SOGNO

D2.1 v1.0

Detailed description of 5G based ICT concepts for supporting grid awareness

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Abstract
This document includes the description of the fifth-generation cellular network technology (5G) Information and Communication Technology (ICT) concepts relevant for the services developed in the SOGNO project for providing situational awareness to the distribution grid operators, and how they support the services. The roll-out deployment scenarios of the services in the power and communications networks is presented. The performance test results of the communications protocols in several 5G test systems are also described.

Keyword list
Grid Awareness services, Power Control service, Power Quality Evaluation service, 5G, ICT, latency, reliability, distributed edge cloud computing, network slicing, protocols, test system

Executive Summary

Improving the existing situational awareness allows grid operators to evaluate the real-time operating conditions of the system, to efficiently manage the network and to identify possible automation and control solutions and settings to be deployed for improving the grid performance. In the past, situational awareness was not critical for operating a distribution system, due to the passive and relatively simple operation of these grids. Today, with the growing penetration of renewable generation and other distributed energy resources, the availability of situational awareness has become essential also at distribution systems level.

The objective of WP2 is the development of the hardware and software components needed to provide advanced situational awareness to distribution system operators by means of cost-effective solutions and virtualized substation intelligence.

This report describes 5G ICT concepts relevant for the Grid Awareness services and their relationship. Performance of the communications protocols proposed to be used by the Grid Awareness services was tested in the lab on several 5G test systems as well as on the Ethernet test system used as a reference. The test infrastructure and the test methodology are described, and the test results are provided. Finally, the Grid Awareness solutions in full roll-out power and 5G network are presented.

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Table of Contents

1. Introduction

This Deliverable (D) 2.1 presents the work of Task (T) 2.3, “5G based ICT concepts for supporting grid awareness” within the wider context of Work Package (WP) 2 and SOGNO.

1.1 Related Project Work

This report is based on the work done in the T1.3, “Requirements placed on scalable ICT for stable and secure grid with 100 % RES” of Work Package (WP) 1, and the tasks T2.1, “Tailoring of techniques for grid awareness” and T2.2, “Development of new power electronics techniques for real time system awareness” of WP2. In the task T1.3, ICT requirements for the SOGNO services are specified as well as the service solution architectures are defined. The tasks T2.1 and T2.2 deal with the design of the main techniques for grid awareness. In particular, T2.1 focuses on the State Estimation service, which is the service allowing the real-time monitoring of the operating conditions of the distribution system, while T2.2 develops the techniques for the management of the power electronic components associated to the distributed generation (Power Control service), providing control and awareness of the behaviour of the system with a large share of renewable energy sources. Task T2.5 discusses the development of low-cost measurement units needed to enable both state estimation and power control. The Advanced Power Measurement Units (APMUs) designed in SOGNO also allow monitoring different power quality parameters, as part of the Power Quality Evaluation service, offering an additional degree of situational awareness for the distribution system operators regarding the quality of the power supply in the grid. Last but not least, T2.5 includes the activities for identifying the interfaces needed to integrate the above-mentioned grid awareness services in the cloud platform for the virtualization of the substation intelligence.

Figure 1-1 shows the overall structure of SOGNO. The communications between the power electronic devices and the substation, that are integrated and tested on the 5G network in WP2 are provided as input to WP4. In this way, tests including the SOGNO services on the 5G network in the lab can be performed before deploying the services in the field (WP5).

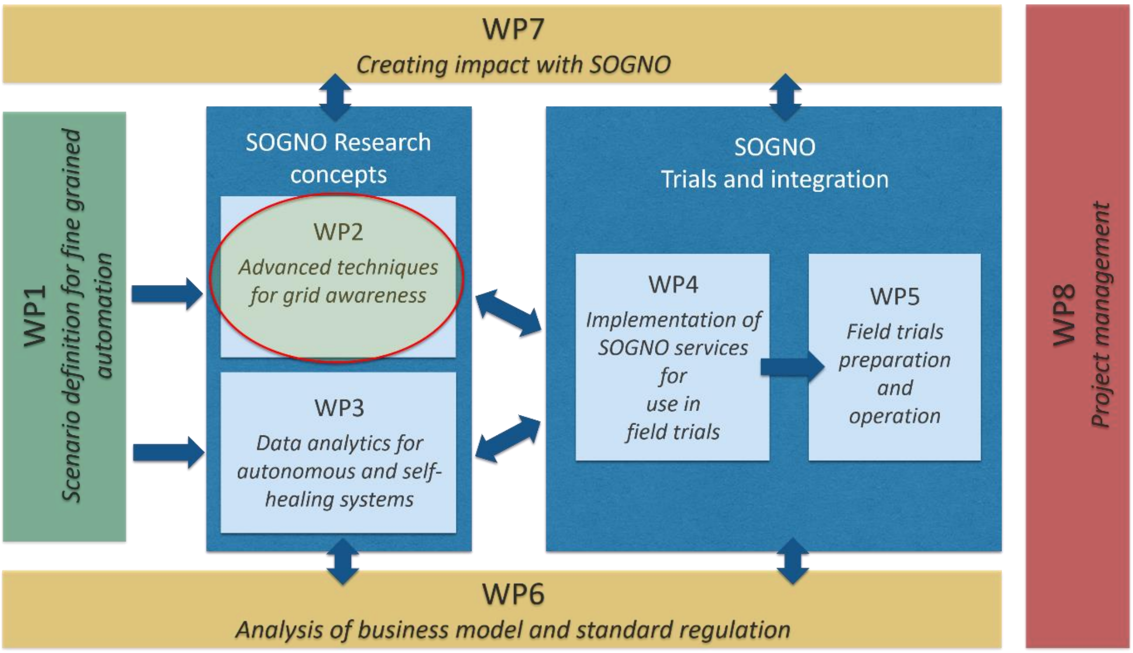

Figure 1-1: Overview of SOGNO activities

1.2 Objectives of the Report

The main objectives of this report are to describe and test relevant ICT approaches as the enablers of the SOGNO services and outline their role with respect to a full rollout scenario.

1.3 Outline of the Report

Chapter 2 provides the theoretical ICT concepts to support the services for grid awareness developed in WP2. In particular, three concepts are employed:

- A new radio interface will provide a lower latency.
- Distributed edge computing increases the reliability and security by keeping the data locally. At the same time the latency is decreased and by means of the distributed architecture scalability is fostered.
- Network slicing will increase the reliability as it reserves virtual resources of the mobile communication network.

Chapter 3 focuses on the peer-to-peer tests that were conducted in the lab with the 5G based mobile networks. These tests are centred around the properties of the new radio interface together with the edge computing capability.

Afterwards chapter 4 examines the impact of the results from chapter 3 on the overall service performance. Additionally, it explores the possibility of utilizing the edge computing in a distributed manner to improve the scalability of the SOGNO services.

1.4 How to Read this Document

This report can be read as a standalone document. However, other deliverables can be helpful to get a better view of the concepts developed in SOGNO and to have more details on the grid awareness services. In particular, other deliverables closely related to this one are as follows:

- D1.1 – Scenario & architectures for stable & secure grid: it includes a description of power system scenarios investigated in the project, and definition of their ICT requirements.
- D2.2 – Description of initial Interfaces & services for grid awareness: it describes the services developed for grid awareness, namely State Estimation, Power Control, and Power Quality Evaluation as well as the interfaces required for integrating the services in the Virtualized Substation.

2. 5G ICT concepts to support system awareness services

This chapter examines 5G ICT concepts relevant for the following Grid Awareness (GA) services:

- State Estimation (SE) and
- Power Control (PC).

The Power Quality Evaluation (PQE) service as one of the Grid Awareness services will not be considered in this document. The PQE is a monitoring service. However, in contrast to the SE it requires only the metering information of one single (local) end-point. Its execution does not rely on 5G mobile network.

2.1 What is 5G?

At its conception, 5G was envisioned to enhance the human user experience and to enable various machine-related use cases [1]. One of the pillars of 5G is to allow multiple access technologies such as satellite, WiFi™, fixed line and 3rd Generation Partnership Project (3GPP) technologies to interwork in order to serve the diverse 5G use cases. 5G will provide wireless connectivity for a wide range of new applications and use cases, including wearables, smart homes, traffic safety/control, critical infrastructure, industry processes and very-high-speed media delivery. As a result, it will also accelerate the development of the Internet of Things [2].

The overall aim of 5G is to provide ubiquitous connectivity for any kind of device and any kind of application that may benefit from being connected.

The specification of 5G will include the development of a new flexible air interface, New Radio (NR), which will be directed to extreme mobile broadband deployments (Figure 2-1). NR will also target high-bandwidth and high-traffic-usage scenarios, as well as new scenarios that involve mission-critical and real time communications with extreme requirements in terms of latency and reliability.

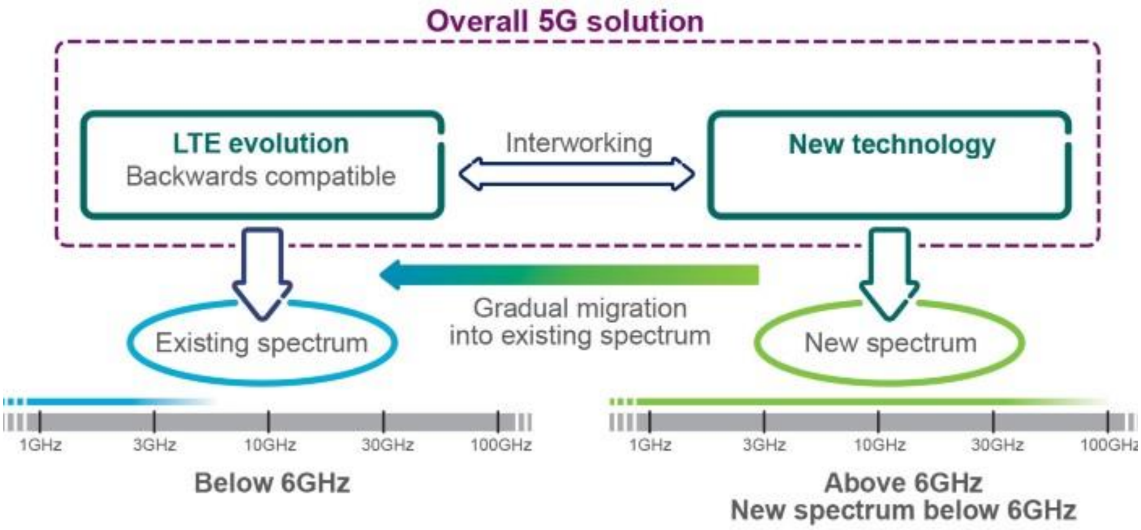

Figure 2-1: The overall 5G wireless-access solution consisting of LTE evolution and new technology

In parallel, the development of Narrow-Band IoT (NB-IoT) in 3GPP is expected to support massive machine connectivity in wide area applications. NB-IoT will most likely be deployed in bands below 2 GHz and will provide high capacity and deep coverage for enormous numbers of connected devices.

Ensuring interoperability with past generations of mobile communications has been a key principle of the ICT industry since the development of Global System for Mobile communications (GSM) and later wireless technologies within the 3GPP family of standards. In a similar manner, Long-Term Evolution (LTE) will evolve in a way that recognizes its role in providing excellent coverage for mobile users, and 5G networks will incorporate LTE access (based on Orthogonal Frequency Division Multiplexing - OFDM) along with new air interfaces in a transparent manner toward both the service layer and users.

The 5G network will enable dual-connectivity between LTE operating within bands below 6 GHz and the NR air interface in bands within the range 6 GHz to100 GHz. NR should also allow for user-plane aggregation, i.e. joint delivery of data via LTE and NR component carriers.

2.1.1 5G use cases

The 5G use cases can be classified in terms of requirements for three essential types of communication with vastly different objectives: massive Machine Type Communication (mMTC), critical MTC, and extreme or enhanced Mobile Broadband (eMBB) [3]. The three types that can be also designed as 5G services are discussed in the following.

Massive machine type communication

Otherwise known as Massive IoT, mMTC is designed to provide wide area coverage and deep penetration for hundreds of thousands of devices per square kilometer of coverage. An additional objective of mMTC is to provide ubiquitous connectivity with relatively low software and hardware complexity and low-energy operation. Many of the devices supported are battery powered or driven by alternative energy supplies, have small payloads, and might rarely be active, so they tend to be relatively delay-tolerant for the most part. While the devices typically have a long lifespan, services and software need to scale and be swapped out relatively quickly to address new business opportunities. Examples that fall into this service category include the monitoring and automation of buildings and infrastructure, smart agriculture, logistics, tracking and fleet management.

Critical MTC or URLLC

The second category of application being addressed is that of cMTC, which is also called Critical IoT. In this type of application, monitoring and control occur in real time, end-to-end latency requirements are very low (at millisecond levels), and the need for reliability is high. The performance objectives of cMTC will be applied to workflows such as the automation of energy distribution in a smart grid, in industrial process control and sensor networking where there are stringent requirements in terms of reliability and low latency at the application layer. Such requirements are often referred to as Ultra-Reliable Low-Latency Communications (URLLC). Careful attention will need to be paid to security in the case of both mMTC and cMTC. While higher network and device complexity is more readily acceptable in critical communication, mMTC will have to address cyber-security assurance with low-complexity devices. A hierarchical approach to the network is necessary to progressively improve security so end-to-end security assurance can be guaranteed.

Extreme mobile broadband

Providing both high data-rate and low latency communications, extreme mobile broadband (eMBB) also offers vast level of coverage – well beyond that provided by the fourth-generation cellular network technology (4G). Connectivity and bandwidth are more uniform over the coverage area, and performance degrades gradually as the number of users increases.

2.1.2 5G radio access

One key component of 5G radio access is an innovative air interface called New Radio (NR), which is designed primarily for new spectrum bands [3]. In industry and academia, it is generally understood that the success of 5G will depend on a diversity of spectrum assets which span low, medium and high spectrum bands. During discussions in the World Radio Conference (WRC-15) [4] emphasis has generally been placed on high spectrum bands such as millimeter wave bands, although many administrations also realize that low bands below 6 GHz will be key to providing the necessary coverage and bandwidth. LTE will of course continue to evolve, including advancements such as Long-Term Evolution for Machines (LTE-M) and narrowband IoT (NB-IoT), and will be an important part of the overall 5G wireless access solution. Many administrations seem to equate 5G with bands above 24 GHz. This is the case in the WRC-15 vision for IMT-2020, and for the U.S. Federal Communications Commission (FCC) which has expressed an intent to release the 28 GHz and 39 GHz bands. NR is expected to migrate to bands below 6 GHz in the near term, eventually occupying existing mobile bands below 3 GHz.

Spectrum relevant for 5G wireless access therefore ranges from below 1 GHz up to approximately 100 GHz, as Figure 2-2 shows.

Figure 2-2: Spectrum relevant for 5G wireless access

A high level of interworking between LTE evolution and new radio access technologies is needed to ensure that 5G functionality can be introduced smoothly and over a long transition period. Such interworking will need to include support for dual-connectivity where, for example, a device maintains simultaneous connectivity to a dense high-frequency layer providing very high data rates as well as to an overlaid lower-frequency LTE layer that provides ubiquitous connectivity. User plane aggregation between LTE and any new radio technology such as NR is another example of this high level of interworking. It is important to note that even though new radio access technologies such as NR will require a new radio bearer, NR and LTE will be fully integrated from a system perspective, so NR can both be added as a stand-alone system – for industry applications, for example – or as a natural evolution of the existing wide area LTE networks.

Additional key technology components for the 5G radio access solution include:

- Advanced multi-antenna technologies such as massive (Multi-Input Multi-Output) MIMO and beamforming with phased antenna arrays
- Ultra-lean transmission to reduce interference caused by common signalling resources and to maximize resource efficiency
- Flexible duplex in certain isolated local network deployments
- Access/backhaul integration, where access and (wireless) backhaul share the same technology and the same overall spectrum pool
- Well-integrated device-to-device communication

These technology components will not only apply to the new technology part of the 5G wireless access systems but also, to a large extent, to the evolution of LTE.

2.1.3 Network Slicing

The technique of Network Slicing allows for the definition of multiple logical networks (or slices) on top of the same physical infrastructure (Figure 2-3) [3]. Resources can be dedicated exclusively to a single slice or shared between different slices.

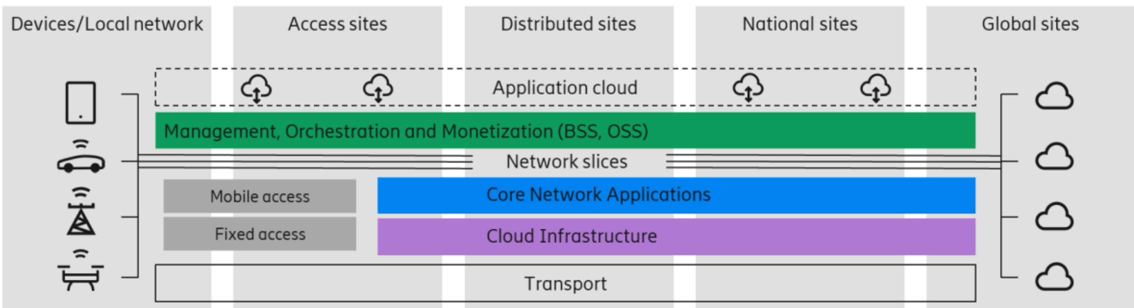

Figure 2-3: 5G Network Slicing

A network slice is built to address a desired behavior from the network. Such behavior can be associated with security, data-flow isolation, quality of service, reliability, independent charging and so on. A network slice may support one or many services and can be used to create a virtual operator network and may provide customized service characteristics. Network slicing can be used for several purposes: a complete private network, a copy of a public network to test a new service, or a dedicated network for a specific service.

For instance, when setting up a private network in the form of a network slice that can be an end-to-end virtually isolated part of the public network, the network exposes a set of capabilities in terms of bandwidth, latency, availability and so on. Thereafter, a newly created slice can be locally managed by the slice owner who will perceive the network slice as his or her own network complete with transport nodes, processing and storage. The resources allocated to a slice can be a mix of centrally located and distributed resources. The slice owner can initiate applications from his or her management center, and applications will simply execute and store data, either centrally, in a distributed management system or a combination of both.

For further details about network slicing, please see Chapter 6.2 of Deliverable D1.1.

2.1.4 Distributed Cloud Computing

As shown in Figure 2-4, Ericsson defines the **Distributed Cloud** [5] as a cloud execution environment that is geographically distributed across multiple sites, including the required connectivity in between, managed as one entity and perceived as such by applications. The key characteristic of our distributed cloud is abstraction of cloud infrastructure resources, where the complexity of resource allocation is hidden to a user or application. Our distributed cloud solution is based on Software Defined Networking (SDN), Network Functions Virtualization (NFV) and 3GPP edge computing technologies to enable multi-access and multi-cloud capabilities and unlock networks to provide an open platform for application innovations.

Ericsson Distributed Cloud solution enables edge computing, which many applications require. It defines **Edge Computing** as the ability to provide execution resources (specifically compute and storage) with adequate connectivity at close proximity to the data sources.

The distributed cloud relies on efficient **management and orchestration** capabilities that enable automated application deployment in heterogeneous clouds supplied by multiple actors. Figure 2-4 illustrates how the service and resource orchestration spans across distributed and technologically heterogeneous clouds. It enables service creation and instantiation in cloud environments provided by multiple partners and suppliers. When deploying an application or a virtual network function (VNF), the placement decisions can be based on multiple criteria, where latency, geolocation, throughput and cost are a few examples. These criteria can be defined either by an application developer and/or a distributed cloud infrastructure provider, serving as input to the placement algorithm.

Each of the layers in the distributed cloud stack will expose its capabilities. The cloud infrastructure layer and the connectivity layer will expose their respective capabilities through the **Application Programming Interface(s)** (API(s)), which will then be used by application developers of the industries making use of the mobile connectivity. By setting developer needs in focus, the exposed API(s) will be abstracted so that they are easy to use.

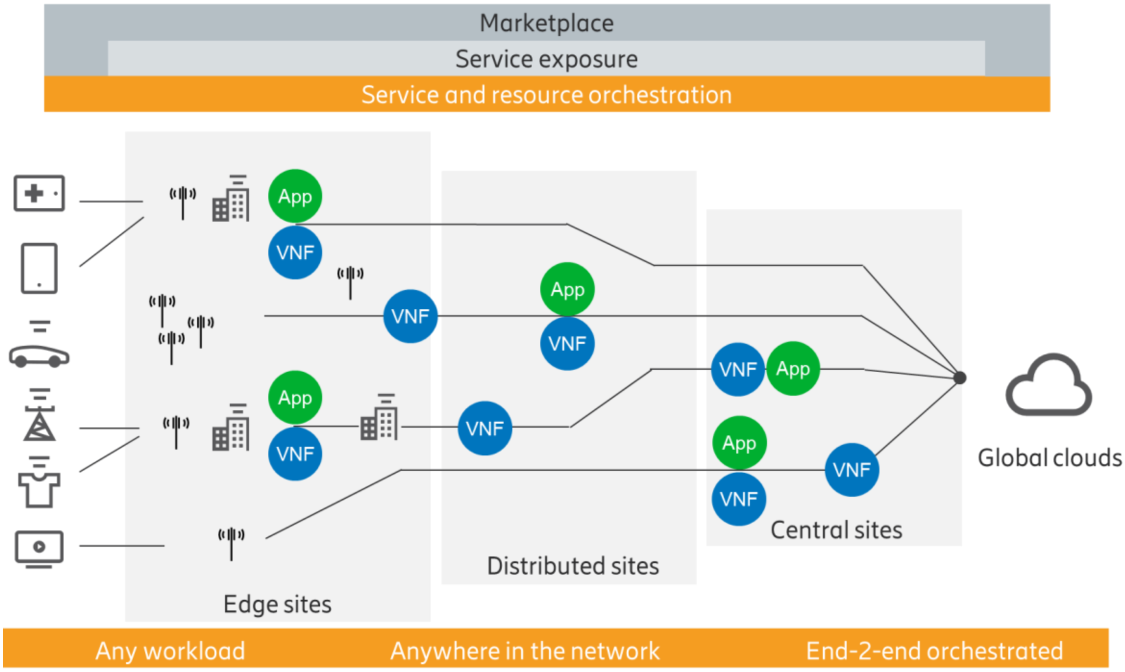

Figure 2-4: Distributed cloud architecture

2.1.4.1 Distributed Edge Computing concepts

What is Edge Computing? Edge Computing places high-performance compute, storage and network resources as close as possible to end users and devices [13]. Doing so lowers the cost of data transport, decreases latency, and increases locality. Edge Computing will take a big portion of today's centralized data centers and cloud and put it in everybody's backyard.

Edge Computing can be split into two layers: Device Edge and Infrastructure Edge layer. Infrastructure edge can be further split into two sublayers: Access Edge and Aggregation Edge sublayer.

Device Edge

The Device Edge refers to edge computing resources on the device side of the last mile network. Some devices will be single function, such as embedded sensors, designed to perform very specific tasks and deliver streams of data to the network. Other edge devices will act as specialized gateways, aggregating and analysing data and providing some control functions. And yet other edge devices will be fully-programmable compute nodes, capable of running complex applications in containers, virtual machines, or on bare metal. The Device Edge will be the basis of many useful applications which require the lowest latency possible, as device edge resources are as close as it is possible to be to the end user.

However, it is already clear that many device edge resources will be connected to the cloud and be managed as extensions of the cloud. They will largely be connected to the Infrastructure Edge (IT resources which are positioned on the network operator or service provider side of the last mile network) over wired and wireless networks and that workloads running on the Device Edge will be coordinated with workloads running on the Infrastructure Edge. In many cases it will be both more reliable and less expensive to run workloads on the Infrastructure Edge rather than entirely on the edge devices.

Access Edge

The Access Edge is the part of the Infrastructure Edge closest to the end user and their devices. Edge data centers deployed at or very near to the Access Edge are typically directly connected to a radio or other front-line network infrastructure, and they are used to operate application workloads for complex tasks such as machine vision and automated decision support for large-scale IoT. Edge data centers deployed at the Access Edge, a sublayer within the Infrastructure Edge, may also connect to other edge data centers which are deployed above them in a hierarchical architecture at the Aggregation Edge sublayer.

Aggregation Edge

The Aggregation Edge refers to a second sublayer within the Infrastructure Edge which functions as a point of aggregation for multiple edge data centers deployed at the Access Edge sublayer. The purpose of this layer is to provide a reduced number of contact points to and from other entities, such as a centralized cloud data center and the Infrastructure Edge and to facilitate the collaborative processing of data from multiple Access Edge sublayer edge data centers. The Aggregation Edge is typically two network hops from its intended users but is still much closer to them than the centralized cloud data center, and it is thus able to achieve far lower latencies.

Cloud interoperation

Figure 2-5 shows edge computing layers and its relation to the central cloud. It is important to notice that the edge computing does not exist by itself. Despite the level of computing power and performance that is achievable between the combination of the Device Edge and Infrastructure Edge, both of these entities benefit immensely from tight, cohesive interoperation with the centralized cloud.

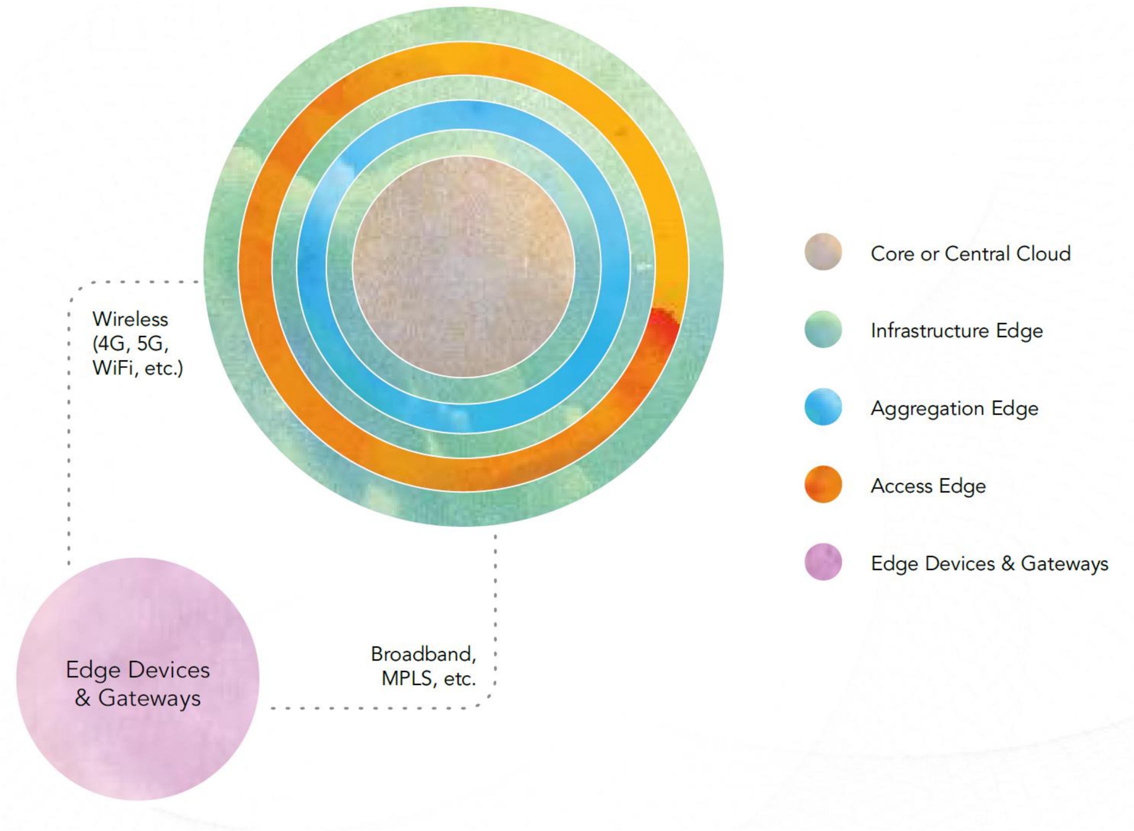

Figure 2-5: Edge cloud layers

As can be seen in Figure 2-5, both the Device and Infrastructure Edge can be viewed as complementary to, and even as extensions of, the existing centralized cloud. By connecting these distributed resources together and creating an edge cloud which spans from the current centralized data center, through the Infrastructure Edge and its sublayers through to the Device Edge, the cloud operator will be able to optimally allocate resources and direct Grid Awareness services workloads to the optimal location for them, regardless of whether that is in the Device Edge, Infrastructure Edge or the centralized cloud. For the optimal deployment of the Grid Awareness services, power grid characteristics, e.g., number of nodes, meshed grid, density, area spanned by a DSO, will have to be taken into consideration.

Edge-native applications, as their name suggests, are applications which require the unique characteristics provided by edge computing to function satisfactorily, or in some cases to function at all. These applications will typically rely on the low latency, local information or reduced cost of data transport that edge computing provides in comparison to the centralised cloud. Note that Grid Awareness applications developed in SOGNO are edge-native applications.

2.1.4.2 Cloud Radio Access Network

Cloud Radio Access Network (C-RAN) is a novel mobile network architecture which can address a number of challenges that mobile operators face while trying to support ever-growing end-users' needs towards 5th generation of mobile networks (5G) [6]. The main idea behind C-RAN is to split the base stations into radio and baseband parts [1], and pool the Base Band Units (BBUs) from multiple base stations into a centralized and virtualized BBU Pool, while leaving the Remote Radio Heads (RRHs) and antennas at the cell sites. This gives a number of benefits in terms of cost and capacity.

C-RAN architecture is targeted by mobile network operators, as envisioned by China Mobile Research Institute, IBM, Alcatel-Lucent, Huawei, ZTE, Nokia Siemens Networks, Intel and Texas Instruments. Moreover, C-RAN is seen as a typical realization of mobile network supporting soft and green technologies in fifth generation (5G) mobile networks.

Figure 2-6 shows an example of a C-RAN mobile LTE network. The fronthaul part of the network spans from the RRHs sites to the BBU Pool. The backhaul connects the BBU Pool with the mobile core network. At a remote site, RRHs are co-located with the antennas. RRHs are connected to the high-performance processors in the BBU Pool through low latency, high bandwidth optical transport links.

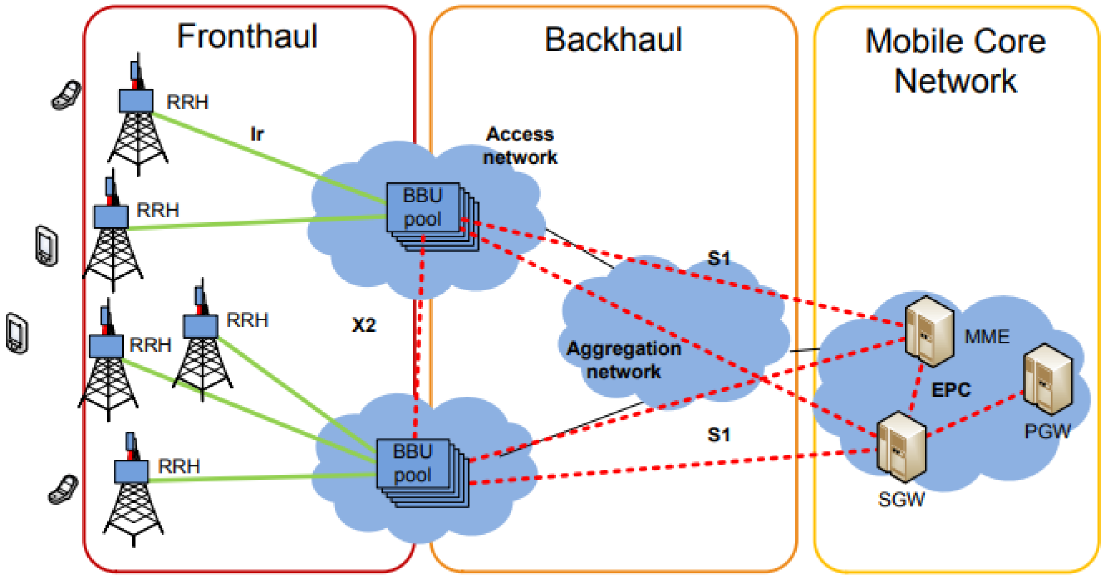

Figure 2-6: C-RAN LTE mobile network

2.1.5 Communications protocols for power systems

Different communications protocols that could be utilised with the Grid Awareness services were taken into consideration. Firstly, the protocols traditionally used in the energy networks (from IEC 61850 protocols family) like Sampled Values (SV) [7] and Generic Object-Oriented Substation Events (GOOSE) were considered. Second group of the ICT protocols extensively used in Internet of Things (IoT) domain like Advanced Message Queuing Protocol (AMQP) [8] and Message Queue Telemetry Transport (MQTT) [9] were considered. Note that User Datagram Protocol (UDP) protocol is used as a reference in the protocol tests.

[1] Baseband refers to the original frequency range of a transmission signal before it is converted, or modulated, to a different frequency range. For example, an audio signal may have a baseband range from 20 to 20,000 Hz. When it is transmitted on a radio frequency, it is modulated to a much higher, inaudible, frequency range.

In each of the mentioned categories (traditional energy protocols and IoT), the focus was set on one protocol. Amongst traditional protocols, the focus is set on SV protocol. Investigations by Ericsson of energy protocols concluded that GOOSE can generate communications problems as it produces bursts of traffic which can suddenly overload wireless channels and cause delays in transmission. Amongst IoT protocols, MQTT prevailed over AMQP because it can be used on lightweight devices and of its popularity in the usage in IoT domain as well as in energy networks, although AMQP has more advanced features but more overhead than MQTT.

2.2 Applying 5G ICT concepts to grid awareness services

Reliability, latency and distributed architecture are characteristics of upmost relevance for the Grid Awareness services as was stated in Deliverable D1.1. Usage of 5G ICT concepts described above in the Grid Awareness services will certainly improve these characteristics. Usage of 5G ICT concepts in the Grid Awareness services is described in detail in this chapter.

2.2.1 Communications reliability

Delivery of messages in the Grid Awareness services must be reliable. This is important especially in first phases of the service deployments as small number of measurement devices will be deployed. If measurements are lost, it will significantly impact the performance accuracy of the monitoring algorithms as described in deliverable D2.3. Message delivery reliability is even more critical for the Power Control service than for the State Estimation because of its active influence on the power grid and potential hazardous effects on the grid if a part of the control signals is not delivered and hence, the control for the individual devices is not aligned.

Deployment of the Grid Awareness service logic on the Distributed Cloud will increase reliability of the services. Distributed cloud computing in 5G concept is explained in D1.1. By deploying of the service logic on the distributed cloud, the communication path will be shorter, that will obviously lower the chances for the message loss, i.e., the service reliability will be increased.

5G is designed to support scenarios that require very high communication reliability, such as 5 nines (99.999%). Network Slicing is a one of the features of 5G which enhances the reliability by isolating the traffic from other mobile traffic, thus Network Slicing can be enabled to achieve high reliability needed for Grid Awareness Services.

2.2.2 Communications latency

The State Estimation service is expected to have transmission rate of once per second. Even though the latency is not critical for one iteration, it is advisable to have low latency to ensure multiple steps of the execution of the algorithm within a specific time frame and roundtrip time of the data. Latency requirements depend on the execution time of the algorithms and the delay on the communication path must be obviously below overall service cycle running time. Therefore, even though the latency is not a very strict requirement the lower the latency, higher the time resolution of the monitoring can be.

Static power control does not have critical requirements on the latency. As long as the latency is sufficiently low it ensures that the devices will react to an estimated state within the same execution step. A lower latency enables the opportunity to deploy dynamic real-time power control which is not within the scope of the project.

Several 5G network features and components, to mention here Distributed Cloud Computing, Network Slicing and 5G New Radio, support stringent requirements for low latency.

Distributed edge cloud hosting Grid Awareness algorithms will enable very low round trip latency.

Network Slicing will provide dedicated resources for the service data transport. By doing so, low latency characteristics of the traffic will be preserved regardless of the overall traffic in the network.

3GPP technical report [12] defines requirements for next generation access technologies (New Radio) for identified typical deployment scenarios. It specifies that the target for user plane latency should be 0.5 ms for uplink, and 0.5 ms for downlink direction.

2.2.3 Power network distributed architecture as enabler of the Grid Awareness services

A key concept of future power grids is distributed architecture to support the very large size of the distribution network. Final design of the State Estimation service will be based on distributed architecture that couples Medium Voltage (MV) State Estimation and Low Voltage (LV) State Estimation. Please refer to deliverable D2.3 for the algorithms of the service enabling a distributed architecture. This leads to necessity to conduct multiple steps to get one set of results. By deploying the service logic on the Distributed Cloud, the service logic is being brought near to the devices shortening the latency on the communication path. Packet latency and packet loss of different power network protocols were measured in the project lab tests on the communication link between end device and distributed cloud. Test results were described in detail in Chapter 3.

3. Communications performance tests

The ICT tests conducted in WP2 were designed to examine applicability of 5G networks for Grid Awareness services keeping in focus their most relevant characteristics: reliability, latency and distributed architecture. Latency and reliability of the 5G communications between communications end-points were primarily tested. End-points were the measurement devices (or power electronic devices), and the distributed edge cloud collocated to the radio base station that will be used to host Grid Awareness algorithms. The ICT lab tests verified the following 5G communications parameters:

- User plane latency,
- Reliability (packet loss), and
- Maximum transmission (update) rate.

The following energy and communications protocols were tested:

- Advanced power protocols based on IEC 61850 standard like Routed-Sampled Value (SV) [14],
- Message Queue Telemetry Transport (MQTT) [9], and
- Advanced Message Queuing Protocol (AMQP) [8].

The behaviour of protocols for wide range of message rates and sizes was observed. As a result, communication network performance indicators, such as latency and packet loss, were provided for different power network protocols under a wide range of conditions.

Network slicing was not tested in the lab because the feature was not available during WP2 duration.

3.1 Test system infrastructure

In the 5G ICT lab tests, three 5G-based systems were utilised: 5G-Ready, Enterprise 5G-Ready and 5G-Prototype system.

The **5G-Ready test system** is using 4G radio access that was located in the laboratories at the Institute for Automation of Complex Power Systems (ACS) in RWTH University in Aachen. Radio access network was connected over a secured IP tunnel to the 5G Mobile Core Network located at Ericsson premises in Aachen.

The **Enterprise 5G-Ready test system** (also called Non-Public or Private network) is a network in a box solution. The Enterprise 5G-Ready system is packed in a single box and does not require any connectivity with an external Mobile Core Network system. The solution consists of all the nodes required to run a fully functional mobile network including the core network nodes. Enterprise Core Network setup is running on Ericsson Cloud Execution Environment that virtualised all the core network functions.

The **5G-Prototype test system** is the state-of-the-art non-standardised prototype version developed in Ericsson for internal testing purposes using 5G New Radio (NR) access [15]. The 3GPP standardised New Radio was commercially launched in mid-2019 as a commercial product. The main difference between the 5G-Ready or the Enterprise 5G-Ready and the 5G-Prototype test systems is that the 5G-Ready systems rely on 4G (LTE) radio access along with a 5G Core Network, while the 5G-Prototype is using New Radio (NR) access, the next generation radio access, without any mobile core network.

In addition to the 5G tests, a test on a local **Ethernet network** was conducted to obtain a baseline for pure protocol characteristics without the influence of a radio system.

Figure 3-1 provides a common overview of the 5G-Ready, the Enterprise 5G-Ready and the 5G-Prototype test system infrastructures. All mobile systems use a Radio Base Station (RBS) and a User Equipment (UE) to establish a radio link. The term “UE” refers to any device that allows a user to connect to the base station. Measurement PC, used as a power traffic generator and traffic measurement tool, was connected to both endpoints of the radio link (RBS and UE) in order to close the measurement loop and to log the latency. A detailed description of the measurement PC is provided in Annex A1.

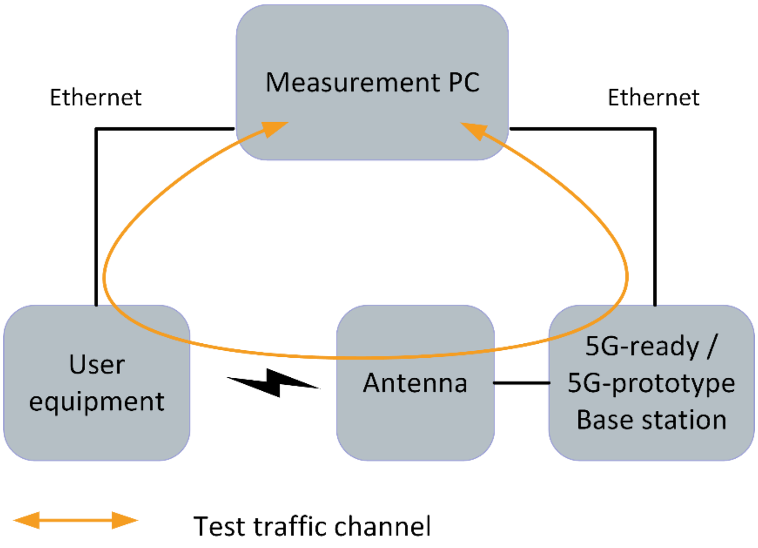

Figure 3-1: 5G system test infrastructure

The 5G-Prototype system shown in Figure 3-2 was set up in the laboratory at Ericsson premises in Aachen. When the experiments were conducted, 5G user equipment chipsets were not available on the market. Therefore, a 5G-Prototype User Equipment installed in a rack was used. Figure 3-2 shows the 5G-Prototype User Equipment and the 5G-Prototype Base Station installed in flight-racks[2].

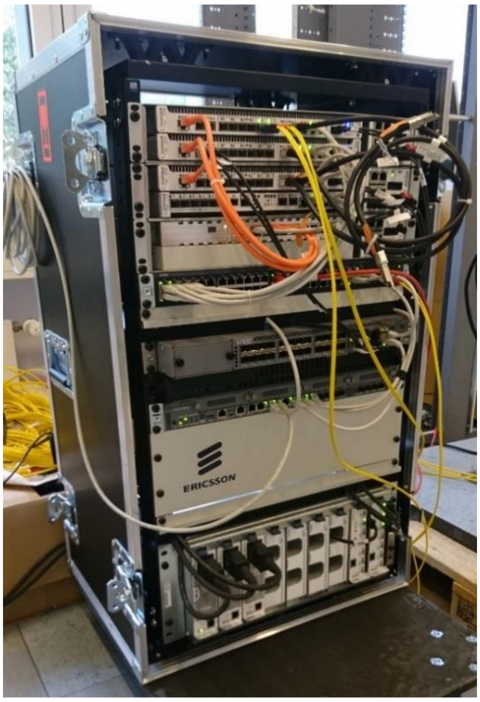

Figure 3-2: 5G-Prototype User Equipment (left) and 5G-Prototype Base Station (right) in flight-racks installed at Ericsson lab in Aachen

[2] 5G flight-rack is the term used in Ericsson to describe portable Ericsson 5G radio network components installed in a rack of a size which is easy to transport by aircraft.

3.2 Test methodology

The behaviour of the power protocols for wide range of message rates and sizes was observed in the tests. The user plane latency experiments were repeated for different transmission rates; 1, 10, 100, and 1000 messages per second. The number of data samples included in each message was varied as well; 1, 10 and 100 values per message. Each value was 64 bits in size. For the reliability test cases, the results of the latency test were reused to analyse the occurrence of packet loss. All protocols were tested with the same test data which consists of a series of at least 10,000 measurement points. Tests were done in ideal traffic conditions like no traffic congestions in the network, small distance to the device, straight line of sight.

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

3.3 Test results

This section shows protocol performance observed in different test systems as well as different protocols performance in the same test system. The protocols AMQP, MQTT and SV were compared over four test systems: 5G-Ready, Enterprise 5G-Ready, 5G-Prototype, and Ethernet. Note that only few representative results are shown in this section. In the annex A.3 of this deliverable a description of how to read the latency plots is provided.

Figure 3-3 shows the SV protocol performance in the 5G-Ready and the Enterprise 5G-Ready test systems. SV protocol results showed lower mean latency on the 5G-Ready system compared to the Enterprise 5G-Ready system for the transmission rates of up to 100 messages per second. For the transmission rate of 1000 messages per second, almost the same mean latency has been observed on both systems. No packet loss was observed from the tests even though the protocol itself is a connection-less protocol.

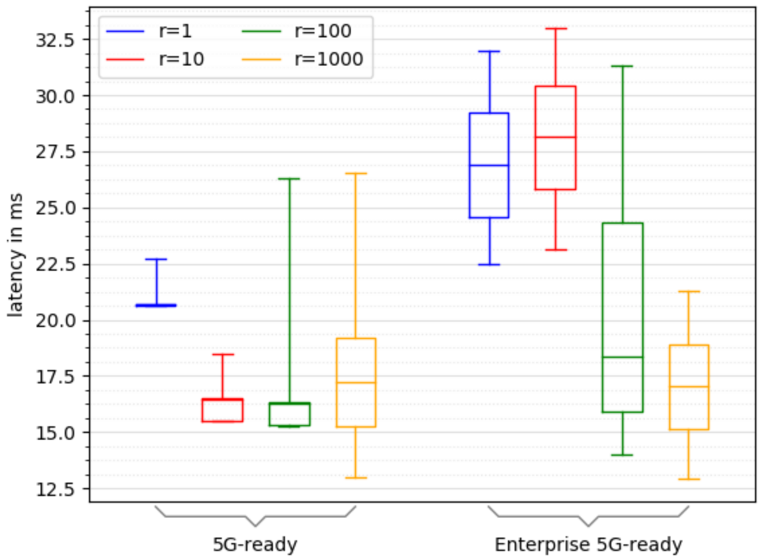

Figure 3-3: SV protocol uplink latency in 5G-Ready and Enterprise 5G-Ready systems

Figure 3-4 shows the MQTT protocol performance in the 5G-Prototype and the Enterprise 5G-Ready test systems. The mean latency of MQTT protocol was much lower for the 5G-Prototype test system compared to the Enterprise 5G-Ready test system. For the 5G-Prototype system the mean latency ranged around 5 ms whereas for the Enterprise 5G-Ready system it showed a decreasing behavior by increasing rate from 1 to 100 messages per second.

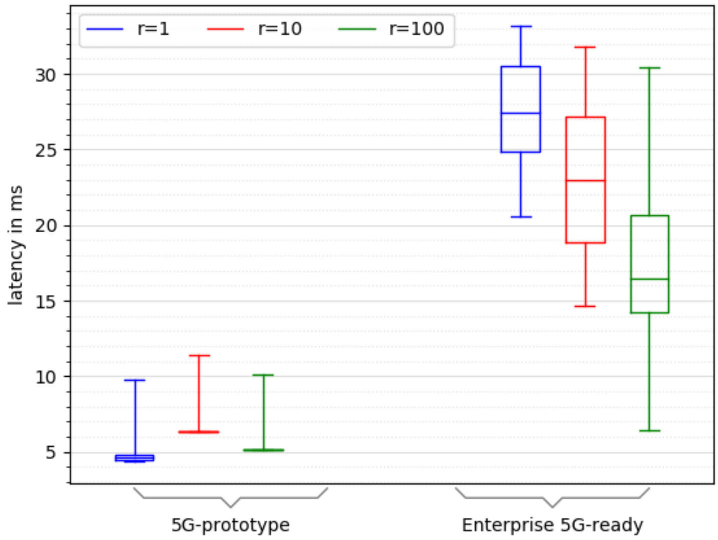

Figure 3-4: MQTT protocol uplink latency in 5G-Prototype and Enterprise 5G-Ready test systems

Figure 3-5 shows AMQP protocol performance in the 5G-Ready, the 5G-Prototype and the Ethernet test system. It was observed that the 5G-Ready system caused a latency in the range between 15 and 20 ms. On the 5G-Prototype system, the latency was in a range between 5 and 10 ms. Comparing that to the 5G-Ready system, an improvement for the latency was clearly demonstrated. As a reference, on the Ethernet system the latency was in a range between 0.3 and 0.5 ms.

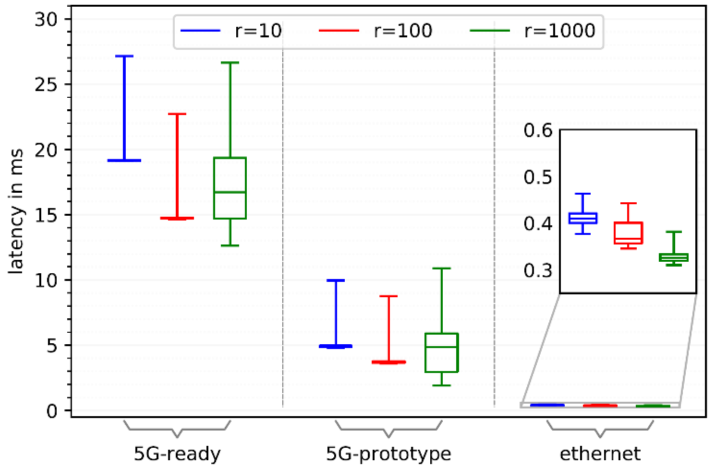

Figure 3-5: AMQP uplink latencies in 5G-Ready, Enterprise 5G-Ready and Ethernet test systems

In Figure 3-6 latencies of MQTT and SV protocols on the Enterprise 5G-Ready system are shown. In general, both protocols could achieve lower latencies at higher rates. Mean latency of MQTT was smaller than the mean latency of the SV for rates 10 and 100. For the lowest rate, MQTT has shown slightly larger mean latency and a larger worst-case latency than the SV.

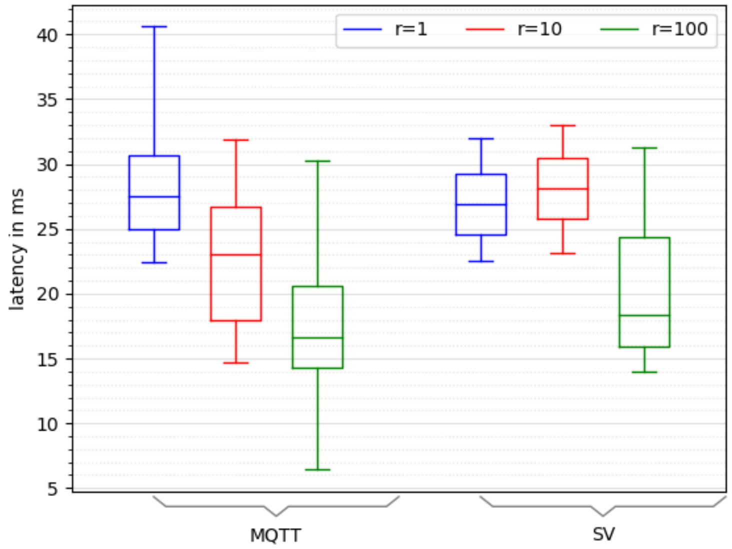

Figure 3-6: Uplink latency boxplot for MQTT and SV on Enterprise 5G-Ready system

The testing showed no packet loss for any of the protocols. MQTT is using TCP as a reliable transport protocol. Hence, there was no visible packet loss on the application layer where we measured the arrival of the messages, but instead the link quality was indirectly represented by increasing variance of the latency. UDP and SV do not guarantee the delivery of the messages, but the load of the testbed networks was too low to cause any congestion-related packet loss.

3.4 The protocol performance in full roll-out network

It is understandable that validation in a lab environment is bringing some limitations comparing to the full-scale deployed solution. The following limitations were identified:

- No handover, device stationary and in fixed relationship of distance to the base station. Note that in full-scale deployment, the device might be connected to two or more radio base stations overlapping in the same area. In case of RBS signal loss, the device will be automatically handed over to another active RBS. The handover might influence the ongoing data transmission.
- In a full-scale deployment solution scenario, devices would have a range of distances to the nearest base station which will affect the signal strength and performance characteristics of the individual radio links to these devices.
- The hardware and software characteristics of the equipment and deployed software used in the lab can differ from the hardware and software used in a full-scale live infrastructure. E.g., processor, memory and discs performance, software versions.
- There were less interferences on the radio interface in the test lab, and the devices had optical visibility to the antenna. In a real deployment, there will be obstacles in the environment, many reflected signals, each with a different time delay and phase, arrives at the receiver, etc.
- In a test environment, limited number of traffic types can be utilised comparing to the full range of traffic types in a real-world application.
- The probability of a packet loss in a real environment is certainly higher than in a test lab.

4. Grid Awareness services solutions in full rollout 5G network

Following the introduction of the presented edge cloud options in Chapter 2.1.4, this chapter will elaborate the question which approach is looking the most fruitful for a full rollout of the SOGNO solution in the 5G network considering the structure of the power system and the Grid Awareness services. First, section **Error! Reference source not found.** describes the power system characteristics that are relevant for the identification of suitable cloud options due to their inherent structure and based on that, section **Error! Reference source not found.** presents the evaluation and selection of the cloud options for a full rollout scenario.

The Power Quality service is not considered in this chapter as the relevant indices are directly computed on the device. Implementation of the Power Quality service on the Device Edge layer may be considered. The focus is set on a practical full rollout cloud solution for the State Estimation service. Based on the power system structure, the aforementioned 5G cloud solutions are analysed and compared. The following considerations apply to the Power Control service as well. Smart inverters would theoretically enable a device edge approach in addition to the access and aggregation solution. Due to the structural similarity to the SE setup the Power Control service is thus not explicitly covered.

4.1 Relevant power system characteristics for Grid Awareness services

The transmission/distribution system is composed of several layers with different voltage levels. Starting from the transmission level (220 kV and 380 kV) and sub-transmission level (60 kV to 150 kV), the relevant levels for the distribution are the medium voltage (1 kV to 35 kV) and the low voltage level (below 1 kV). Thus, by means of the connecting transformers, it is possible to make a clear distinction between MV grids and LV grids.

MV grids are connected to the overarching sub-transmission level by means of primary substations with HV/MV transformers. In general, the layout of the MV grid follows either a radial, ring or meshed structure (see Figure 4-1).

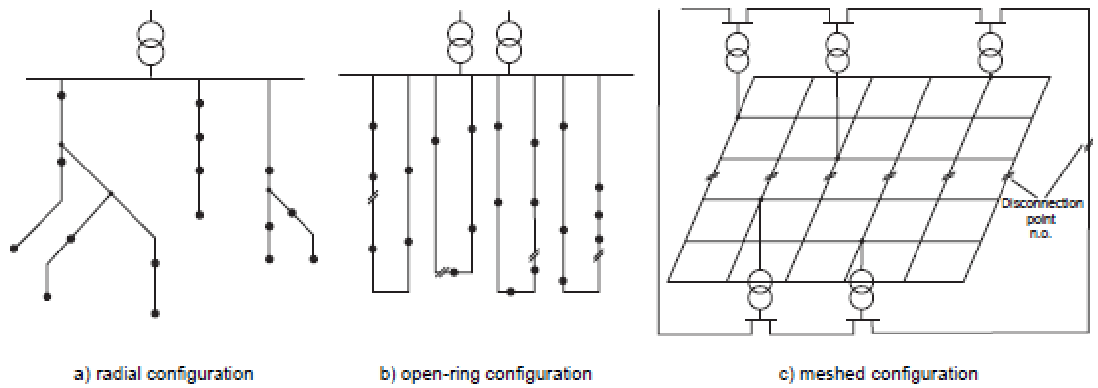

Figure 4-1: Examples of a) radial, b) ring and c) meshed configurations of MV grids [16]

For the radial configuration, each node has only one path to the originating substation. The main feeders are connected via circuit breakers to the MV side of the primary substation. In the open ring configuration, two feeders compose a ring with a switch between them that is normally open.

The underlying LV grid is typically of radial structure and connected by one (or a few) main feeders to the MV grid. Figure 4-2 and Figure 4-3 show typical topologies of a European MV and LV grid together with some dimensions. The individual customers on the LV grid are lumped together and therefore represent strings of household customers connected to the grid. The average number of customers supplied by a secondary substation is in the range of 50 to 250 households in residential areas and less in commercial and industrial areas.

However, for an individual grid the topology and the exact figures, i.e. area spanned by the distribution system, distance between secondary substations and number of connected customers per LV grid, may vary. Rural grids tend to span larger areas and host less customers while following a radial and open ring MV grid structure, while urban grids could be meshed and have by definition a higher density.

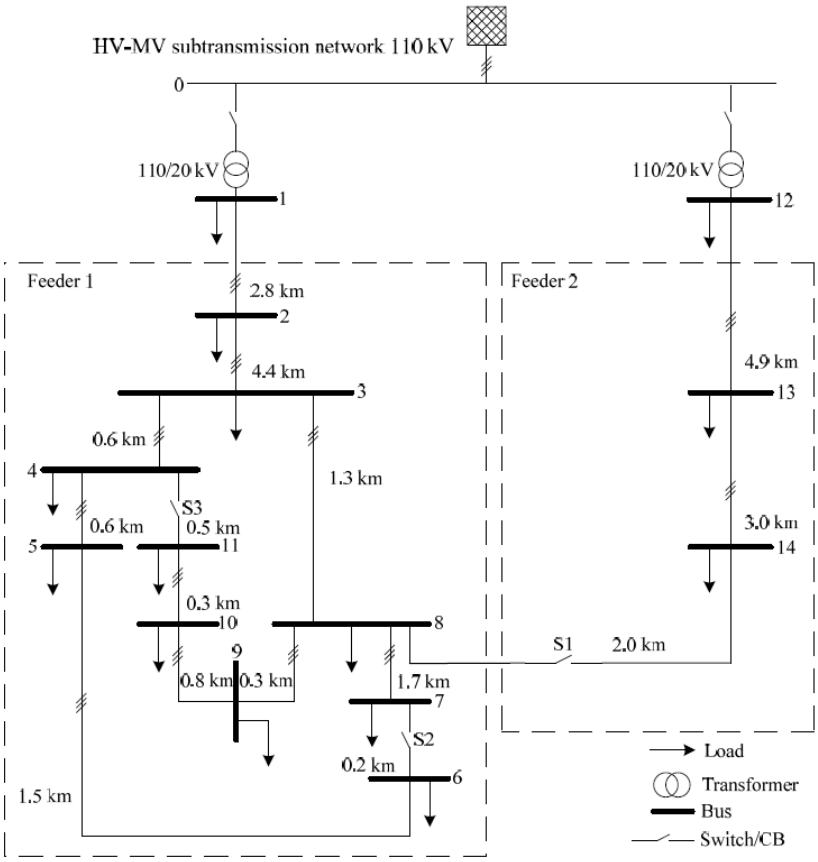

Figure 4-2: Typical topology of a European MV feeder [17]

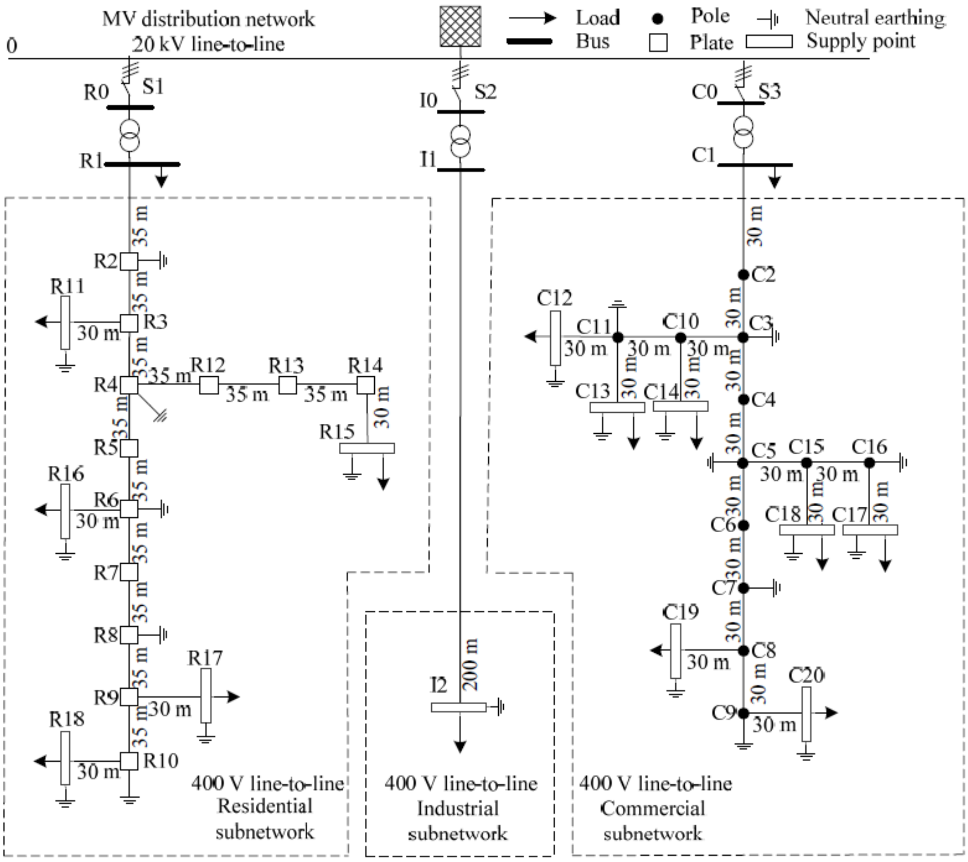

Figure 4-3: Typical topology of a European LV feeder [17]

4.2 Cloud solutions for Grid Awareness services in full rollout

Based on the aforementioned archetypes and characteristics of grids, Figure 4-4 depicts a single exemplary distribution feeder on a schematic level with the medium voltage (yellow) connected to the HV/MV substation (black box) and the low voltage layer (black) that is connected to MV nodes by its secondary substations (blue). Each dashed red circle shows the structural entity of one complete LV grid starting from its secondary transformer. The exact placement of the measurement devices within each LV grid may be chosen arbitrarily with respect to the communication requirements because it will always stay within the same circle.

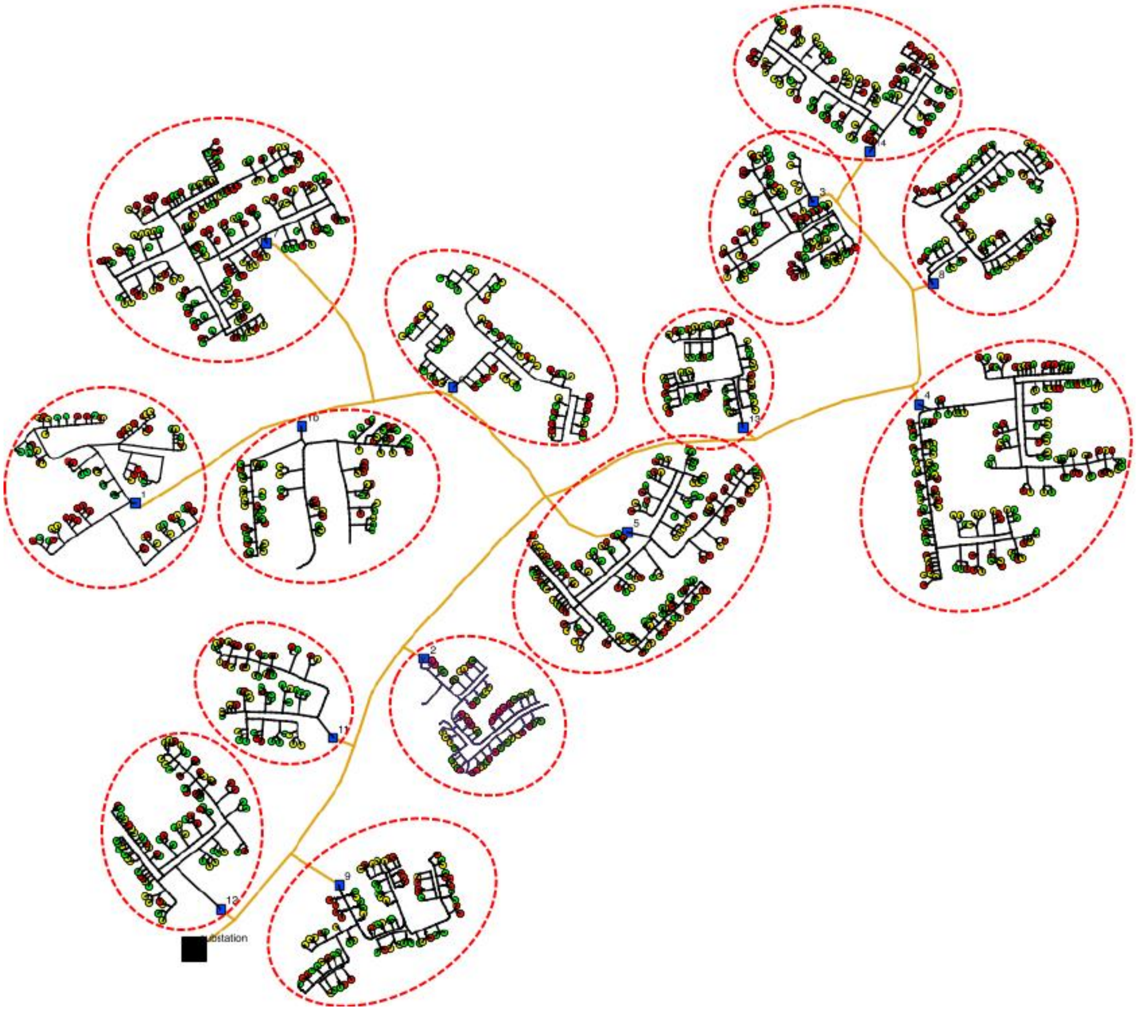

Figure 4-4: Example distribution feeder [18]

Regardless of the individual shape, the logical structure of the grid remains the same. Each individual LV grid is connected at distinct nodes to the upper MV level. This enables the opportunity to split up the State Estimation and the Power Control service at the secondary substations in two layers in analogy to the grid.

Splitting the state estimation results in the full rollout representation in Figure 4-5. This means that for each of the LV grids the state estimation is carried out separately. The MV state estimation is carried out for the whole MV feeder and requires the input from MV sensors in the grid and the results from the LV state estimators.

The MV state estimation is run in the aggregation edge as it will directly process the data collected by MV sensors within different base station areas.

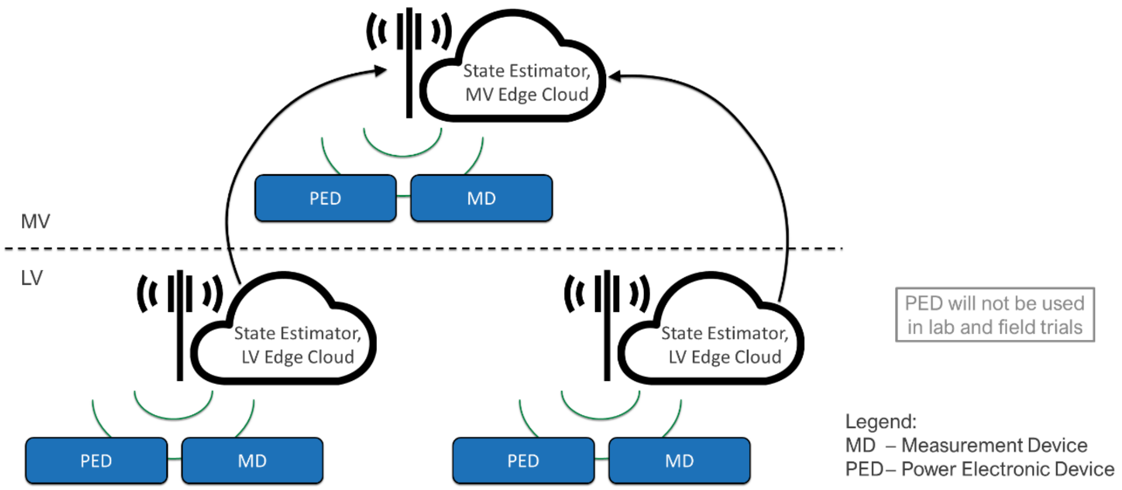

Figure 4-5: Distributed state estimation for full rollout deployment

Each individual LV grid has typically a geographic spread of a few hundred meters, at least in urban areas. So, each LV grid should be covered by a single 5G base station. This means that the secondary substations and the base stations are overlapping. Thus, the LV edge cloud is assumed to be hosted either in the access edge cloud on the 5G base stations or in the aggregation edge cloud. The two options are shown in Figure 4-6 and the implication on the data flow are explained below. The selected cloud option will directly determine the communication path during the operation of the services and hence, determine performance indices such as the latency

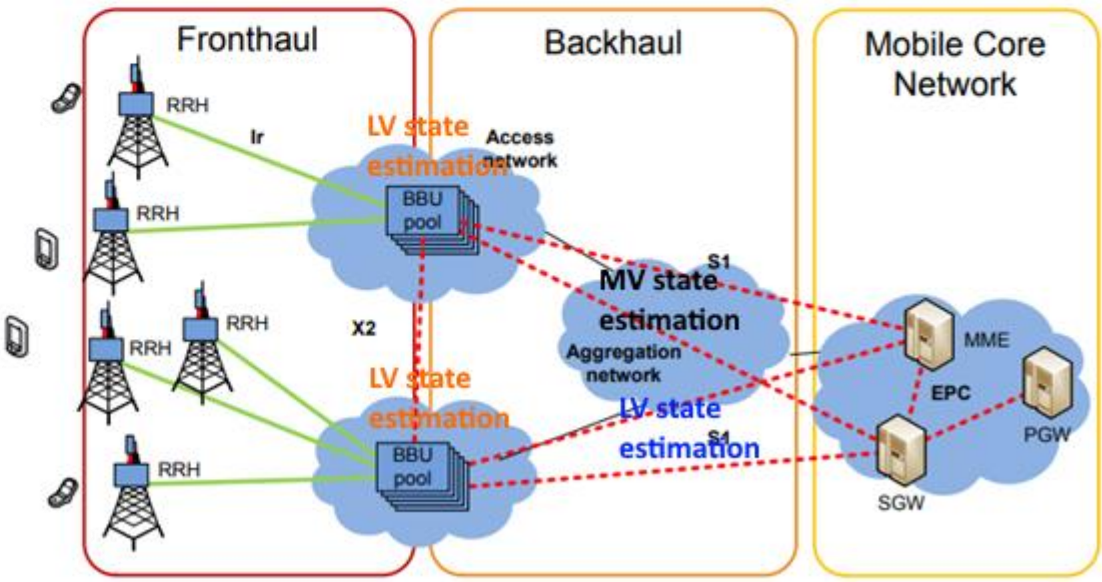

Figure 4-6: Full rollout cloud options with MV state estimation in the aggregation edge and LV state estimation either in aggregation edge (dark blue) or access edge (orange)

LV State Estimation in Access Edge Cloud deployment

Hosting the LV State Estimation in the access edge is the obvious choice as its structure is similar to the distributed state estimation. After the first estimation step, the results are shared between the MV and LV state estimators which enables a second calculation step leading to more accurate estimates. A simplified version of the end to end processing time for the state estimation is shown step-by-step in Table 4-1. The feedback from the MV state estimation to the LV state estimation is not considered in the step-by-step procedure. The table shows an exemplary process description of distributed state estimation without considering feedback. After sending the measurements to the individual LV state estimator, a first step of the state estimation is executed by the LV state estimator. The result of the first state estimation is sent to all other LV state estimators which do a second iteration before sending the updated results to the MV state estimator.

In this exemplary process it is presumed that MV and LV state estimators are deployed in access edge using 5G network to exchange data among themselves as well as with measurement devices and the control centre. 5G communications are depicted in Table 4-1 in steps 1, 3, 5 and 7. The following three communications paths are utilised:

- Communications path between the measurement device and the Radio Base Station (RBS) hosting LV state estimator depicted in Step 1. The signal is transmitted over the air (5G NR).
- Communications path between RBSs hosting LV and MV state estimators depicted in Step 3 and 5. The signal between RBSs is transmitted either over the air (5G NR or microwave link) or the fibre optic cable.
- Communications path between RBS hosting MV state estimator and the control centre depicted in Step 7. The signal is transmitted within the 5G mobile core network and other communications networks to the call centre over fixed communications links.

Step	Process / Communication	Estimated processing time or latency [ms]	Comment
1	MD (Measurement device) to LV-Edge Cloud 1 (EC1)	1 [1)]	Communication between device and RBS (Radio Base Station)
2	Execution LV-EC1 (1)	20	Processing time
3	LV-EC1 to LV-ECn	1	Communication between RBSs
4	Execution LV-State Estimation n (SEn) (2)	5	Processing time
5	LV-ECn to MV-EC	1	Communication between RBSs
6	Execution MV-SE	10	Processing time
7	MV-EC to control centre	1	Communication between RBS and control centre
Note1: The latency estimation is based on the targets set in 3GPP standards [13].			

Table 4-1: Simplified step-by-step communication flow for distributed state estimation with LV State Estimation in Access Edge Cloud deployment

In case that a feedback loop exists, several of the steps shown above will be conducted multiple times. The estimated latency for the intra-cloud communication is assumed to be 1 millisecond. The tests with the 5G-Prototype network described in Chapter 3 have already shown a latency of approximately 5 ms.

LV State Estimation in Aggregation Edge Cloud deployment

Hosting the LV State Estimation in the aggregation cloud eliminates the need for intercloud communications between LV and MV state estimation instances. The second iteration of the state estimation is still being processed by the other LV state estimators. Table 4-2 shows a simplified version of the end to end processing time and communication delay for the state estimation deployed in aggregation edge cloud.

The main difference to the previous deployment scenario is that the LV and MV estimators are deployed in the same cloud where internal communications links are utilised (Step 2, 3 and 4). The following two communications paths are utilised in this deployment scenario:

- Communications path between the measurement device and the Radio Base Station (RBS) hosting LV state estimator depicted in Step 1. The signal is transmitted over the air (5G NR).
- Communications path between RBS hosting MV state estimator and the control centre depicted in Step 5. The signal is transmitted within the 5G mobile core network and other communications networks to the call centre over fixed communications links.

Step	Process / Communication	Estimated processing time or latency [ms]	Comment
1	MD (Measurement Device) to LV-EC1	1	Communication between device and RBS (Radio Base Station)
2	Execution LV-EC1 (1)	20	Processing time
3	Execution LV-SEn (2)	5	Processing time
4	Execution MV-SE	10	Processing time
5	MV-EC to control centre	1	Communication between RBS and control centre

Table 4-2: Simplified step-by-step communication flow for distributed state estimation with LV State Estimation in Access Edge Cloud deployment

Evaluation of edge cloud deployment options

Advantages of the deployment scenarios described above are examined in further text and summarised in Table 4-3.

In case of the LV State Estimation service deployment in aggregation cloud, duration of one state estimation process cycle is smaller compared to the service deployment in access edge. At the end of processing cycle, power grid status gets updated meaning that the resolution of the service deployed on aggregation cloud is higher, i.e., quality of the service itself is higher.

Another important aspect influencing the service characteristics in the different edge cloud deployments is the number of nodes involved in the service execution. Concretely, the number of nodes involved in the service execution is lower in the aggregation edge cloud deployment than in the access edge cloud deployment. In the same time, the number of communication channels is decreased. Consequently, the number of lost and retransmitted packets is decreased, and the services execution time is shortened. If a package is lost, this equals the loss of one measurement for this time step and will cause a degradation of the state estimation accuracy. A loss of package for the measurement of one cycle may be compensated depending on the utilised communication protocol. E.g., the package will be resent if Transmission Control Protocol (TCP) based protocols are utilised but it still might lead to prolonging the service execution time. For a more detailed view of the impact of the loss of measurements on the state estimation accuracy, please refer to Deliverable D2.3.

Furthermore, the service reliability and availability are improved in case of the deployment in aggregation cloud because of lower probability of the nodes or communication channels failure or fall out. Security is improved due to smaller number of nodes involved in the execution. As a result, total execution time is decreased, and security, reliability and availability of the service is improved.

LV State Estimation in Aggregation Edge Cloud Deployment	LV State Estimation in Access Edge Cloud Deployment
Higher service status resolution comparing to access edge	Possibility to handle signals for Power Control service locally. This may increase the DSOs trust

	in the location or entice them take the ownership of parts of the infrastructure.
Elimination of communication between different algorithms instances lowers overall execution time	
Cyber security improved due to smaller number of nodes involved in the execution	
Less packages lost or repeated due to smaller number of nodes involved in the execution	

Table 4-3: Advantages of LV State Estimation in edge cloud deployment options

According to the analysis above, it is concluded that the LV State Estimation in Aggregation Edge Cloud deployment is optimal solution.

5. Conclusions

This deliverable shows that the Grid Awareness services have demanding requirements for high-performance, reliable, secure and fast communication networks, to ensure that the Grid Awareness services can swiftly respond to any deviations in the grid.

Grid Awareness services deployments in full rollout 5G networks were considered. Two most relevant options were selected analysed in detail: State Estimation service deployment in access edge cloud and aggregation cloud. It was concluded that State Estimation in aggregation edge cloud deployment is optimal solution.

The experiments conducted in the lab revealed that a new 5G-Prototype system allowed for significantly lower latencies than a 5G-Ready system. In the same time, latencies on the 5G-Prototype system and the Ethernet system are getting closer. The experiments also revealed that an increasing transmission rate tends to decrease the latency. However, average latency increases by considerably higher rates.

The 5G lab tests resulted in recommendations for protocols and architectures which provide optimal performance. The extensive protocol performance 5G network test results will be used in SOGNO WP5 as a communication reference for the service end-to-end feasibility check in the scalability analysis. In addition to it, communication performance limits achieved in the lab test will be incorporated in the service feasibility theoretical test to prove theoretical limits of the services.

Different deployment scenarios of the Grid Awareness services in full roll-out power and 5G mobile networks were studied in detail in this deliverable. It was shown that the Grid Awareness services deployed on the aggregation edge cloud would have better characteristics, i.e., higher service quality would be achieved.

6. List of Tables

7. List of Figures

8. Bibliography

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9. List of Abbreviations

3GPP	3rd Generation Partnership Project
4G	Fourth generation cellular network technology
5G	Fifth generation cellular network technology
AMQP	Advanced Message Queuing Protocol
BBU	BaseBand Unit
cMTC	critical Machine Type Communication
C-RAN	Cloud Radio Access Network
DSO	Distribution System Operator
EC	Edge Cloud
eMBB	enhanced Mobile Broadband
FCC	Federal Communications Commission
GOOSE	Generic Object-Oriented Substation Events
GSM	Global System for Mobile communications
HV	High Voltage
IEC	International Electro-technical Commission
ICT	Information and Communication Technology
IoT	Internet of Things
IT	Information Technology
LTE	Long-Term Evolution
LTE-M	Long-Term Evolution for Machines
LV	Low Voltage
mMTC	massive Machine Type Communication
MQTT	Message Queuing Telemetry Transport
MIMO	Multi-Input Multi-Output
MV	Medium Voltage
NB-IoT	Narrow-Band IoT
NR	New Radio
PC	Power Control
PQE	Power Quality Evaluation
RBS	Radio Base Station
RRH	Remote Radio Head
SE	State Estimation
SOGNO	Service Oriented Grid for the Network of the Future
SV	Sampled Values
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
URLLC	Ultra-Reliable Low-Latency Communications
WP	Work Package

WRC	World Radiocommunication Conference

Annex

A1 Measurement PC - HW and SW configuration

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

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

VILLASnode software version:

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

MQTT/AMQP Broker:

- RabbitMQ Adapter 3.7.7

A2 Reading the latency plots

In this report, grouped box-whisker plots are used to present the results of latency measurements. The plots either compare different protocols on one system or one protocol on different systems. For instance, in Figure A-1, the uplink latencies on the 5G-Ready test system are grouped by two different protocols: AMQP and SV as indicated on the x-axis. For both groups, different message transmissions rates (r=10, 100, 1000) per second are considered and indicated by a colour scheme.

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

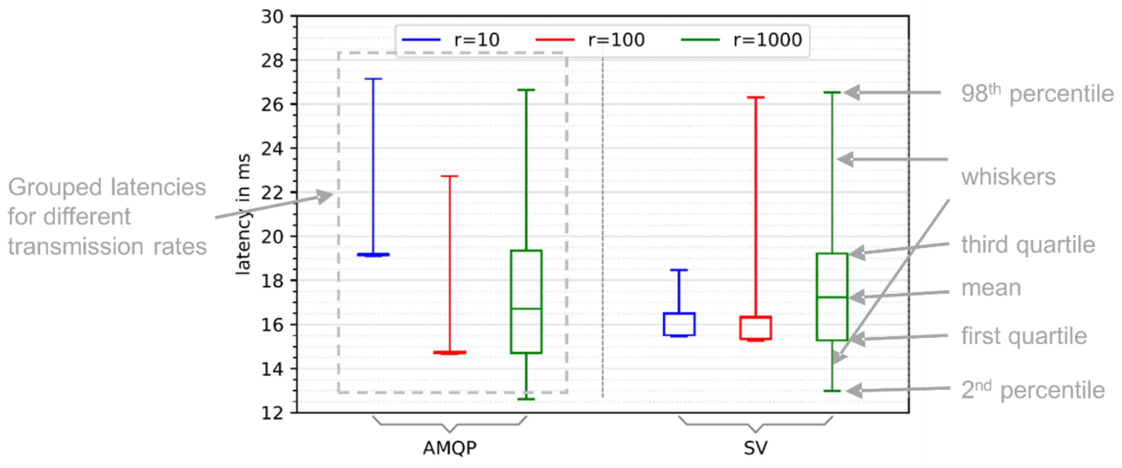

Figure A-1: Exemplary box-whisker plot for uplink latency on 5G-Ready system