on Ubuntu 14.04 with Linux NetEm enhancement [10], [11]. Three Ethernet interfaces are bridged together providing the basic Ethernet switch functionality for the emulation. The emulation management software is controlled by a browser-based GUI. The software consists of two Python scripts that perform packet sniffing, control the flow profiles, and provide a web server for the GUI components.

A typical use of the emulator includes the following steps:

1. Selecting data flows for emulation from the monitored traffic,
2. Attaching predefined profiles to selected flows,
3. Activating a filter containing the attached profiles.

During activation, data flows matching the filter are modified based on the profiles, whereas other data flows go through intact.

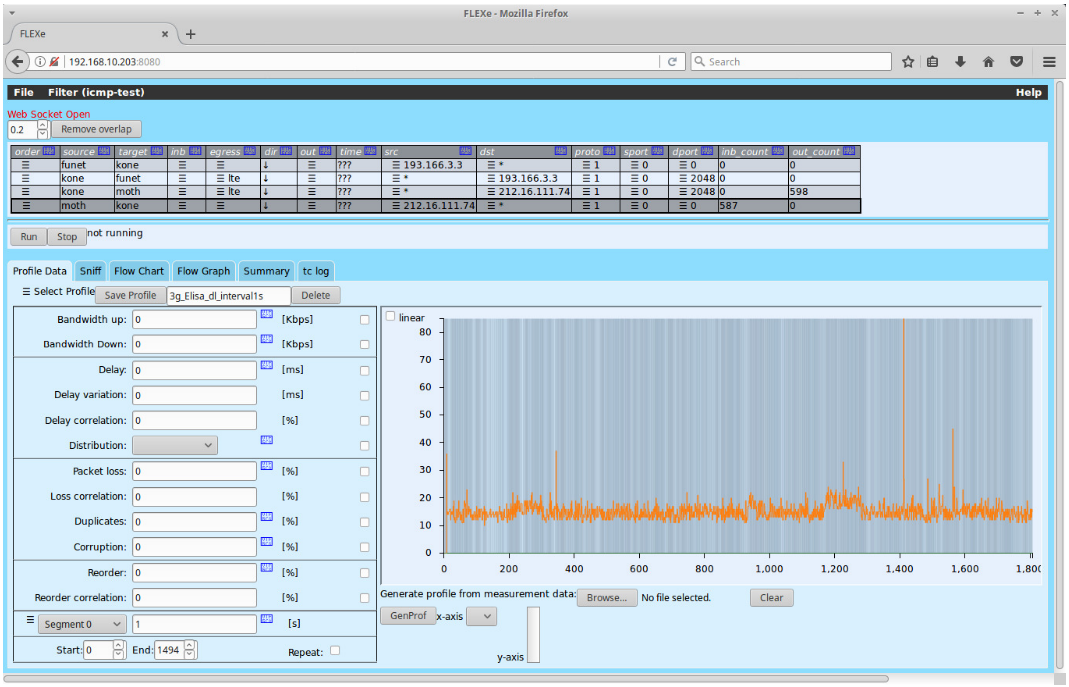

Figure 17. GUI of the Communication emulator.

4.4.2.2.1 Artificial profiles for the Communication Emulator

Artificial profiles can be used to test the performance of the communication equipment or to find performance limits. Typical artificial profiles are stair-like increased delay, packet loss, or jitter profiles that are symmetrical to both uplink (UL) and downlink (DL) directions. Those profiles can be created and modified with the GUI based on predefined and existing emulator profiles, e.g., for Ethernet, GSM/GPRS, UMTS, and LTE.

Examples of modified artificial profiles:

- *Increasing delay*: Delay increases from 0 to 40 ms with 1 ms steps. Other parameters are kept intact (see Figure 18). The profile consists of 41 segments. The length of one segment is 600 s and total length is 6 h 50 min. In the figure below, the x-axis shows the time in seconds and y-axis the delay in ms.

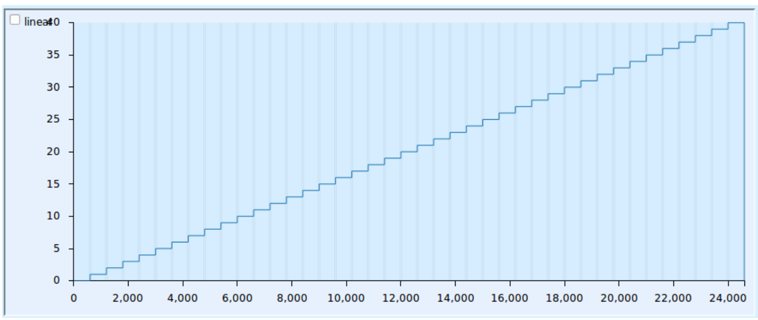

Figure 18. Increasing delay profile.

- *Increasing packet loss*: Delay is constant, e.g. 20 ms in Figure 19, but packet loss is increased from 0 to 2 % with 0.125 % steps. Other parameters are kept intact. The profile consists of 20 segments. The length of one segment is 600 s and total length is 2 h 50 min. In the figure below, the x-axis shows the time in seconds and y-axis the percentage of lost packets.

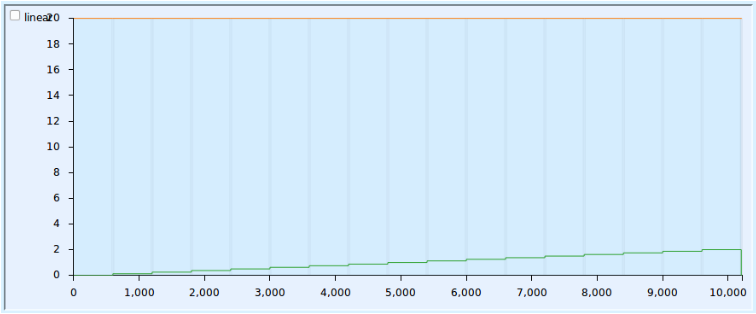

Figure 19. Increasing packet loss profile.

- *Increasing jitter*: Delay is constant, e.g. 20 ms in Figure 20. Jitter is increased from 0 to 5 ms with 0.25 ms steps while other parameters are kept intact. The profile consists of 21 segments. The length of one segment is 600 s and total length is 3 h 30 min. In the figure below, the x-axis shows the time in seconds and y-axis the jitter in ms.

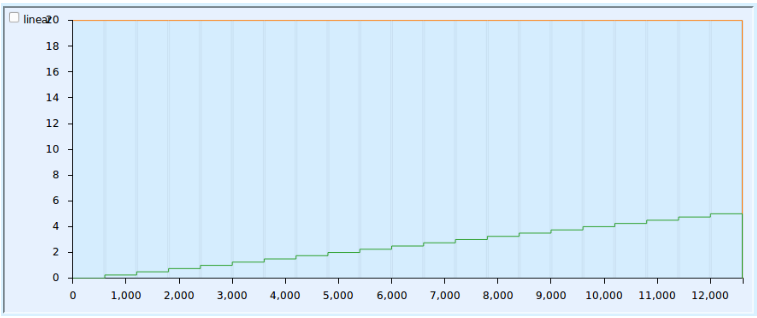

Figure 20. Increasing jitter profile.

4.4.2.2.2 Measurement and synthetic profiles for the Communication Emulator

The second option is to use measurement-based profiles or synthetic profiles generated from statistics of several measurements. The communication emulator profiles presented in this chapter are from the trial measurements performed in Odense, Denmark, and Espoo, Finland. The measurements were conducted in good, average, and bad wireless communication conditions to generate different types of performance profiles. The emphasis was put on mobile technologies due to their high flexibility and expected cost-efficiency especially in rural areas. The main focus was in commercial network measurements, but in Finland, measurements were also performed in the 4G/5G test network of 5G Test Network Finland (5GTNF) [12].

The measurement trial in Odense concentrated on measuring communication between two Certified Data Gateways (CDGs) that are used in the Danish pilot. The pilot system design is presented in Figure 21.

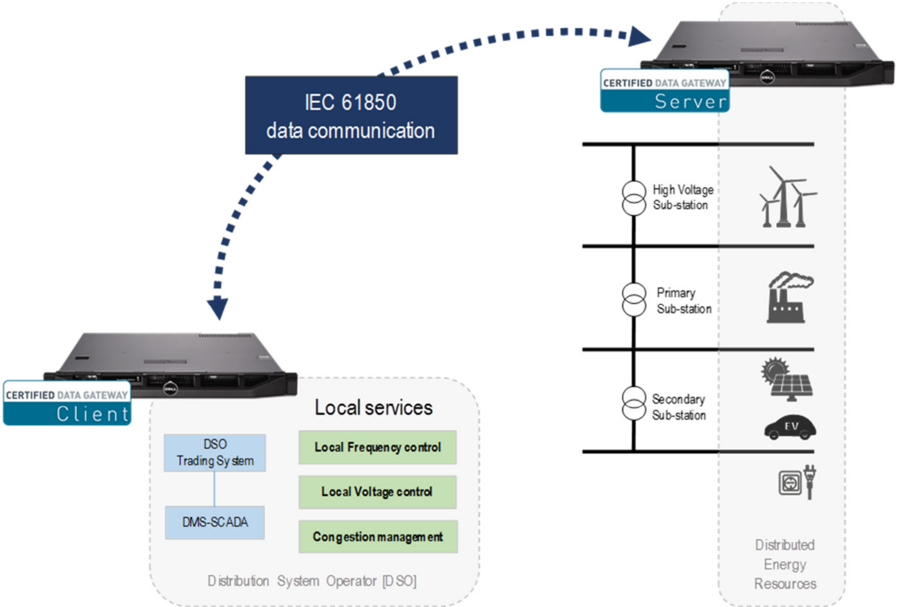

Figure 21. Overview of the Testbed for the Danish pilot (SYSTEM 2).

The measurement setup connected to the CDGs is presented in Figure 22. The upper part of the picture represents the test system being measured over a fixed or wireless link, and the lower part the measurement system used for collecting latency, jitter, and packet loss values. The CDG server is connected to Internet through a mobile connection (either LTE or UMTS), and the CDG client is connected to the Internet through an ISP connection (broadband). IP packets are mirrored by switches and Qosmet Client and Server components are measuring the performance values both in UL and DL directions. The measured values are averaged over one second time interval.

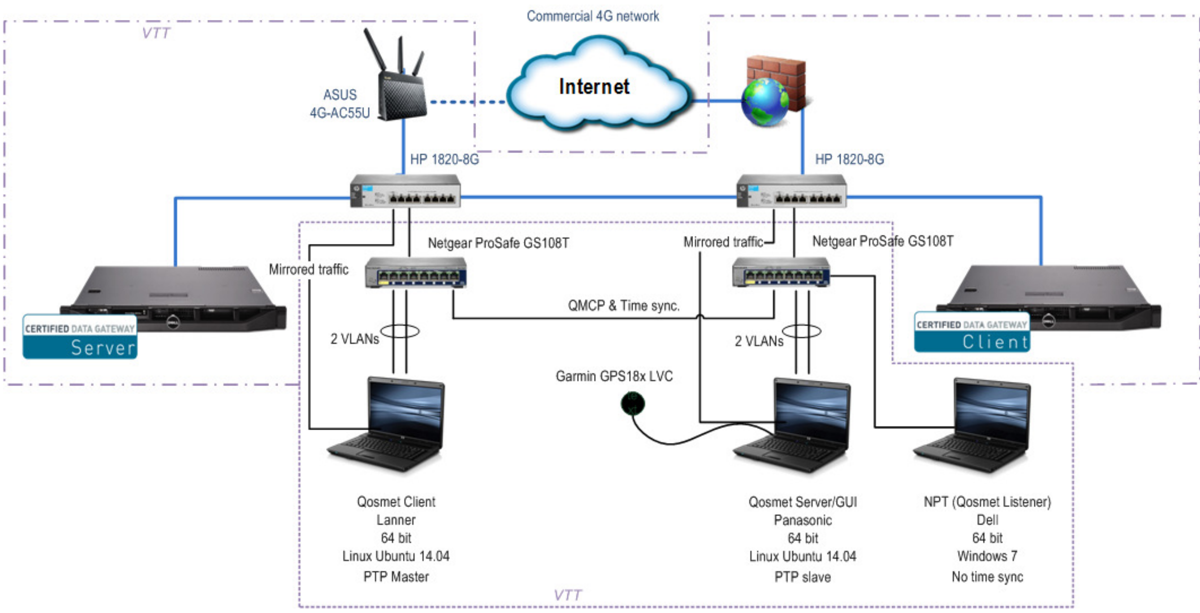

Figure 22. Measurement setup for measuring commercial network in Odense, Denmark.

Figure 23. Physical installation of the measurement setup in Odense, Denmark.

The measurement trial was repeated with a similar setup in Finland. In this setup, CDGs were replaced with traffic generators (Iperf / TCPReply) shown in the left and right sides of Figure 24. Moreover, the time synchronization was arranged using National Metrology Institute (Mikes) PTP time service instead of GPS device used in Odense.

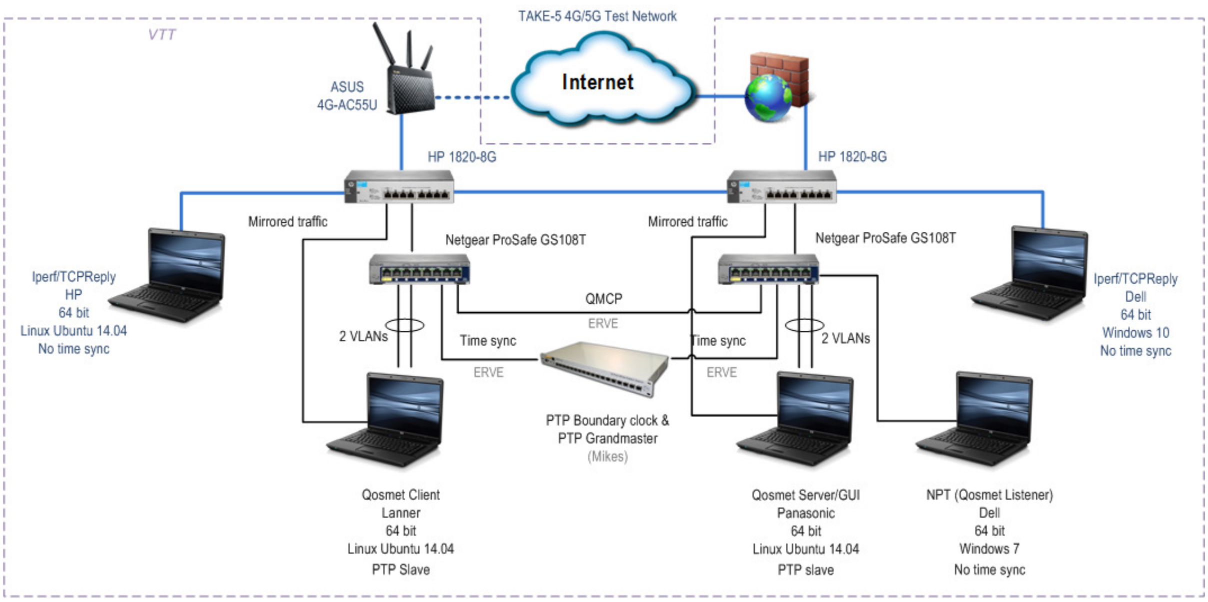

Figure 24. Setup3: Measurement setup for measuring commercial and TAKE-5 4G/5G test network in Espoo, Finland.

The following profiles were created from the trial measurements in Odense. Figure 25 and Figure 26 present the measured delay profiles in case of a Danish commercial UMTS (3G) network in UL and DL directions.

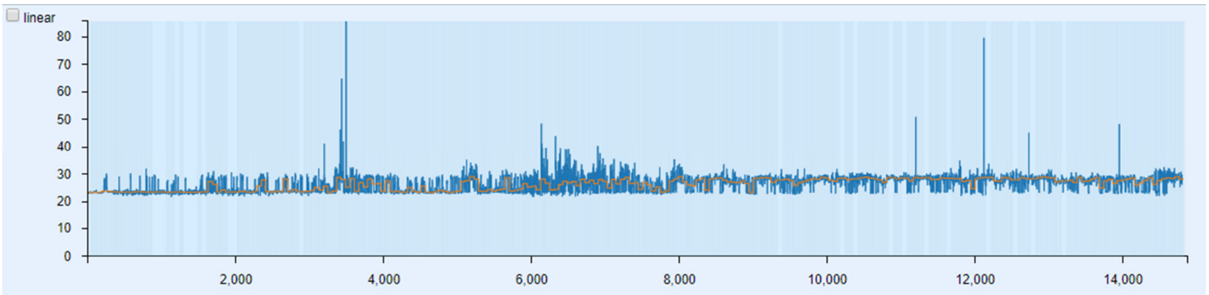

Figure 25. Example of 3G UL delay profile.

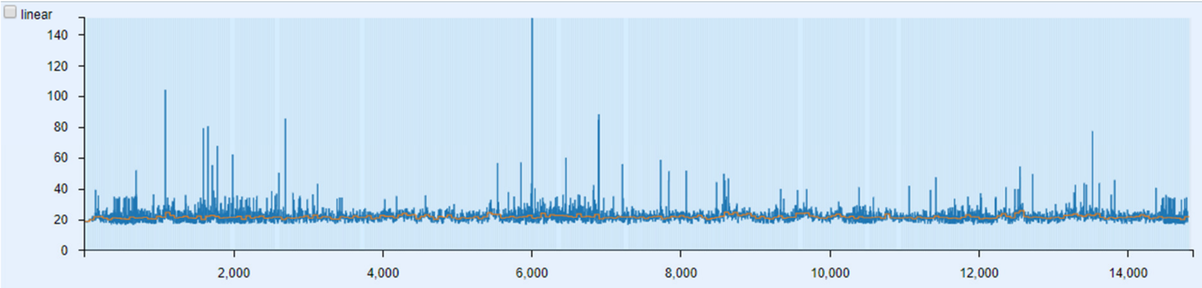

Figure 26. Example of 3G DL delay profile.

Respectively, Figure 27 and Figure 28 below show delay profiles in commercial LTE (4G) network. In this case, the profiles include measurements from good and bad radio conditions. The bad radio condition in UL direction is visible in the middle of the profile where latencies are temporarily increasing over 200 ms. The profile to the DL directions in Figure 28 is more constant and shows latency values in average around 24-26 ms.

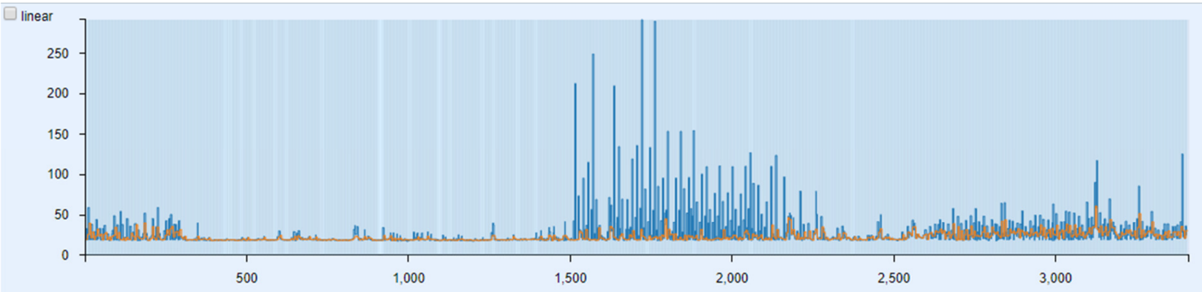

Figure 27. Example of 4G UL delay including good and bad radio conditions.

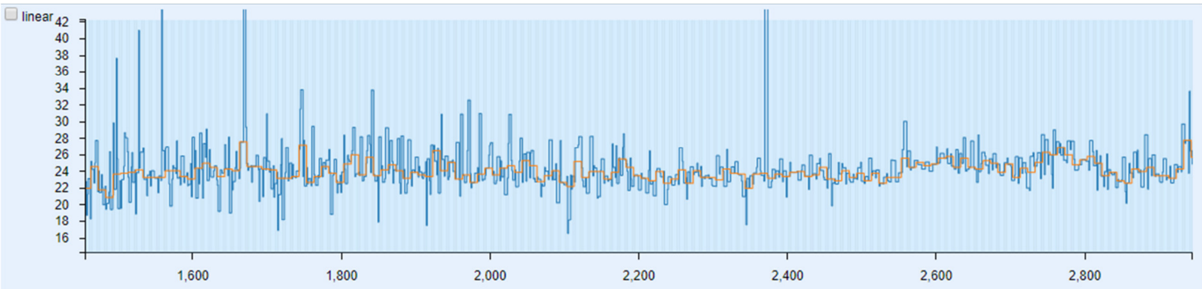

Figure 28. Detailed view of 4G DL delay including good and bad radio conditions.

The last profile example shows combined delay (blue) and jitter (red) profiles in good and bad radio conditions to the UL direction, see Figure 29. The bad radio condition section can be seen in the middle of the graph where both latency and jitter values are increasing significantly.

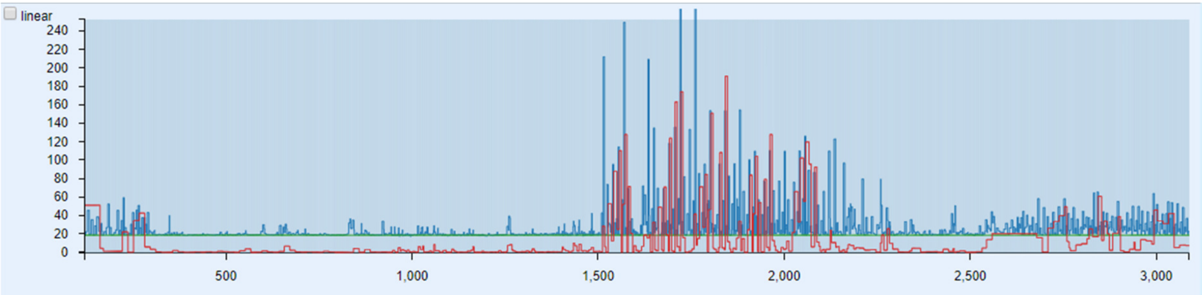

Figure 29. Example of 4G UL delay + jitter profiles including good and bad radio conditions.

The third option is to create statistical, or synthetic, profile from one or more measurements. For this, a tool implemented by SINTEF was used. A Python-script was developed with the Pandas library [13] that is widely used for time series analysis. The data was loaded from the QosMet files for both visual assessment and analysis.

Figure 30 shows the distribution graphs in UL and DL directions. The x-axis shows the delay in ms and y-axis the number of measurement samples. The profiles are different, where the DL has wider distribution with two peaks and the UL has only one sharp peak and a long tail up to 60 ms. UL latencies are between 20-50 ms and DL between 22-26 ms. The performance margin for the UL direction is smaller than in the DL direction, which indicates that separate profiles are needed for both directions.

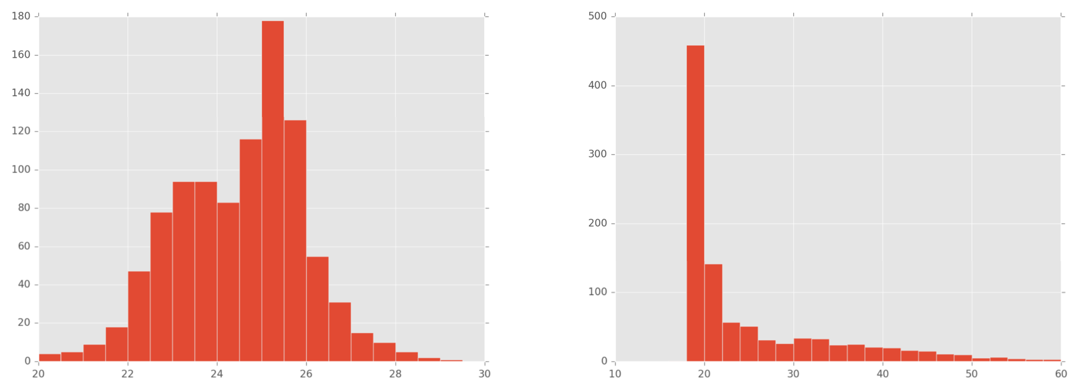

Figure 30. Distribution on downlink and uplink latencies in milliseconds for Odense 4G test.

The generated distribution function and statistical parameters by SINTEF's tool can be fetched and used by the network emulator. The network emulator is very flexible, so both measured or synthetic profiles can be attached to the selected data flows. The profile with multiple segments can be run from the beginning to the end or only a part of the segments. The emulator can also be configured to keep a specif-

ic delay value longer to allow us to examine effects of adjacent long delays to the system performance. It is also possible to change the statistical profile on the fly based on the incoming data flow.

Figure 31 shows an example of a long latency measurement conducted in commercial 3G network in Espoo. The time-varying behavior is visible in the graph. UL latencies are oscillating during the day. The peak latency values are measured between office hours 8:00 to 18:00 when the amount of other traffic is the highest. DL latencies stay more constant, but high peaks can be detected between 15:00-18:00 (second day) and between 9:00 – 14:00 (first day). During the night from 2:00 – 8:00 AM, both UL and DL latencies are rather constant and around 10 ms (right picture). During those hours, the network load is low. The result shows that the main communication problems are likely to happen during the office hours and thus the performance tests need to be done with data from busy hours. The average latency during busy hours is below 20 ms, which still leaves a large margin compared to the defined requirements.

For performance testing, it is also feasible to use those segments in Figure 29 that contain the transition from a good radio condition to a bad one and back. This profile allows to test how connected devices can tolerate changing latencies and jitter values during their operations.

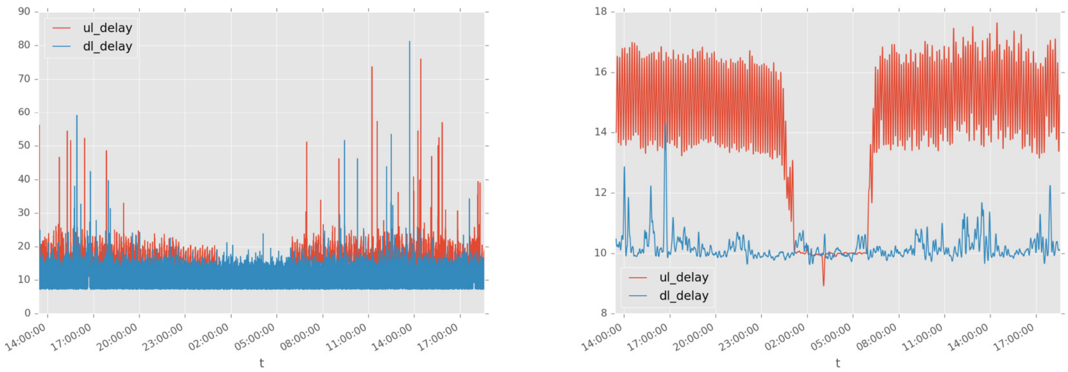

Figure 31. Uplink and downlink latencies in milliseconds for Espoo 3G test (full measurement in left and zoomed part of the measurement in right).

4.4.2.3 Laboratory Setup and Configuration

For this test case the SmartEST laboratory was used as seen in Figure 32. This is the same setup as for Test Case 1 with the only difference that the communication emulator is connected between the SCADA/DMS and the PPC.

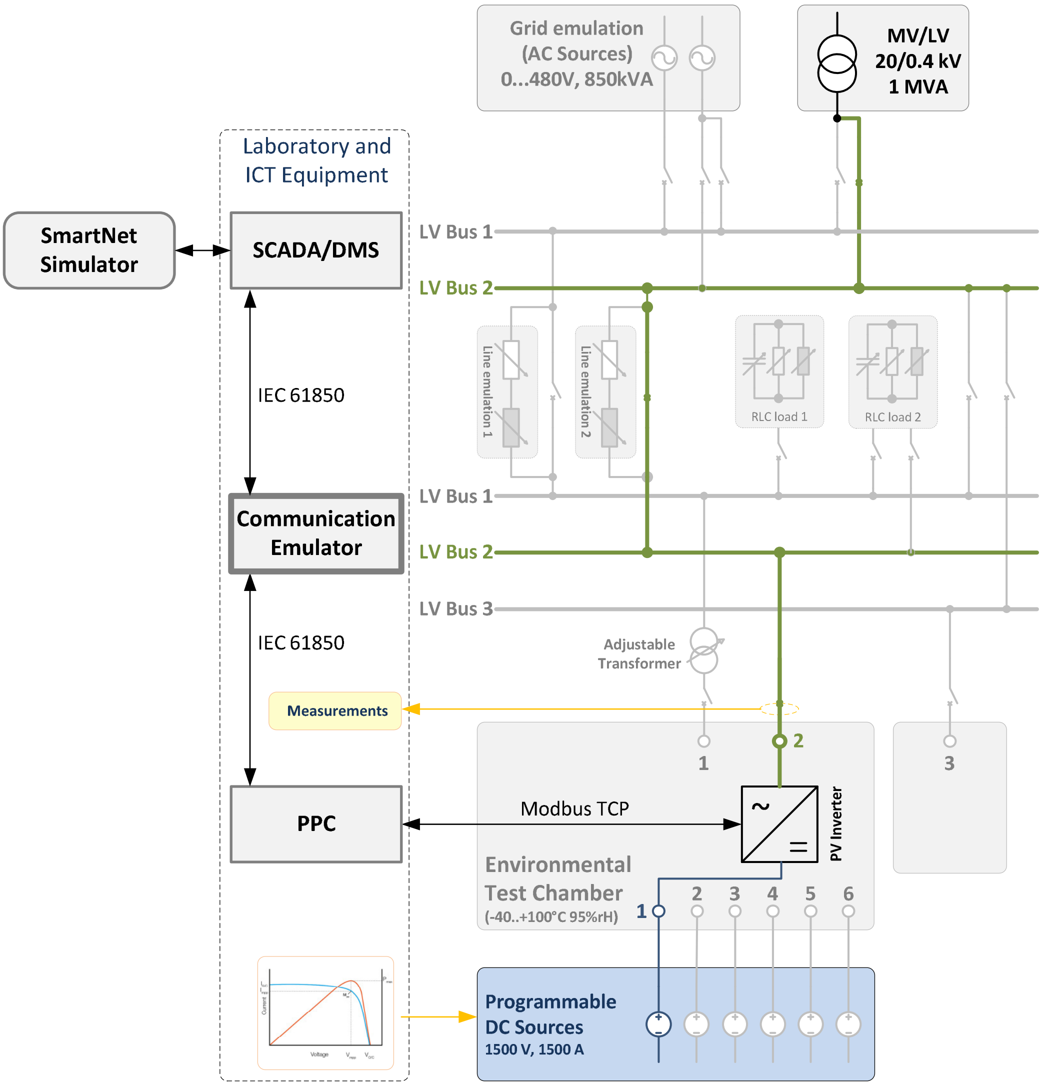

Figure 32: SmartEST laboratory setup for Test Case 2.

4.4.3 Performed Experiments and Results

The emulator gives an opportunity to mimic the behavior of different types of fixed and wireless communication technologies in different radio conditions. This means that communication profiles can be applied to all the IEC 61850 communication between the SCADA/DMS and the PPC. Since the DMS is responsible for disaggregating the control signal for the secondary frequency regulation, it has to send a new active power setpoint to the PPC every ten seconds. Potential problems can occur if these setpoints do not arrive correctly. Thus, the communication profiles were applied to these messages.

A profile representing communication over a GPRS network was used as a basis and on top of that different packet loss settings were applied. For the base case, no problems were detected in the communication between the SCADA/DMS and the PPC. This is seen in Figure 33 where the results from the test with

the GPRS settings is compared to a test with ideal settings, in which case the emulator is acting as a normal Ethernet switch.

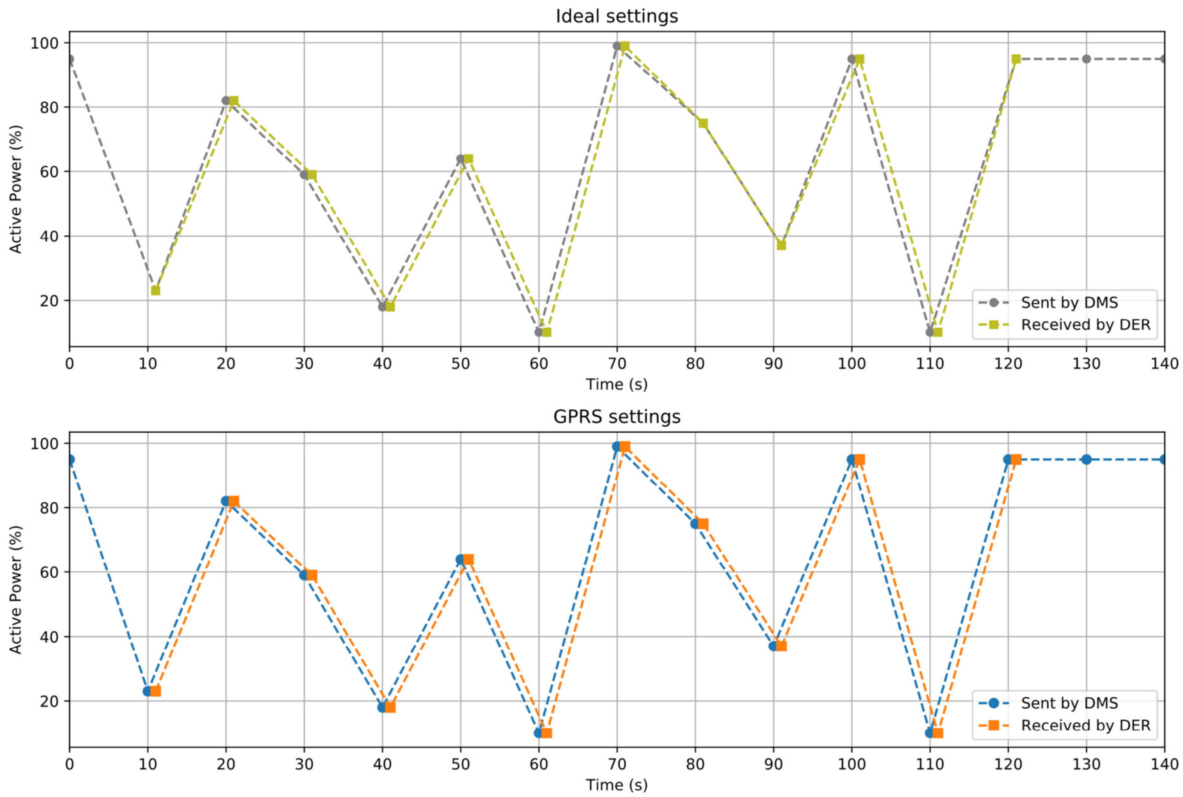

Figure 33: Results from Test Case 2 with an emulated GPRS network compared to ideal settings.

Once the packet loss was increased, there were cases where the system was not able to comply within the 10 s interval. In Figure 34, results from a test using a packet loss of 10% and 25% are shown and compared to a test only using the GPRS settings. The effects of the packet loss are especially shown in the lower plot of Figure 34, where the packet loss was increased to 25%. This is an unnatural high percentage but was used in this case to see the effects of successive package losses.

A conclusion from these tests is that the implementation of the different SmartNet coordination schemes is possible even with today's ICT technologies. Based on the lab test, it shows that also older technologies are able to comply to the 10 s interval. These results are interesting since they confirm what was found in the theoretical analysis, made previously in the project. For the SmartNet project in general, this is also an important result since it shows that the proposed approaches can be implemented on ICT systems with today's standards. This reduces the complexity—and perhaps most importantly the costs—of implementing the SmartNet concepts, which can help to increase the acceptance of such new solutions.

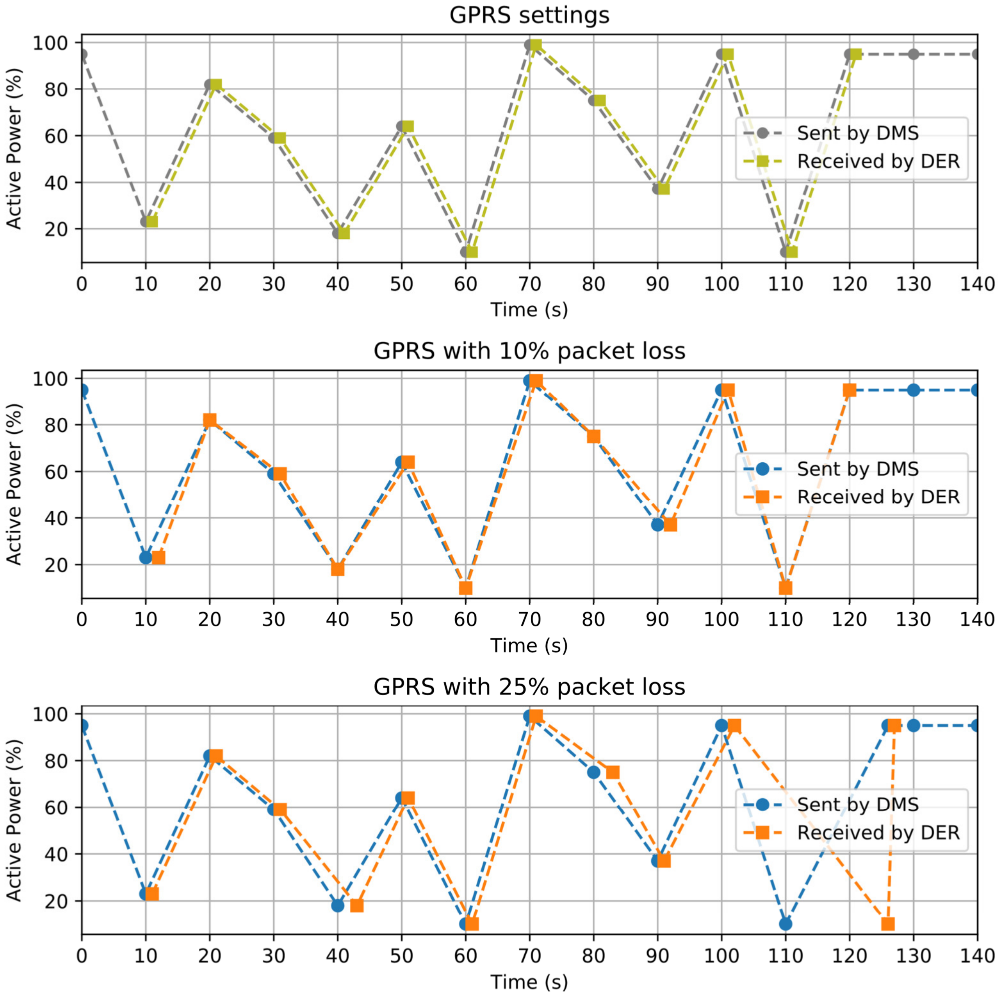

Figure 34: Results from Test Case 2 with an emulated GPRS network and different settings for the packet loss: 10% and 25%.

4.5 Test Case 3: Price-Based Control in Combination with SmartNet Coordination Schemes

4.5.1 Test Case Description

This test case is based on Validation Case 3, which is detailed in Section 3.2.2. The main idea with this test is to connect the laboratory to the summer houses located on site in Denmark. Thus, not only the local controllers for the swimming pool heaters at the summer houses, but also the aggregator, developed for the Danish pilot by ONE are used as intended for the Danish pilot. Furthermore, since real-time measurements of the active power consumption are available for the summer houses the reaction of the swimming pool heaters can be monitored and used for the evaluation of the test. For the laboratory test case two summer houses were integrated. An overview of this test case is seen in Figure 35.

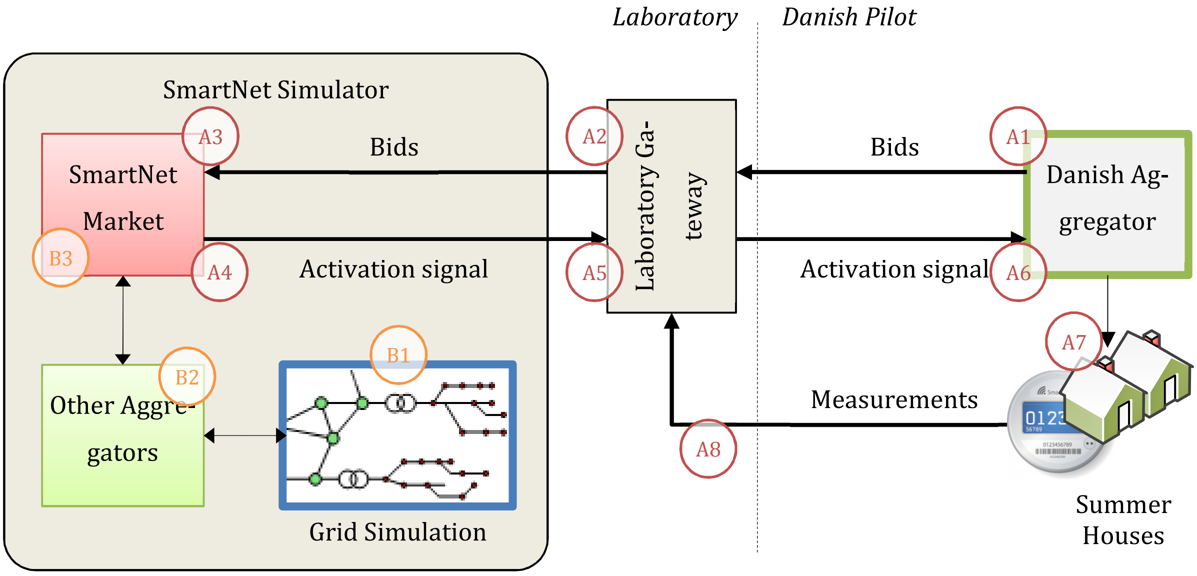

Figure 35: Overview of Test Case 3

The setup of this test case uses the SmartNet simulator, where a scenario based on the Danish pilot is simulated. Together with the simulation of the transmission grid, the SmartNet simulator also simulates the market and any other aggregators. In the market simulation the coordination scheme developed for the Danish scenario is used. Since the Danish aggregator only acts for two summer houses, other aggregators are also needed to be able to simulate a proper market. The SmartNet simulator is running on the AWS.

In order to integrate the components from the Danish pilot, three main connections are needed. First of all, bids sent from the Danish aggregator must be forwarded and integrated into the SmartNet market simulation. Secondly, once the market has cleared activation signals are created for all accepted bids and sent back to the aggregators. Thus, the Danish aggregator also must be able to receive these activation signals. Thirdly, the reaction of the summer houses needs to be monitored. These three connections are seen on the right-hand side of Figure 35. To interface the SmartNet simulator running on the AWS with the components running in the Danish field, a gateway was developed and installed in the SmartEST laboratory. Besides forwarding bidding and activation signals between the Danish aggregator and the SmartNet market simulation, the gateway was also responsible for recording the response of the summer houses.

The test case has one main sequence and one sub-sequence within the simulator. The main sequence A is depicted with A1-A8 in Figure 35 and described below:

A1. Bids are calculated by the Danish aggregator and sent to the laboratory gateway every 15 minutes.

A2. When the laboratory gateway receives a bid from the aggregator this is automatically forwarded to the SmartNet simulation platform.

A3. When the bids from the Danish aggregator are received by the market simulation they are included into the clearing process.

A4. After the clearing process for the next 15 minutes is finished the activation signals are sent by the market simulation to the laboratory gateway.

A5. The laboratory gateway forwards the activation signals to the Danish aggregator.

A6. Based on the activation signal (bid accepted or not) the Danish aggregator calculates a new price signal and sends it to the summer house controllers.

A7. Based on the current situation in the summer houses (swimming pool water temperature, occupancy of the summer house, etc), the received price signal is reacted upon or not.

A8. In the last step, the reaction of the summer houses is monitored.

Sequence B is executed partly in parallel with sequence A and is seen as steps B1-B3 in Figure 35. The steps are the following:

B1. Simulation of the Danish transmission system.

B2. Calculation of bids for the other simulated aggregators.

B3. In the third step the bids from all aggregators (simulated and real) are integrated into the market simulation, where a market clearing is calculated. This step is synchronized with step A3 and A4 in sequence A.

4.5.2 Validation Environment and Setup

4.5.2.1 Simulation Scenario and Setup

The simulation time of the Danish scenario is not limited by the size of the transmission network. The main limitation in this case is represented by the high number of devices. In order to reduce the simulation time and make it compatible with the lab, only the transmission network is considered, neglecting all the distribution networks. Furthermore, the devices connected to distribution networks were aggregated and their exchanged power was assigned to the corresponding transmission node. Only the individual models of TCLs connected to distribution were maintained so that they can be compared with the bids coming from the lab. The devices connected to transmission network remain unchanged.

4.5.2.2 Danish Aggregator

As described above the main goal of the Danish pilot is the field test and proof of concept of the control of DERs, in particular of demand response (DR), within the SmartNet perspective. This is done through indirect control, set-up by means of a broadcasted price signal to the lower-level controllers, but also through participation in the existing market mechanism of bidding/clearing. The translating party role is assumed by the aggregator, who on the one hand is an active market agent in the day-ahead, intraday and real-time balancing markets (as well as a supplier of the DERs) and develops the capability and aggre-

gates flexibility of heterogeneous nature and even stochastic nature, developing the risk management tools to let this flexibility participate to the market.

4.5.2.2.1 General Architecture

During the Danish pilot, the aggregator infrastructure was hosted on AWS and included the following details:

- Implementation and maintenance of the AWS service.
- Structuring of LAMP[2] server into the AWS environment.
- A series of memory increase to deal with the increasing amount of data in the server (partially resolved by daily data extractions).
- Optimization of runtime execution of the scripts for enhanced performance.
- Update to the latest Linux version.
- Implementation of automatic clean-up routines.
- Development of integrations with different APIs (e.g., with the Nord Pool spot market)
- Management of connection errors with the server through Https messages.
- REST[3] server installation for communications with market operator

The setup of the aggregator system is shown in the Figure 36.

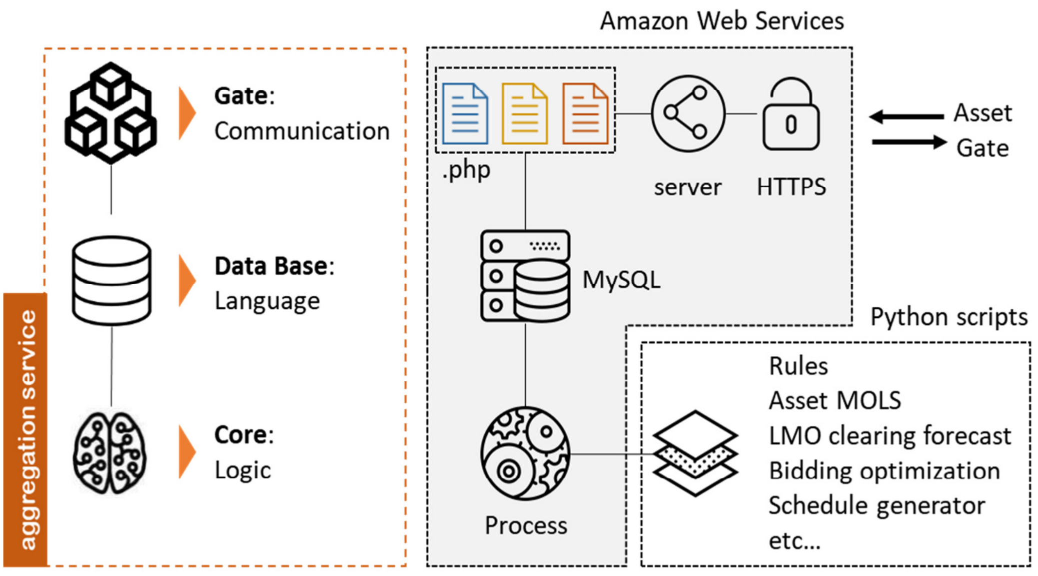

Figure 36: Architecture of the different services implemented in the aggregator system.

[2] The acronym was originally popularized from the phrase "Linux, Apache, MySQL, and PHP"
[3] Representational State Transfer

In order to effectively communicate with other components and partners, the following Python scripts were implemented:

- Creation of 'createOffer.py' script that collects the daily intraday data of Nord Pool through their API and generates a bid (in the XML format) from a bid curve made in our aggregator.
- Implementation of a new script 'sentOffer.py' that is in charge of generating the requests and HTTPS replies to send the offer to the market operator (represented by EURISCO in the Danish pilot and the gateway at the AIT SmartEST laboratory for this test case).
- Creation of script 'sentJson.py', which is responsible for collecting the market results accepted in the market, to proceed to operate with our algorithm generated in the aggregator and send the final price to ENFOR.

These scripts are necessary to ensure correct communication with all counterparties. All communications through the ONE Asset Gate are made through port 443 over HTTPS. The interpretation of all communications arriving at the server is done through PHP management and HTTPS POST requests and through an encrypted connection. The logical unit R-server executes a series of scripts that result from the implementation of the algorithm of aggregation, management and optimization, shown as the Process in Figure 36.

4.5.2.2.2 Software Setup

The software architecture designed for the aggregator is shown in Figure 37

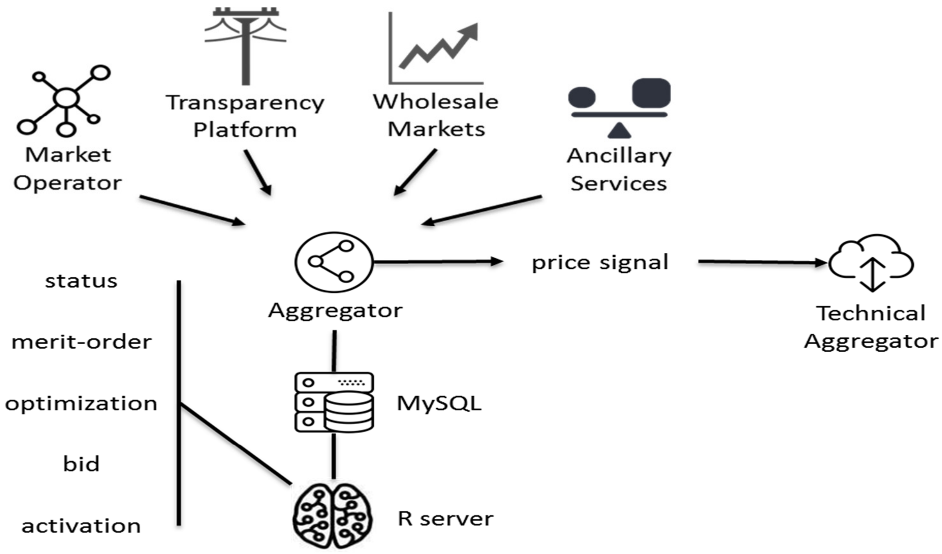

Figure 37: Software architecture from the aggregator's point of view.

For the logical unit, Python was chosen as the development language and it was run from a Ubuntu(Linux) desktop mounted on an AWS server. In Figure 38 the timeline of the process is highlighted.

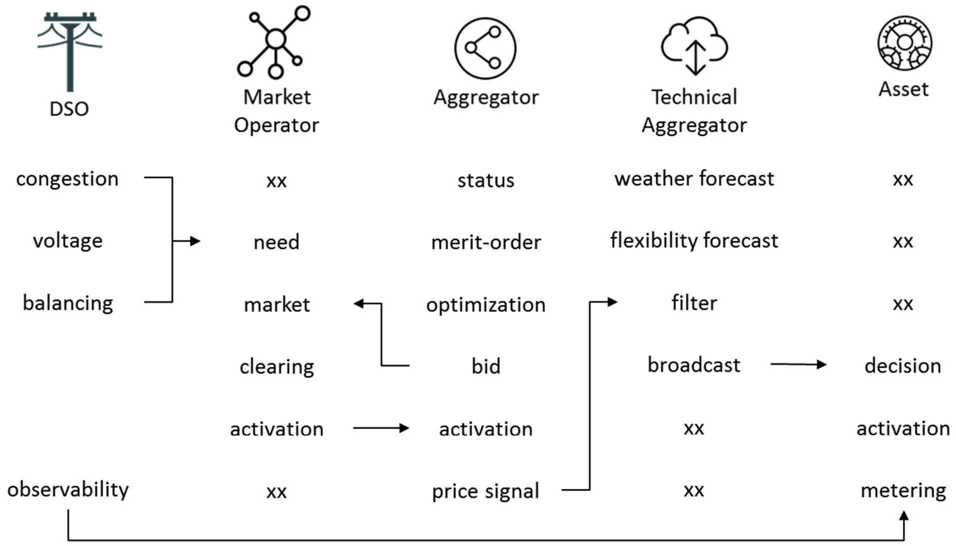

Figure 38: Diagram of the timeline for the process from the aggregator's point of view.

As for our aggregate bidding strategy, we have implemented a global process that consists of:

- Acquisition of spot (day-ahead) and intraday prices from the Danish spot market (Nord Pool)
- Calculation and characterization of the difference between these two prices for the current delivery time.
- Based on this characterization two bidding curves are defined: the ascending regulation and the descending regulation.
- Calculation of an appetite layer of "activation" for a given direction (regulation up or down) based on historical activations as well as on the current state of the pools.
    - The bounces from previous activations are analyzed (read the current baseline and, provided there is no activation, what the asset would try to do).
    - This appetite is reflected in the displacement of the bidding curve up or down, so it makes it easier to activate the asset in the "right direction".
- With the two previous levels, an aggregate bid curve is generated that is sent to the market.
- The bid curves are stored with a characterization of which asset is behind each of the individual bid points, so that disaggregation becomes a trivial consideration.
- Continue to listen to market results and activation messages on the aggregator server.

In case an activation signal is received, the activation is stored, and immediately processed. The effect of these activations that are stored in the baselines for the next market (these effects are added to the previous ones) are calculated. Once the bids are sent and the activations made, a price signal must be generated and broadcasted to the technical aggregator, i.e., the local controller of the summer houses. This signal is generated considering the economic balance equation for the aggregator.

In the target setup, the aggregator is also the supplier of electricity of the DER assets, and it is important to mention the significance of the choice of price control mechanics; as explained above, an opt-

out for a price-based signal was made, where the price indicates the price for the whole load of the DER during the activation period. Different methods would derive different equations and probably different challenges.

Assuming the figure of the aggregator isolated and prior to any considerations for the considered hour, it must be assumed for simplicity that an amount of energy equal to the baseline was bought on the day-ahead market at spot price S. This creates an energy account of L units on the Aggregator account for a cost of L×S monetary units.

Participating to SmartNet market, the aggregator bids for delivering/receiving additional volume $\hat{A}$ for a price $\hat{E}$. In the same way, E is denoted as the auction clearing price. Furthermore, $\hat{A}$ is denoted the response volume and it is assumed its sign convention is set to match the one for the baseline load L. Hence $\hat{A} > 0$ stands for an increase in consumption and $\hat{A} < 0$ a reduction of load.

Finally, it is assumed that there is a comfort cost related to the activation of the flexibility C in monetary terms. This term considers not only the amount of flexibility intended to activate, but also the risk premium for rebound effects, availability and complex constraints (e.g. no more than X activations per week).

Hence, the total cost for the aggregator is:

$$Total\ Cost = \mathrm{L} \cdot \mathrm{S} + \hat{\mathrm{A}} \cdot \mathrm{E} + \mathrm{C}$$

Now, the aggregator must recover at least this cost from the agreement to procure energy to the DER in the target hour. This is the effective volume

$$\mathrm{L}^{*}=\mathrm{L}+\hat{\mathrm{A}}$$

The price of the effective volume is denoted P^*, which is the actual price signal that is aimed to be conveyed to DERs; hence:

$$L^{*} \cdot P^{*} = \mathrm{L} \cdot \mathrm{S} + \hat{\mathrm{A}} \cdot \mathrm{E} + \mathrm{C} \rightarrow P^{*} = \frac{\mathrm{L} \cdot \mathrm{S} + \hat{\mathrm{A}} \cdot E + \mathrm{C}}{L^{*}}$$

If $L = L^* - \hat{A}$, then

$$P^{*} = \frac{S \cdot L^{*} + (E - S) \cdot \hat{\mathrm{A}} + C}{L^{*}}$$

$$P^{*} = S + (\mathrm{E} - S) \cdot \frac{\hat{\mathrm{A}}}{L^{*}} + \frac{C}{L^{*}}$$

Hence the price signal can be derived from the spot price, adding the spread between the expected MO clearing price and spot price, which is weighted by a factor calculated from the expected reaction and the expected profile of the new load and the response costs per new load energy unit.

Overview of used units for the equations above:

- *L*: baseline profile
- *S*: spot price
- *L**: expected profile
- *Â*: expected reaction; L+Â=L*
- *P**: price signal
- *Ê*: expected MO clearing price
- *E*: MO clearing price
- *C*: risks, margins, etc.

4.5.2.3 Summer Houses

As already mentioned, the main characteristic of the Danish pilot is a large thermal mass represented by the water in the swimming pool of the summer houses. The pilot benefits from the use of price-based indirect mechanism to control the set-points of thermostats of swimming pools in rental summer houses, alleviating many of the issues arising in both transmission and distribution grids.

In the price-based indirect mechanism, DERs (swimming pools), after receiving the control signals, calculate: *(i)* the optimal consumption profile within the forecast horizon, and *(ii)* the set-point for the thermostat of each individual summer house. This control signal is based on the grid load forecasts, the price forecasts, the weather forecasts, and the booking information. Measurements from the summer houses are afterwards collected and used, among other information, to feed price-responsiveness information in the price response model. Field testing of the proposed setup is to involve a small but representative number of summer houses. For the Danish pilot, several summer houses, located in Blokhus and Blavand in Denmark, as shown in Figure 39, are used to show their potential in the provision of ancillary services. In the Danish pilot, summer houses on two 400 V feeders as a flexibility asset have been considered. Therefore, the DSO only monitors the load on the 10/0.4 kV stations and 60/10 kV stations directly above these summer houses, as shown in Figure 40.

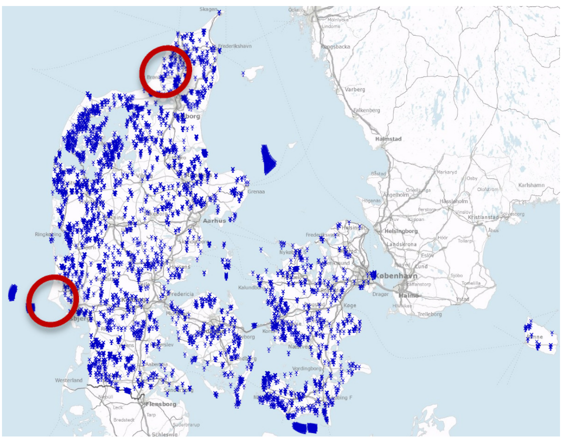

Figure 39: Geographical locations of summer houses in Denmark.

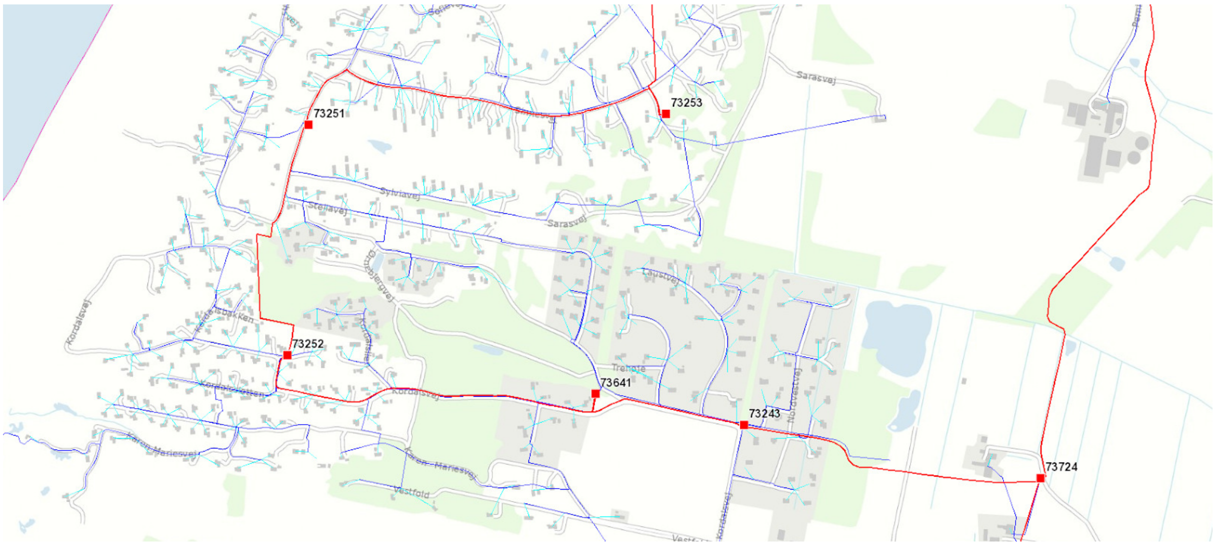

Figure 40: The distribution grid considered in the practical setup of Danish Pilot.

4.5.2.4 Laboratory Setup and Configuration

For this test case the SmartEST laboratory was used to host a so-called laboratory gateway. It was developed and installed in the laboratory to forward signals and messages between the aggregator in Denmark and the SmartNet simulator. In this case the SmartEST setup described in Section 4.1.2 was not needed. However, to keep the SmartNet simulator environment as simple as possible—and to reduce the load of the AWS server—it was decided to install the laboratory gateway in the SmartEST lab. The gateway consists of two main components: a bid-platform and a measurement logger, seen in Figure 41.

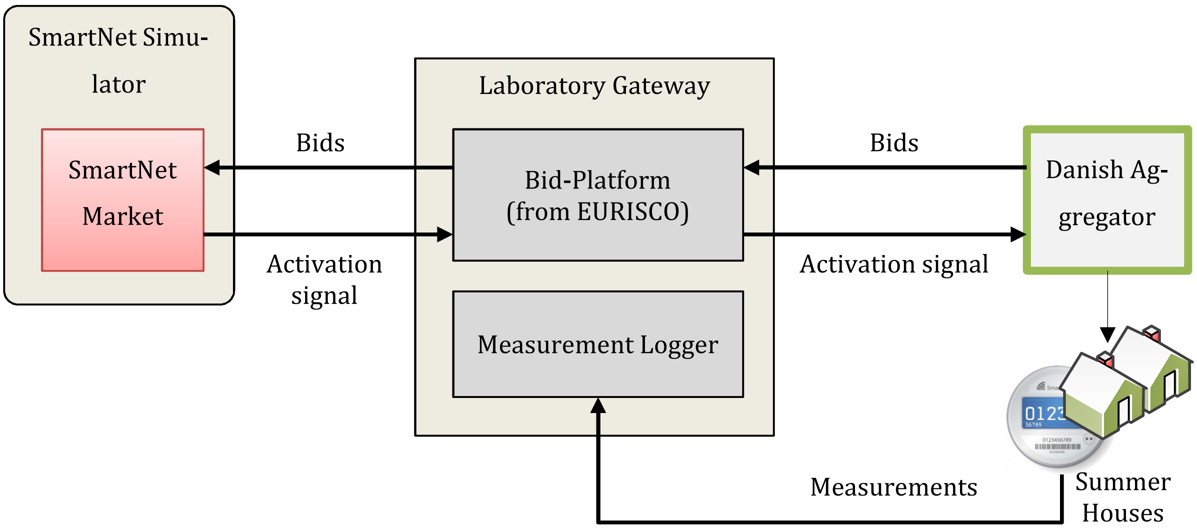

Figure 41: Overview of the two main components contained in the laboratory gateway.

The bid-platform was originally developed by EURISCO for the Danish pilot. For this test case, it was slightly adapted and reduced to the server where bids can be placed by participating aggregators. This

means that for the Danish aggregator the interface used for bidding (and receiving activation signals) remains the same for both the pilot and the laboratory test. As an addition to this bidding server, an interface was added for connection to the market simulation running on the AWS server. This interface is described in more detail in Section 4.2.2.

The bid-platform receives bids from the Danish aggregator in XML format using an HTTP post. Upon receiving this bid, the platform forwards it to the SmartNet simulator on the AWS platform. This is done by updating an XML-file located on the AWS server. In turn, the SmartNet simulator detects changes to this same XML-file and interprets such a change as a new bid. Consequently, the updated file is read, and the new bid is integrated into the market simulation.

When a new activation signal is calculated by the market simulation, this is also placed in an XML-file located on the AWS server. Once this XML-file is updated, the change is detected by the bid-platform in the gateway, the activation message in the updated XML-file is read and forwarded to the Danish aggregator.

The second main component of the laboratory gateway is the measurement logger, which reads measurements from the summer houses and logs these for later use. Measurements from the summer houses are available on a web-platform provided by ENFOR and are updated in real-time every 5 minutes.

4.5.3 Performed Experiments and Results

Based on the test case description and the validation environment and setup two experiments were selected. They are motivated below:

- *Connection setup between the Danish aggregator and the market operator*: The same bid-platform is used for both the laboratory test and the pilot. This can be exploited to test the connection between the bid-platform and the Danish aggregator in the laboratory environment, before used in the pilot. This includes sending/receiving bids and sending/receiving activation signals.
- *Integration of price-based control with the SmartNet coordination schemes*: Once a successful connection has been achieved between aggregator and bid-platform longer tests can be performed to validate how the price-based control scheme of the Danish pilot integrates with the SmartNet coordination schemes.

The tests done for these two experiments as well as the results are described in more detail in the sections below.

4.5.3.1 Connection Setup between Aggregator and Market operator

Different types of tests have been established to check the behavior of the developed aggregator, the tests carried out are as follows:

- Https communication tests between ONE - EURISCO and ONE - AIT.
- Communication tests of the REST server between ONE - ENFOR.
- ONE Aggregator Tests

4.5.3.1.1 Communication Tests Between Aggregator and Market Operator

For this test the Http communication was tested between the Danish aggregator and market operator (both EURISCO and SmartEST laboratory). Two main tests were made:

- Stability of requests and Http response through port 443 between both parties to check the frequency with which we receive market results from the market platform.
- Check the data structures of the enabled houses (pools), defined and supplied by EURISCO and adapt them to the system.

In principle, a connection was possible both between the aggregator and EURISCO and between the aggregator and the SmartEST laboratory. Initially, there were some problems with the wrong XML-format used for the bids by the aggregator, which resulted in unsuccessful interaction with the market platform. Once the XML-format was corrected the interaction worked.

4.5.3.1.2 Communication Tests between Market Aggregator and Technical Aggregator

The goal here was to test the connection between the market aggregator and the technical aggregator (i.e., the local controller of the summer houses). Three main tests were carried out:

- Stability of the REST connection and execution times in the transfer of information.
- Correct sending of files (json format) to the technical aggregator.
- Carry out a complete cycle of communication between market aggregator and technical aggregator, so that offers and activations are sent and received by both parties on a continuous basis.

All tests were carried out successfully.

4.5.3.1.3 Market Aggregator Test

Once communication was established between the Danish aggregator and the other systems, these tests were intended to validate the correct operation of the aggregator. Four tests were made:

- Check the input frequency of files (.xml) by MO.
- Execution of all aggregation processes on a continuous basis.
- Check that we receive the available stations, send the bids correctly and get the market results within the agreed upon time frame (5 minutes for the pilot and 15 minutes for the laboratory test).
- Stability and availability of pools available in each market.

During the initial setup of the laboratory tests it was noticed that the aggregator received activation signals also when no bids had been sent. This was due to the bid-platform run by EURISCO, which sent "empty" activation signals every 5 minutes when no bids had been received. Since these "empty" activation signals were sent to the same interface as the activation signals provided by the market simulation in the laboratory tests the aggregator received "real" activation signals every 15 minutes from the laboratory and "empty" activation signals every 5 minutes from EURISCO. Once this was detected, two interfaces were created by ONE for the communication between the aggregator and the market operator: one for communication with EURISCO and one for communication with the laboratory.

4.5.3.2 Integrating Price-Based Control and SmartNet Coordination Schemes

The second experiment was carried out after the initial communication and connection tests were finished. The main goal with this test is to see how the price-based control interacts with the SmartNet coordination schemes. These coordination schemes have been integrated into the market simulation but were initially not intended to be used directly with price-based control. Therefore, also the market simulation of the SmartNet simulator was not developed to directly handle such situations.

The main difference of a price-based solution compared to a direct-control solution is that the actual response of the controlled system (i.e., the heater of the swimming pools for the summer houses) is not known when a price signal is sent. Consequently, a control scheme designed for a direct-control solution that is used without changes with a price-base control solution will most certainly not produce the exact same results. Nevertheless, by monitoring a price-based solution over time, it is possible to "learn" how the system will react to certain price signals.

Since the laboratory tests were carried out in parallel with the Danish pilot, there was a limited amount of time slots available for laboratory tests. One of the tests is seen in Figure 42. The upper plot shows the measured active power for the two summer houses (labeled C7224 and D7105). The middle plot shows the swimming pools' heater states and the lower plot shows the activate bids from the market simulation.

As can be seen in the figure there is a certain mismatch between activated bids and actual activations of the swimming pool heaters. This is because the summer houses have multiple criteria for activating the heaters, see Section 4.5.2.3 for details. Therefore, the heaters may also be activated without any activation signals coming from the market. Also, the tests were run in the middle of summer, with outside temperatures of around 30° C, so there was not much need for additional heating of the water. This is also the case why the heating of C7224 is never activated during this period. In this case the temperature of the water was high enough, so no heating was needed.

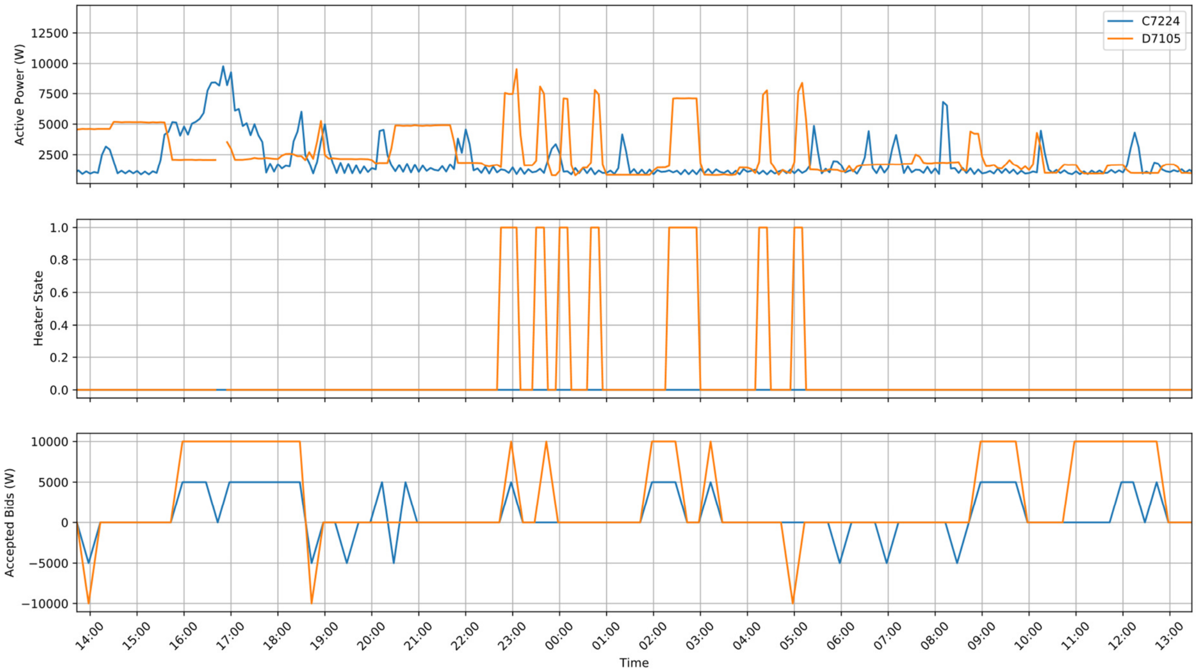

Figure 42: Test results for integration of price-based control with the SmartNet coordination schemes; test started 2018-07-25 at 2 pm.

As comparison to the test seen in Figure 42, which was made in summer, another test was made in December. The results from this test are shown in Figure 43. However, also in this case the activations of the swimming pool heaters do not follow the control signals from the simulation very well. One reason why little response is seen is that both pools were heated in the days prior to the test. Furthermore, summer house P32424 was neither booked for the period before, nor for the period after test. In such cases the setpoint for the water temperature is decreased, which prevents unnecessary heating. In order for the heating to be activated, the price offered by the aggregator must be high enough, which it was not for this test.

From the results shown in Figure 42 and Figure 43 it is clear that the price-based control used in the Danish pilot can technically be integrated into the SmartNet market coordination schemes. This can be validated by looking at the Aggregator Price, which is only sent to the summer houses during a test. However, the results also show that although this is technically feasible the expected results will be something different than with a direct-control solution. It should also be pointed out that these tests were done with only two aggregated summer houses. Therefore, the impact of the price-based control is even more visible. With more houses, there is a higher probability that some of the houses react as expected, which also increases the chances for the aggregator to make accurate bids.

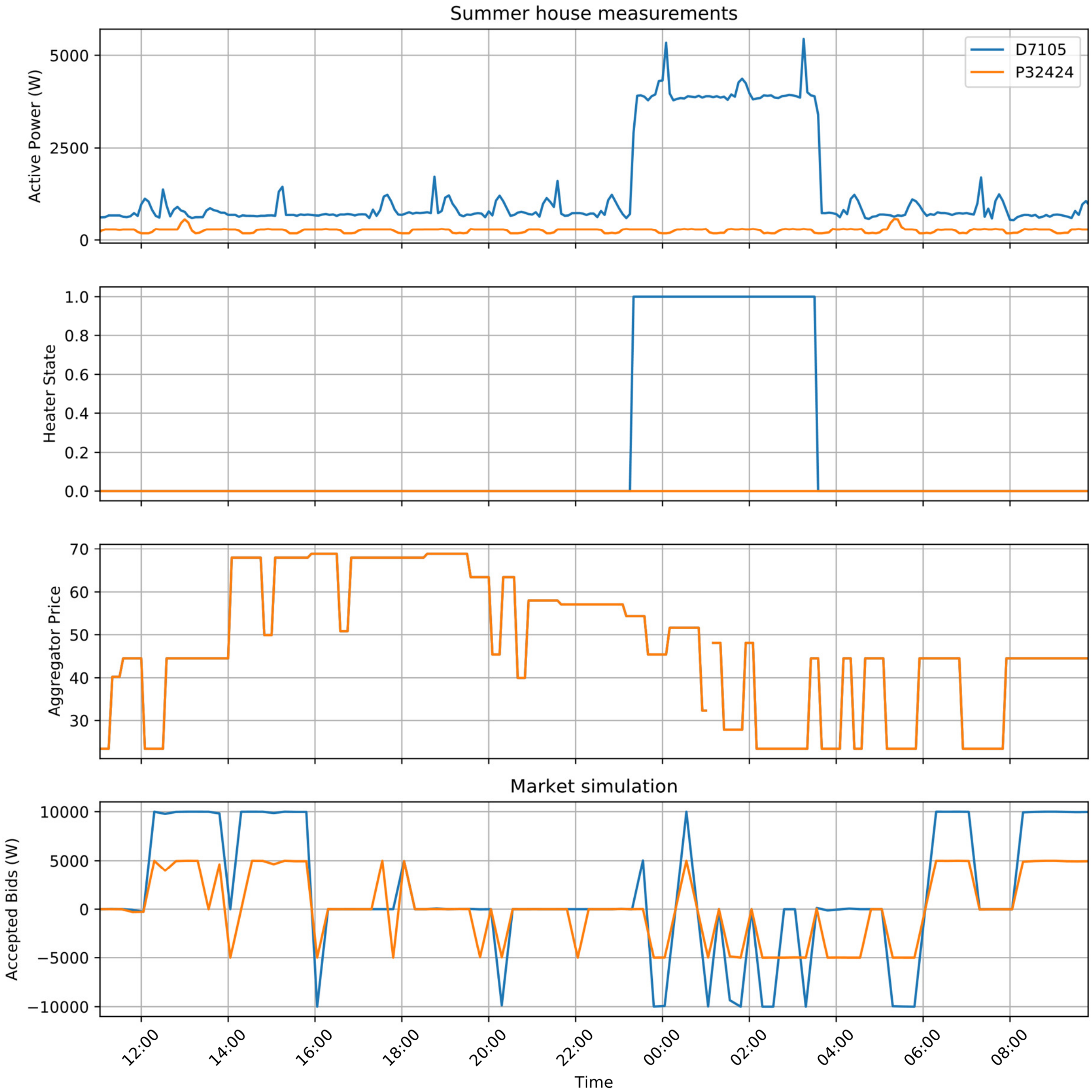

Figure 43: Test results for integration of price-based control with the SmartNet coordination schemes; test started 2018-12-17 at 11:03 am CET.

4.6 Discussions and Lessons Learned

In general, all tests were successfully executed and the main goals for this task could be achieved. Each test gave results that were of high interest, for the further development of the different pilot cases, but also for future work and how to continue the development of the SmartNet approaches.

The test in the laboratory showed the importance of testing the SmartNet solutions together with different equipment. This was especially visible in Test Case 1, where the PPC has a general design that allows it to be interfaced with any type of DER. However, the algorithms developed in the SmartNet project were developed for the pilot, where hydro power plants are used. In the laboratory tests the PPC was

connected to a PV inverter, which is in many ways different than a hydro power plant. For example, the PV has no capability of upward regulation of active power. These findings gave important hints on what needs to be considered for a future real-world rollout of a SmartNet approach.

Another interesting result from the laboratory tests concerned the investigation on how different ICT network characteristics influence the performance of the SmartNet approach. These results also confirm what was found in the theoretical analysis previously in the project, namely that the proposed approaches can be implemented on ICT networks of today's standards. For the SmartNet project in general this is interesting, since it reduces the complexity—and perhaps most importantly the costs—of implementing the SmartNet approach. Hopefully, this can help to increase the acceptance of such new solutions.

The tests also pointed out several interesting aspects when price-based control is used together with the proposed coordination schemes of SmartNet. The implementation of the coordination schemes in the SmartNet simulator were made with the assumption that a direct control scheme is used between the aggregator and the DERs. When price-based control is used instead—as is the case in the Danish pilot—this may lead to suboptimal situations, such as absent responses to control signals. Based on the laboratory tests, future implementations of the SmartNet coordination schemes should take these aspects into account in order to assure an optimal operation.

Aside from the results above, all tests have contributed to the following two main conclusions:

- *Importance of laboratory setups to prevent issues in the field:* In all three tests issues with the setup and connection of the equipment were found. Due to the relatively small scale of the laboratory environment compared to the field installations, these issues were soon identified and corrected. Therefore, these issues could be avoided in the pilots, which improved the pilot results.
- *Adaptions are needed:* The SmartNet simulator was an integral part of all three laboratory tests. This was also considered during the development of the simulator, but nevertheless HIL adaptions were needed in order to integrate the existing equipment with the simulation of the coordination schemes. In the tests above, rather small adaptions were made to be able to show that an integration is possible. If more extensive tests are wanted larger adaptions would have been necessary, such as redesigning the simulator to handle price-based control.

These conclusions also suggest that more extensive laboratory tests could have provided more information. As discussed for the validation cases in Section 3, the laboratory setting has also been used to test the equipment together with some of the SmartNet coordination schemes. However, not all combinations between components and coordination schemes were tested. In the end this would have required more extensive testing, beyond the initial project's scope. However, when combining the results from the laboratory tests with the simulations and the pilots, the SmartNet project provides a very comprehensive validation approach with promising results for future activities.

5 Conclusions

The current increasing integration of RES into the power system is causing challenges, both for the TSO and the DSO. Using ancillary services to handle these challenges is seen as one of the key measures that needs to be integrated into future systems. Since this is a problem that can be monitored from the transmission and distribution system's sides, the coordination between TSO and DSO will be necessary. For this purpose, the SmartNet project investigates TSO-DSO interactions to allow the participation of distribution resources to ancillary services market. Besides pilot tests in Denmark, Italy, and Spain, these TSO-DSO interactions are also validated using a laboratory-based approach, shown in this deliverable.

Three different validation cases have been executed: a validation of a DMS and a PPC used in the Italian pilot, the impact of communication network characteristics, and the compatibility of price-based control with the TSO-DSO coordination schemes. These test cases were implemented using HIL setups at the SmartEST lab. From the results, several conclusions were made. First of all, it was possible to analyze the setup of selected equipment and elaborate suggestions about their utilization in the pilots and also to analyze how the components interact with other equipment, that was not directly included in the pilots. This was of high importance since it gave insights into several problems related to the setup, which could be avoided in the pilots. Secondly, through the tests of the communication aspects it was shown that even current ICT technologies can handle the SmartNet coordination schemes. As this was one of the outcomes of the theoretical ICT analysis earlier in the project, it was important to see these concepts confirmed by real tests. Thirdly, the last test case also showed that price-based control needs a separate consideration within the TSO-DSO coordination schemes, since it is not based on the same paradigm as direct control. This is something that should be considered for future works where these combinations are intended.

The work here also shows how laboratory tests can complement field trials. Although many aspects can be covered in field tests, there are still limitations, such as when the current regulatory framework is blocking. Another possibility is to use laboratory tests to pre-check field equipment, thereby reducing the amount of time, and often costly manual work, needed for error correction in the field trials. When combining the results from these laboratory tests with the simulation results and the results from the pilots, they all show the possibilities the SmartNet approach and gives important input for future work.

6 References

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7 Appendix

The following tables show descriptions of the three Test Cases in the deliverables according to the ERIGrid approach (see Section 2.2) [5].

Table 1: ERIGrid Test Case Description of Test Case 1

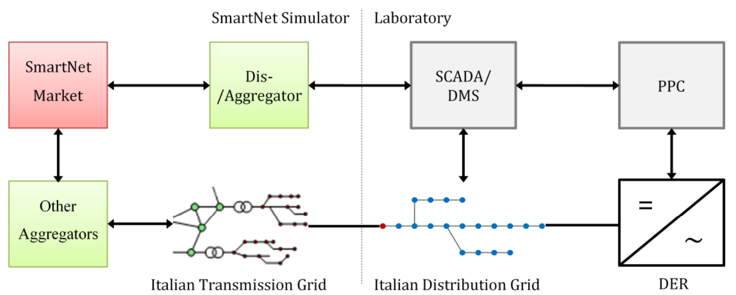
Name of the Test Case	*Validation of DMS and PPC used in the Italian Pilot*
Narrative	This test case is related to the Italian pilot. It shows how low-level components and DERs can be integrated with the SmartNet coordination schemes based on the Italian scenario used in the pilot. The main components under study are the SCADA/DMS and PPC from SELTA.
System under Test (*SuT*): Systems, subsystems, components included in the test case or test setup.	
Object under Investigation (*OuI*) "the component(s) (1..n) that are to be qualified by the test"	• SCADA/DMS • PPC
Functions under Investigation (*FuI*) "the referenced specification of a function realized (operationalized) by the object under investigation"	• DMS functionality • Gateway functionality between Modbus and IEC 61850 in PPC
Domain under Investigation (*DuI*): "the relevant domains or sub-domains of test parameters and connectivity."	• Power system • Control/ICT
Purpose of Investigation *(PoI)* The test purpose in terms of Characterization, Verification, or Validation	The purpose for this test case will focus on the following points: • Connection setup between SCADA/DMS, PPC, and DER • Integration of the SCADA/DMS with SmartNet coordination schemes • Effectiveness of different PPC control schemes for flexibility provision

Table 2: ERIGrid Test Case Description of Test Case 2

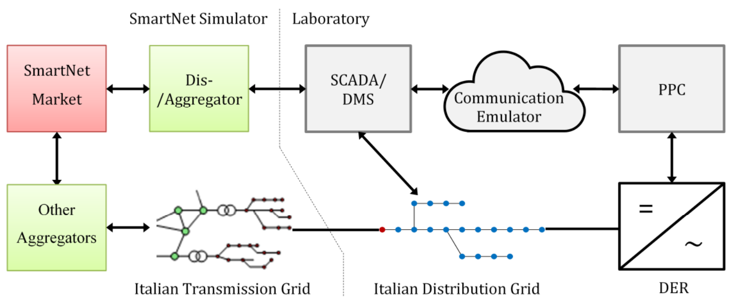
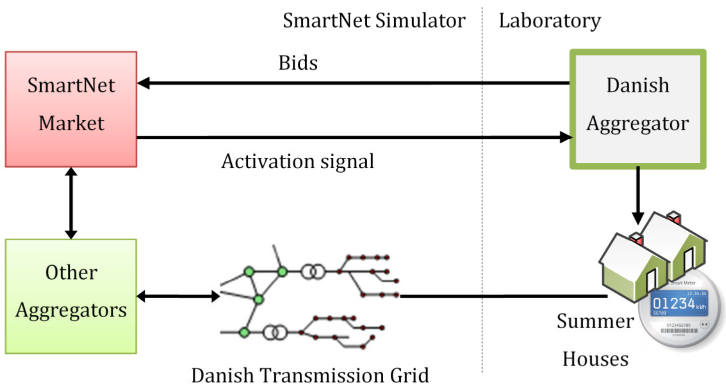
Name of the Test Case	*Validating the Impact of ICT on the Italian Scenario*
Narrative	This is test case can also be seen an extension of Test Case 1 (see Table 1). It includes some of the knowledge acquired during the ICT requirements analysis of the SmartNet project. By adding a communication emulator between the SCADA/DMS and the PPC real communication problems can be tested. It can be validated if this affects the coordination schemes and how the components react to changing communication situations.
System under Test (*SuT*): Systems, subsystems, components included in the test case or test setup.	
Object under Investigation (*OuI*) "the component(s) (1..n) that are to be qualified by the test"	• Communication system between SCADA/DMS and PPC • SCADA/DMS
Functions under Investigation (*FuI*) "the referenced specification of a function realized (operationalized) by the object under investigation"	• Data transmission between SCADA/DMS and PPC • SCADA/DMS: DMS functionality
Domain under Investigation (*DuI*): "the relevant domains or sub-domains of test parameters and connectivity."	• Control/ICT
Purpose of Investigation *(PoI)* The test purpose in terms of Characterization, Verification, or Validation	The purpose for this test case will focus on the following points: • Communication effects on the performance of the DMS.

Table 3: ERIGrid Test Case Description of Test Case 3

Name of the Test Case	*Price-Based Control in Combination with SmartNet Coordination Schemes*
Narrative	This test case analyses the integration of price-based control with the SmartNet coordination schemes. It uses the summer houses on-site in Denmark and connects them to the SmartNet simulation through an interface over internet.
System under Test (*SuT*): Systems, subsystems, components included in the test case or test setup.	
Object under Investigation (*OuI*) "the component(s) (1..n) that are to be qualified by the test"	• Danish Aggregator • Summer Houses • SmartNet Market
Functions under Investigation (*FuI*) "the referenced specification of a function realized (operationalized) by the object under investigation"	• Aggregation • Heating of swimming pools in the summer houses • Integration of summer houses into the market
Domain under Investigation (*DuI*): "the relevant domains or sub-domains of test parameters and connectivity."	• Power system • Control/ICT
Purpose of Investigation *(PoI)* The test purpose in terms of Characterization, Verification, or Validation	The purpose for this test case will focus on the following points: • Connection setup between the Danish aggregator and the market operator • Integration of price-based control with the SmartNet coordination schemes • Effectiveness of different price-based control schemes for flexibility provision