RESERVE

D2.5 v1.0

Definition of ICT Requirements for Frequency Control, V2

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Abstract:

This document is a report on the Information and Communications Technology Requirements for the solutions developed in RESERVE and it focuses mainly on the 5G aspects of the requirements and the potential solutions which 5G offers for these requirements.

The requirements are based on the latest RESERVE frequency control scenarios identified in Deliverable (D) 2.6 for future power systems with share of generation from Renewable Energy Sources (RES) up to 100%. It builds on the results of D2.4 and broadens the results to take into account new energy scenarios and provides a detailed analysis of the solutions which 5G can provide in relation to the requirements.

Keyword list:

Information and Communications Technology Requirements, 5G, 100% RES Energy Networks, Frequency Control, Power Networks

Executive Summary

The title of this deliverable D2.5 has been changed from the original „Definition of ICT Requirements for Linear Swing Dynamic Operations, V2“ to “Definition of ICT Requirements for Frequency Control, V2”. The reason for the change is that the document will now cover all scenarios for frequency control in this project, and not just Linear Swing Dynamics.

This deliverable D2.5 presents the work of Task T2.5, “Requirement on scalable ICT to implement frequency control concepts” within the wider context of Work Package WP2 and RESERVE. WP2 focuses on the detailed analysis of the challenges and solutions for frequency control in general, and linear swing dynamics in particular. These topics are highly relevant in future energy networks with 100% renewable energy sources (RES).

This deliverable (D2.5) replaces and extends deliverable D2.4 with the same aim to define the Information and Communication Technology (ICT) requirements for the frequency control scenarios. The new frequency control scenarios introduced after release of deliverable D2.4 are included and considered in this deliverable. Timescales and preconditions relevant to the commercial scale use of the frequency control scenarios as well as possible ICT communication solutions are elaborated.

In this deliverable, ICT communication aspects of the frequency control techniques are considered with the focus on novel 5G wireless systems. At the beginning of this deliverable, 5G concepts and features relevant for the frequency control are described. Afterwards, these 5G features are related to the frequency control scenarios.

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1. Introduction

This Deliverable 2.5 presents the final output of Task 2.5, "Requirement on scalable ICT to implement frequency control concepts" updating and expanding the requirements analysis presented previously in D2.4 and D1.3.

As RESERVE has a strong focus on 5G systems and their potential to support new management techniques in the energy sector, the focus of the investigations of potential solutions to the requirements is on the use of 5G cellular wireless systems. In this deliverable, we elaborate additionally on the steps that need to be taken to commercially introduce each of the new techniques as part of the general work of RESERVE on developing the exploitation of project results and also to provide a time and regulatory perspective for the solutions we propose.

1.1 Task 2.5 of WP 2

This deliverable is the final output of Task 2.5 in WP2. This task collects and analyses the requirements for scalable Information and Communications Technology for frequency control in energy systems with up to 100% RES and relates the requirements to the capabilities of 5G systems. As this document is covering all scenarios for frequency control in this project, and not just Linear Swing Dynamics, the title of the deliverable is accordingly changed from the original "Definition of ICT Requirements for Linear Swing Dynamic Operations, V2" to "Definition of ICT Requirements for Frequency Control, V2".

1.2 Objectives of the Work Reported in this Deliverable

The objective of the work reported in this deliverable was to describe the role new 5G-based ICT systems could play in supporting new frequency management techniques in the power infrastructure in the 100% RES context.

1.3 Outline of the Deliverable

The document starts with an introduction to cellular wireless generations and to 5G features, in particular in Chapter 2. The definition of the 5G ICT implications of the energy scenarios currently in use in RESERVE for frequency control is described in Chapter 3. Chapter 4 discusses relevant general issues and conclusions of this work.

1.4 How to Read this Document

Relationship between version 1 of this document (D2.4) and this version 2 (D2.5)

This deliverable elaborates ICT requirements of the frequency control concepts considered in WP2. During the runtime of the project new frequency control concepts were introduced and further elaborated. This deliverable elaborates only the scenarios described in D2.6 and D2.7 that have ICT implications. Consequently, the scenarios elaborated in D2.4 were regrouped in order to follow the new structure of the frequency control concepts. Generally, the scenarios with mechanical inertia described in D2.4 are grouped in scenario S1 in D2.5. The scenarios without mechanical inertia described in D2.4 are kept. In addition, the new concepts were added to the scenarios with mechanical inertia in D2.5.

Relationship of this document to other deliverables of the RESERVE project

This document can be read independently of other RESERVE deliverables. Should the reader desire to learn about the details of the scenarios from the electrical point of view, the authors suggest readers should look at deliverables D2.6 and D2.7.

Overall, this deliverable (D2.5) is related to the following documents from the RESERVE project:

- D1.3 ICT Requirements (preliminary report, that has been appropriately updated based on the developments of the project and replaced now by D2.5 and D3.7)
- D2.1 Definition of Frequency under High Dynamic Conditions
- D2.2 Review of relevance of current techniques to advanced frequency control
- D2.3 Linear Swing Dynamics Validation and Application in Future Converter-Based Power Systems

- D2.4 Definition of ICT Requirements for Linear Swing Dynamic Operations, V1 (deprecated and replaced by this document)
- D2.6 Drafting of Ancillary Services and Network Codes Definitions V1
- D2.7 Drafting of Ancillary Services and Network Codes Definitions V2

The following figure summarised the workflow in Work Package 2, and the related input and output work packages.

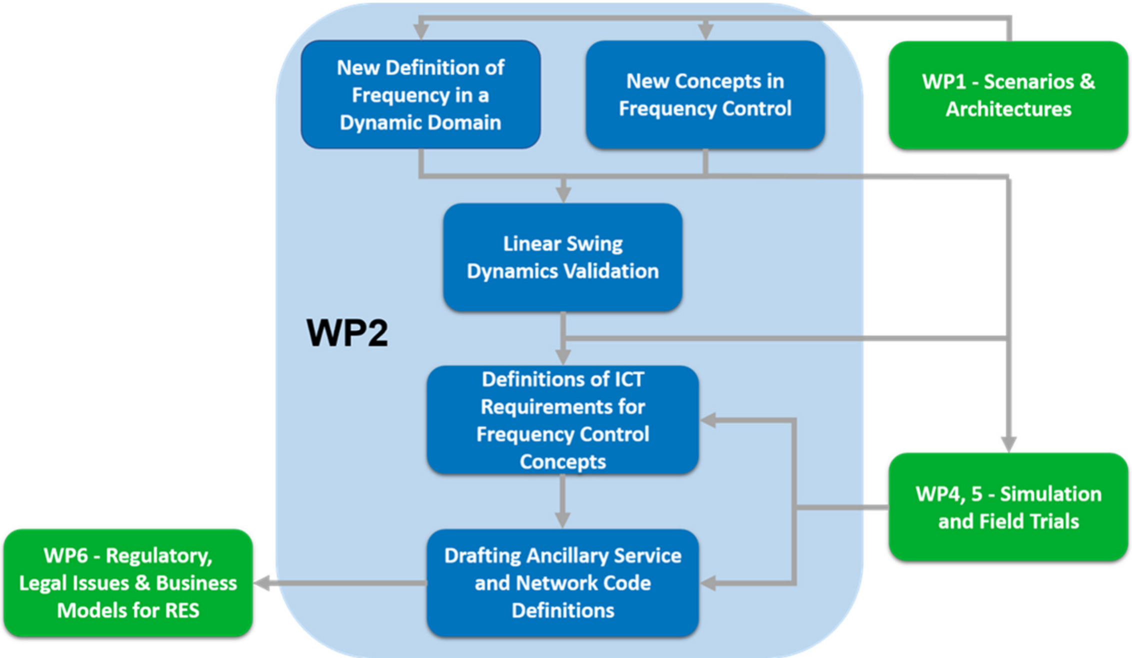

Figure 1-1: Workflow with Work Package 2

1.5 Approach Used to Undertake the Work

- A detailed investigation of the key energy scenarios developed by Work Package 2 was performed with the partners active in WP2 in the project. D2.4 and D2.6 were key inputs to this work.
- The 5G ICT implications of the scenarios were investigated and documented.
- The commercial use of the energy techniques and the key steps which need to be taken to enable their use was investigated to be relate the ICT requirements and solutions to exploitation timescales and changes in network code and ancillary services proposed by RESERVE.

2. 5G Cellular Wireless Systems

5G systems are the focus of RESERVE project investigations as they offer the potential to flexibly and cost-effectively support the commercial deployment of new techniques for frequency management in power networks, which will be needed to support power networks with up to 100% RES generation sources. Such new techniques were developed and elaborated in WP 2 and validated through simulations in WP 5 of the RESERVE project and the scenarios for their use form the basis for our definition of their ICT requirements and the solutions which 5G could provide.

2.1 Evolution of mobile networks and introduction to 5G

Compared with previous generations of wireless communications technology (Figure 2-1), including 4G, the rationale for 5G development is to expand the broadband capability of mobile networks, and to provide specific capabilities not only for consumers but also for various industries and society at large, hence unleashing the potential of the Internet of Things (IoT). 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.

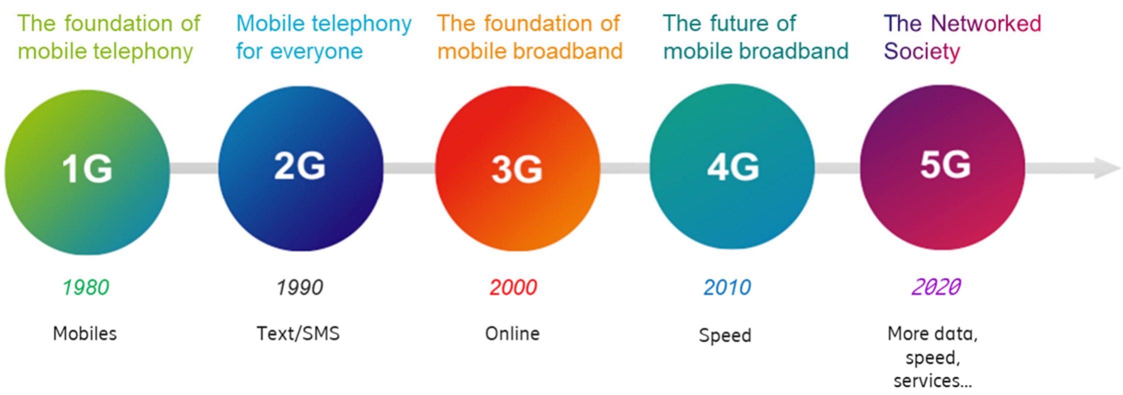

Figure 2-1 Wireless access generations

2.2 Basic 5G functionality

In order to enable connectivity for a very wide range of applications with new characteristics and requirements, the capabilities of 5G wireless access must extend far beyond those of previous generations of mobile communication. These capabilities will include massive system capacity, very high data rates everywhere, very low latency, ultra-high reliability and availability, very low device cost and energy consumption, and energy-efficient networks. Performance requirements of 5G are depicted in Figure 2-2 [15].

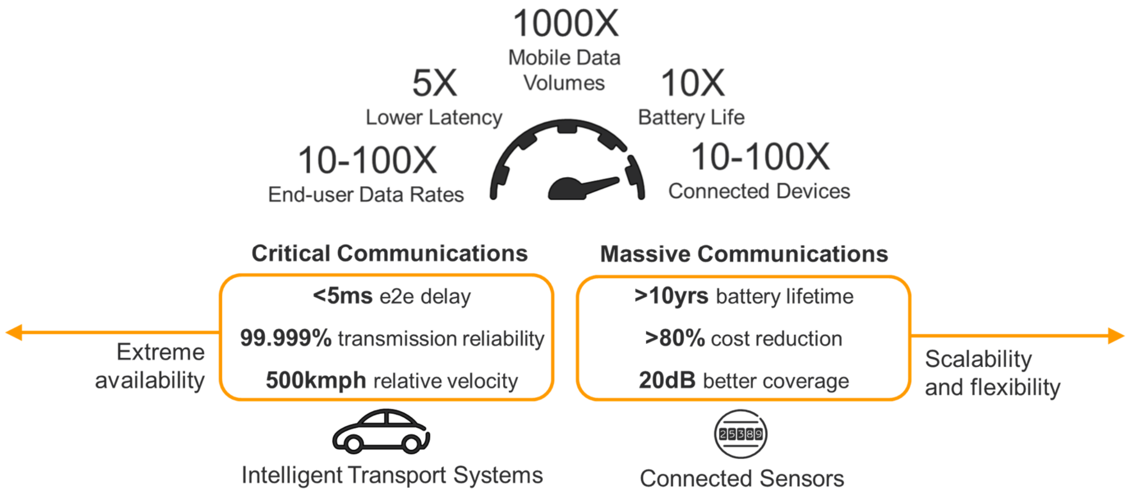

Figure 2-2 Overview of performance requirements for 5G

5G should support **data rates** exceeding 10Gbps in specific scenarios such as indoor and dense outdoor environments. **Very low latency** will be driven by the need to support new applications. Some envisioned 5G use cases, such as traffic safety and control of critical infrastructures and industry processes, require much lower latency compared with what is possible with the mobile-communication systems of today. To support such latency-critical applications, 5G should allow for an application end-to-end latency of 1ms or less. In addition to very low latency, 5G should also enable connectivity with **ultra-high reliability** and ultra-high availability. For example, some industrial applications might need to guarantee successful packet delivery within 1ms with a probability as high as 99.9999 percent. To enable the vision of billions of wirelessly connected sensors, actuators and similar devices, a further step has to be taken in terms of **device cost and energy consumption**. It should be possible for 5G devices to be available at very low cost and with a battery life of several years without recharging. **Energy efficiency** on the network side has recently emerged as an additional Key Performance Indicator (KPI).

In order to support increased traffic capacity and to enable the transmission bandwidths needed to support very high data rates. 5G will extend the range of frequencies used for mobile communication (Figure 2-3). This includes **new spectrum** below 6GHz, as well as spectrum in higher frequency bands. Frequency spectrum relevant for 5G wireless access therefore ranges from below 1GHz up to 100GHz. 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.

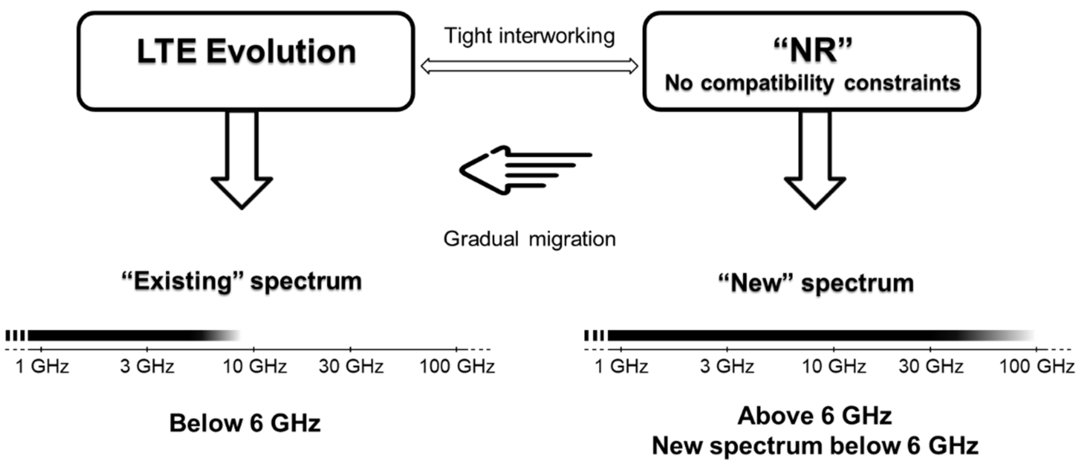

Figure 2-3 5G Frequency Spectrum for LTE Evolution and New Radio

It is important to understand that high frequencies, especially those above 10GHz, can only serve as a complement to lower frequency bands, and will mainly provide additional system capacity and very wide transmission bandwidths for extreme data rates in dense deployments. Spectrum allocations at lower bands will remain the backbone for mobile-communication networks in the 5G era, providing ubiquitous wide-area connectivity.

2.3 Cellular IoT use cases

Cellular Internet of Things (IoT) has the capability to address both the relatively simpler requirements of the Massive IoT market as well as the highly specific, sensitive demands of complex environments and applications [12]. The number of Cellular IoT connections enabled by Narrowband IoT (NB-IoT) and Long Term Evolution for Machines (LTE-M) continues to grow. The number of devices connected by Massive IoT and other emerging cellular technologies is forecast to reach 4.1 billion by 2024.

Cellular IoT itself is a rapidly growing ecosystem based on 3GPP global standards, supported by an increasing number of mobile network providers as well as device, chipset, module and network infrastructure vendors. It offers better performance than other Low Power Wide Area (LPWA) network technologies in terms of unmatched global coverage, Quality of Service, scalability, security and the flexibility to handle the different requirements for a comprehensive range of use cases.

Figure 2-4 shows four 5G use case segments proposed for the evolution of Cellular IoT.

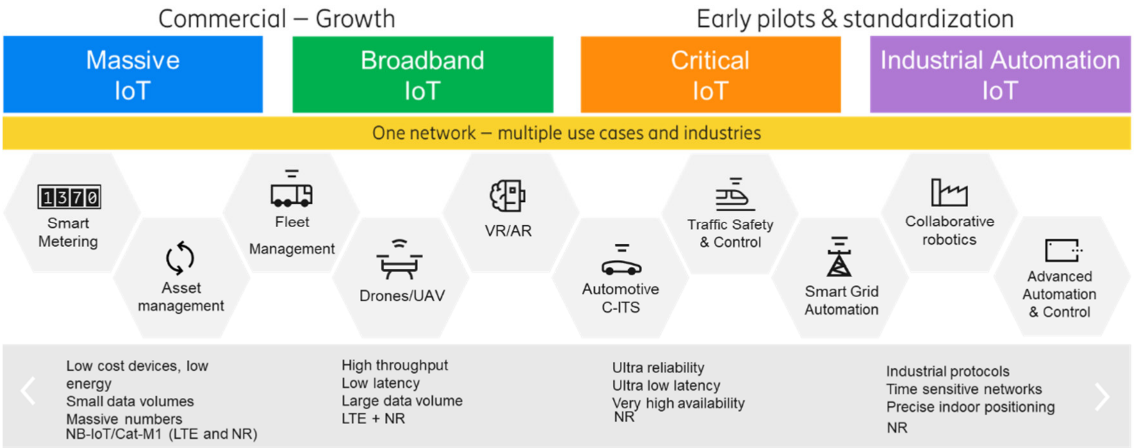

Figure 2-4 5G use case segments proposed for the evolution of Cellular IoT

The **Massive IoT** segment supports very low-cost devices with long battery life, deployed in massive numbers and supporting use cases that demand very low data usage in the networks – use cases such as fleet management or logistics, asset management or smart metering. This segment is already deployed in today's Long-Term Evolution (LTE) commercial networks and is continuing to grow in terms of ecosystem and numbers of connections.

3GPP standardised three new technologies for massive Machine Type Communications (MTC) in Release 13: Extended Coverage GSM IoT (EC-GSM-IoT), LTE-M and NB-IoT. LTE-M extends LTE with new features for improved battery life, extended coverage and support for low-complexity device category series, named Category M (CAT-M). NB-IoT is a standalone radio access technology based on LTE that enables extreme coverage and extended battery lives for ultra-low complexity devices.

LTE-M and NB-IoT should target complimentary use cases. LTE-M is better suited for applications that require higher throughput, lower latency, better positioning and voice connections. Typical LTE-M use cases include wearables, sensors, trackers, alarm panels and customer support buttons, all with support for data and voice connections. On the other hand, NB-IoT is the technology of choice for very low throughput applications that are tolerant of delay but require very good coverage, such as simple utility meters and sensors deployed in challenging radio conditions.

The **Broadband IoT** segment uses the capabilities of Mobile BroadBand (MBB) to achieve higher throughput, low latency and larger data volumes than Massive IoT can support and together with some additional functionality can support IoT use cases for drones or Unmanned Aerial Vehicles, Augmented Reality and Automotive. This segment can already be supported in today's 4G network and will be able to support even more advanced use cases when moving from 4G to 5G with the higher speed, lower latency and other capabilities that 5G will bring.

The **Critical IoT** enables extremely low latencies and ultra-high reliability at a variety of data rates. This segment addresses extreme connectivity requirements of many advanced wide area and local area applications in intelligent transportation systems, smart utilities, remote healthcare, smart manufacturing and fully immersive Augmented Reality/Virtual Reality. Powered by the most innovative capabilities of 5G NR, Critical IoT is expected to enable many new use cases within the IoT arena.

For the most complex segment, the **Industrial Automation** segment, some very challenging use cases specific to the industrial campus and manufacturing environments can be supported – use cases such as collaborative robotics which would require functionality such as industrial protocols in addition to time sensitive networks and very precise positioning.

2.4 Device availability

Figure 2-5 shows the approximate timing of 5G device availability [14]. Early Fixed Wireless Access (FWA) devices have been developed to meet market needs in the USA and Australia for example. The first 3GPP-compliant 5G smartphones and tablets are already launched in 2019. To date, the IoT business has primarily been driven by the affordability of devices. Costs of 3GPP-compliant devices have come down significantly recently, and as they approach 5–10 euros, we are starting to see the cellular-delivered IoT market becoming better established. The market for industrial IoT services is at an earlier stage but will likely be a significant market in the longer term. We foresee 3GPP systems becoming the IoT technologies of choice for operators and industry in the longer term.

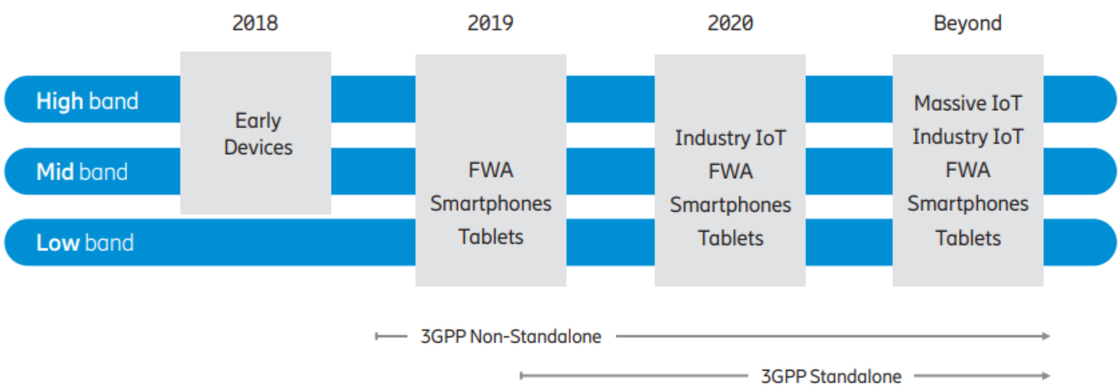

Figure 2-5 5G device availability

2.5 The global spectrum picture

Figure 2-6 gives a general indication of spectrum availability across all mobile network generations over time [14]. The spectrum available to 5G will vary from market to market, according to whether it is already in use and the timing of auctions and licensing processes.

More spectrum will be needed for 5G, because its benefits are fully achieved in new millimeter wave frequencies, with extremely wide bands. Here, the ultra-high peak rates and low latency are most likely to be used to add new levels of capacity and throughput for enhanced mobile broadband, especially as a way of offloading congested 4G networks (and for new special use cases). But there is also broad interest in deploying 5G technology in new mid bands (3.5–6GHz) and existing, legacy mid bands (1.8–2.6GHz) as a way of achieving national 5G coverage as rapidly as possible.

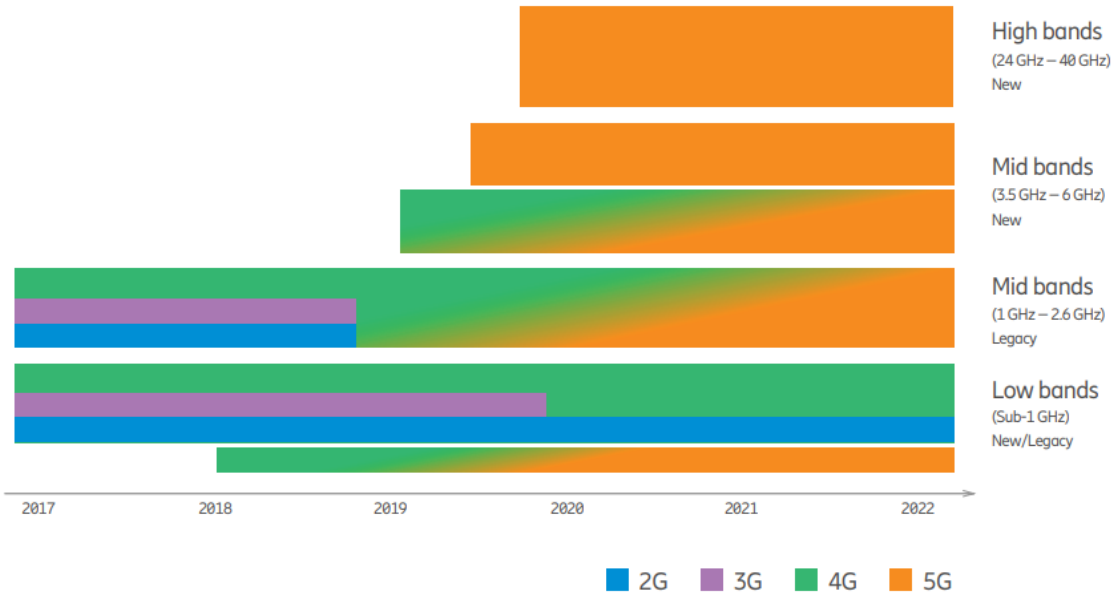

Figure 2-6 Spectrum allocation over time

Each spectrum band has different physical properties, meaning there are trade-offs between capacity, coverage and latency, as well as reliability and spectral efficiency, as illustrated in Figure 2-7. If the network is optimised for one metric, there may be degradation of another metric.

Low-band spectrum has historically been used in 2G, 3G and 4G networks for voice and mobile broadband services, as well as broadcast TV. The available bandwidth is typically between 10 MHz and 30MHz. This makes this spectrum most suitable for wide-area and outside-in coverage from macro base stations. For a typical 5G mobile broadband use case, capacity and latency are similar to 4G on the same band.

Legacy mid-band spectrum is currently used for 2G, 3G and 4G services. New mid-band spectrum has typically been allocated in 3.5 GHz spectrum bands. In these bands, especially in the new higher spectrum, we are likely to see larger bandwidths (50–100MHz). This will enable high-capacity, lower latency networks which can be used for new 5G use cases, with better wide-area and indoor coverage than higher-band spectrum.

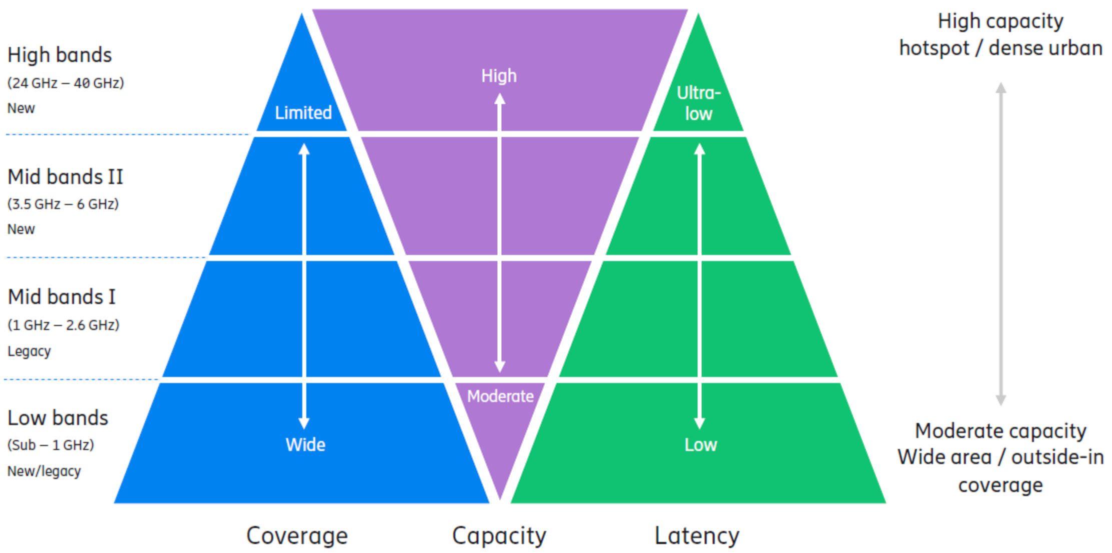

Figure 2-7 Spectrum trade-off

High-band spectrum provides the quantum leap in performance promised by 5G. These new spectrum bands are typically in the 24–40GHz range, with bandwidths in 100MHz (or larger) blocks. Such large bandwidth enables ultra-high spectrum capacity networks (5–10 times higher than today), with latency as low as 1ms. However, these higher frequencies come with a coverage limitation compared with lower bands.

2.6 Two-phase approach

As 5G will need to coexist and interwork with 4G for many years to come, we are likely to see the vast majority of these deployments as non-stand-alone (NSA) initially, as a way of reducing time to market and ensuring good coverage and mobility. The 5G stand-alone (SA) mode, which requires a new (service-based) core network architecture (known as 5G Core, or 5GC), will enable deployments of 5G as an overlay to, or independent, of 4G coverage.

To achieve nationwide coverage as fast as possible, we're also likely to see 5G deployed in low/mid bands, which will also be suitable for massive IoT use cases in the future. SA 5G in high bands is more likely to be used mainly for data offload in high-traffic areas, as separate networks in factories or campuses, and for critical IoT in data-intensive applications.

Ericsson favors a two-phase approach to deploying 5G as shown in Figure 2-8. 3GPP standardised options shown in the figure will be followed. In the phase 1 (left half of the figure), enhanced MBB is supported and Low Latency IoT use cases will be supported during 2019/2020. This is referred to as 5G NSA mode. In the phase 2 (right half of the figure), 5G network will operate in SA mode, with both control and user planes carried over 5G NR access.

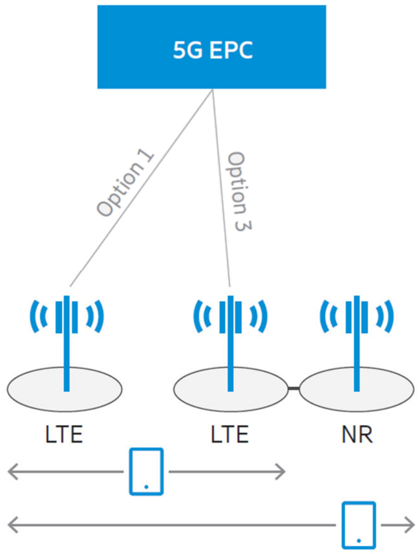

Figure 2-8 LTE-NR connectivity options towards evolved packet core and 5G core

2.7 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 2-9 [15]. Resources can be dedicated exclusively to a single slice or shared between different slices.

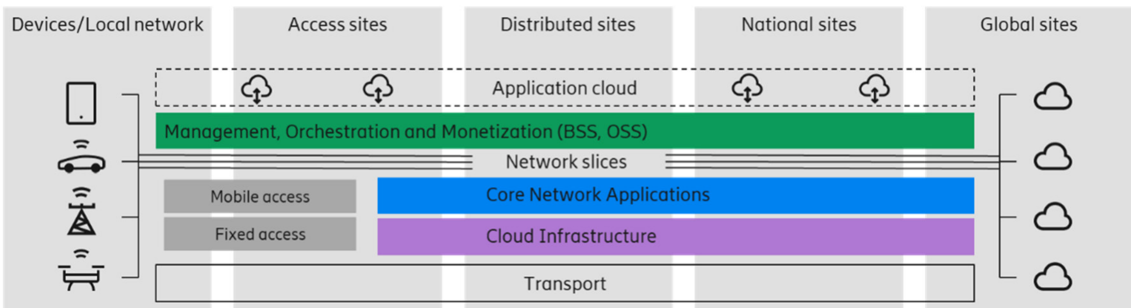

Figure 2-9: 5G Network Slicing

A network slice is built to address a desired behaviour from the network. Such behaviour can be associated with security, data-flow isolation, quality of service, reliability, independent charging and so on. A network slice may support one or several services and can be used to create a virtual operator network and may provide customised 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 its 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 its management center, and applications will simply execute and store data, either centrally, in a distributed management system or a combination of both.

2.8 Distributed cloud

As shown in Figure 2-10, Ericsson defines the **distributed cloud** [18] 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 2-10 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.

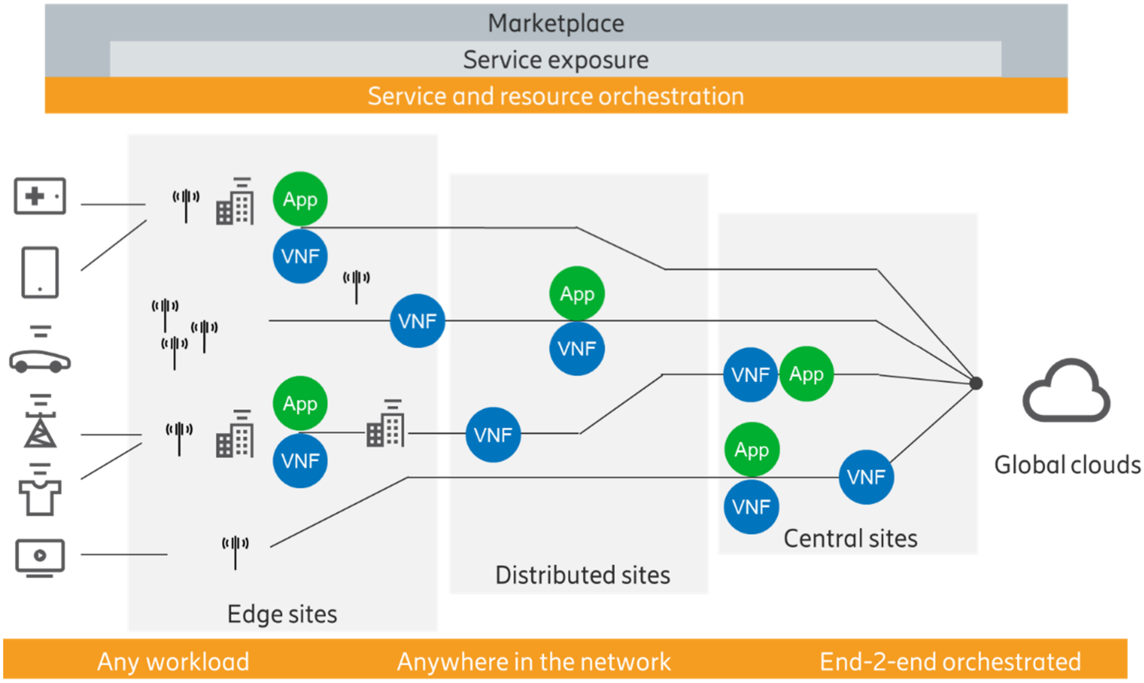

Figure 2-10 Distributed cloud architecture

2.9 5G security

Connected devices and mobile applications require wireless network access that is resilient, secure and able to protect individuals' privacy, and the 5G system is designed with these requirements in mind [11]. Figure 2-11 shows five core properties that contribute to the trustworthiness of the 5G system: resilience, communication security, identity management, privacy and security assurance. These properties of the 5G system contribute toward creating a trustworthy communications platform that is an ideal foundation on which to build large-scale, security-sensitive systems, including those used in industrial settings.

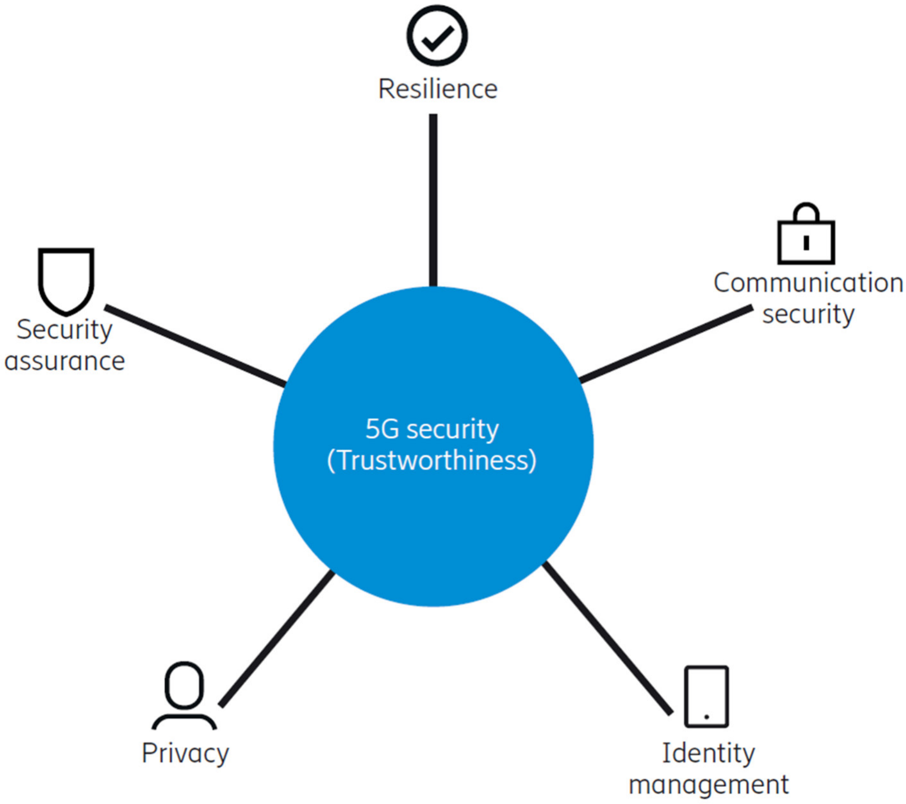

Figure 2-11 Five properties that contribute to the trustworthiness of the 5G system

Resilience

The 5G system's resilience to cyberattacks and non-malicious incidents comes through a variety of complementary and partially overlapping features. First, the 5G NR access was developed for Ultra-Reliable Low Latency Communications (URLLC). Even greater resilience against failures and attacks can be obtained by deploying a single base station as two split units, called a central unit and a distributed unit. Next, the 5G core network architecture itself is designed around resilience concepts. For example, network slicing isolates groups of network functions from other functions. Service Based Architecture principles are another architectural concept that enhances resilience. These principles make use of software and cloud-based technologies that improve on the more static and node-centric designs of previous generation networks. The resilience of the 5G system also stems from the strong mobility support that it shares with previous generation 3GPP networks, which ensures continuous secure connectivity for devices moving from one location to another. In addition to these general features providing resilience, there are more specialised functions introduced to operate a radio access network in extreme situations, such as when it has become separated from its core network. This is called isolated Evolved UMTS (Universal Mobile Telecommunication System) Terrestrial Radio Access Network (E-UTRAN) operation for public safety in 4G/5G and is very useful in disaster areas, for example. Finally, partly due to strong regulations and associated high fines, cellular networks have long adhered to high carrier-grade availability requirements.

Communication security

The 5G system provides secure communication for devices and for its own infrastructure. In particular, the new Service Based Architecture (SBA) for core network communication takes threats from the interconnect network into account. The 5G system includes protection against eavesdropping and modification attacks. Signalling and user plane traffic is encrypted and can be integrity protected. The strong and well-proven security algorithms from the 4G system are reused. These are encryption algorithms based on SNOW 3G (word-based synchronous stream cipher with name SNOW) [20], Advanced Encryption Standard Counter (AES-CTR) [21], and ZUC (Cryptographic algorithm with name ZUC) **Fehler! Verweisquelle konnte nicht gefunden werden.**; and integrity algorithms based on SNOW 3G, Advanced Encryption Standard Cipher-based Message Authentication Code (AES-CMAC) [22], and ZUC. The main key derivation function is based on the secure Hash-based Message Authentication Code Secure Hashing Algorithm 256-Bits (HMAC-SHA-256) [23]. Mobility in the 5G system also inherits different security features from the 4G system.

Identity management

At its heart, the 5G system has secure identity management for identifying and authenticating subscribers, roaming or not, ensuring that only the genuine subscribers can access network services. It builds on strong cryptographic primitives and security characteristics that already exist in the 4G system. One of the most valuable new security features in the 5G system is the new authentication framework where mobile operators can flexibly choose authentication credentials, identifier formats and authentication methods for subscribers and IoT devices. Previous mobile network generations required physical Subscriber Identity Module (SIM) cards for credentials, but the 5G system also allows other types of credentials such as certificates, pre-shared keys and token cards. Another valuable new security feature is the ability of a subscriber's operator to determine the presence of the subscriber during an authentication procedure – even when roaming. The 5G system also inherits a mechanism from legacy systems, called Equipment Identity Register (EIR) check, which can be used to prevent stolen devices from using the network services, thereby discouraging device theft.

Privacy

Data traffic, including phone calls, internet traffic and text messages, is protected using state-of-the-art encryption. The devices and the network mutually authenticate each other and use integrity-protected signalling. Another privacy enhancement is protection of subscriber identifiers, both long-term and temporary, e.g., subscriber's long-term identifier concealment mechanism that is based on the Elliptic Curve Integrated Encryption Scheme (ECIES) [24]. In addition, the 5G system enforces a stricter policy for update of temporary identifiers. Further, the 5G system is also able to detect false base stations that are the root cause of International Mobile Subscriber Identity (IMSI) or Temporary Mobile Subscriber Identity (TMSI) catchers.

Security assurance

In 3GPP, security assurance is a means to ensure that network equipment meets security requirements and is implemented following secure development and product lifecycle processes. This assurance is especially important for mobile systems, as they form the backbone of the connected society and are even classified as critical infrastructure in some jurisdictions. 3GPP and GSM (Groupe Spéciale Mobile) Association (GSMA) took the initiative to create a security assurance scheme called the Network Equipment Security Assurance Scheme (NESAS), which is suitable to the telecom equipment lifecycle. NESAS comprises two main components: security requirements and an auditing infrastructure. The security requirements defined on node basis and collected in so-called SeCurity Assurance Specifications (SCAS) are defined jointly by operators and vendors in 3GPP. The auditing infrastructure is governed by the GSMA, the global mobile operator organization, that conduct the audits of vendors' development and testing processes.

2.10 5G public and private networks

New 5G deployment architectures options are being investigated considering public and non-public network deployment options for verticals such as manufacturing [16]. In the coming years, 5G will enable many new industrial automation applications using public and non-publicly operated 5G networks. Private networks can be deployed as isolated, standalone networks and in conjunction with a public network. In certain deployments of a private network in conjunction with a public network, private and public networks can share part of a radio access network. 3GPP specifications include functionality that enables RAN sharing [17].

3. ICT Requirements for Frequency Control Concepts

This section describes the scenarios for frequency control, their associated ICT communications requirements and potential solutions based on 5G. The scenarios are divided into two groups – those with mechanical inertia (S1 to S5) and those without mechanical inertia (S6 and S7), as follows:

- S1 – Frequency Control of Distributed Energy Resources in Distribution Networks.
- S2 – Frequency Makers and Frequency Takers
- S3 – On-line Rotor Speed Estimation
- S4 – Frequency Control of Grid Connected Microgrids
- S5 – Two-level Secondary Frequency Control with Inclusion of Virtual Power Plants
- S6 – LSD and Virtual Inertia, Inertial Control, Decentralised Topology
- S7 – LSD and Virtual Inertia, Secondary Control, Distributed Topology

The new frequency control scenarios (S2 to S5) were introduced in the project after the release of D2.4. ICT implications of the new scenarios are further elaborated in this deliverable. Comparing the scenarios above with those proposed in Figure 2-2 of Deliverable D2.4, it can be seen that Scenarios S1 through S4 of D2.4 have been grouped together as S1 in this document, where four sub-scenarios (S1.1-S1.4) have been defined following the same structure as in D2.4. Scenarios S6 and S7 of this document correspond to S10 and S11 of D2.4. Finally, Scenarios S2 through S5 of this document have been defined based on the research concepts developed during the second half of the project, i.e., after completion of D2.4. A full description of Scenarios S2-S5 from the energy perspective can be found in D2.6 and D2.7.

The ICT Communications requirements are best estimates, agreed by the energy and ICT experts of the RESERVE project, based on their expectations of the likely configuration of systems for the large-scale use of the techniques researched in WP2 of RESERVE.

3.1 Scenarios with Mechanical Inertia

3.1.1 S1 Frequency Control of Distributed Energy Resources in Distribution Networks

3.1.1.1 Energy system requirements

Frequency control is done currently by large power plants located mainly in the transmission grid. While these large power plants will be replaced to some extent by smaller ones located in the distribution grids, frequency control will focus also on using Distributed Energy Resources (DERs).

The following four sub-scenarios of S1 are examples of frequency control in Medium Voltage (MV) and distribution networks. They combine power generation units with some mechanical inertia that is hydro power plants with wind turbines and solar plants which lack such inherent inertia. There is no need for virtual inertia injected by Linear Swing Dynamics in these scenarios as they have own inertia. The DERs installed in distribution networks comprise of converter-interfaced generation (wind and solar), other components controlled by means of power converters such as ESSs, and thermostatically controlled loads and other frequency-dependent loads.

Energy aspects of the four sub-scenarios were described in deliverable D2.4. Those descriptions are repeated in this deliverable without changes. The ICT aspects studied during the work on this deliverable were added.

- S1.1 Low Mechanical Inertia, Sf_A, Primary Control, Decentralised

  This scenario is used as basic reference scenario for later comparisons with the other scenarios.

  All converter-interfaced DERs use individual Phase-Locked Loop (PLL) signals to synchronize their converters (generally Voltage-Sourced Converters) with the grid. Each one of the signals provided by the PLLs shall be characterised by a certain level of latency and noise. There is no central unit for gathering the frequency signals from the DERs. Therefore, there is no need for any advanced communications network. The frequency regulation is executed independently by each DER units. Only local frequency measurements are considered here.

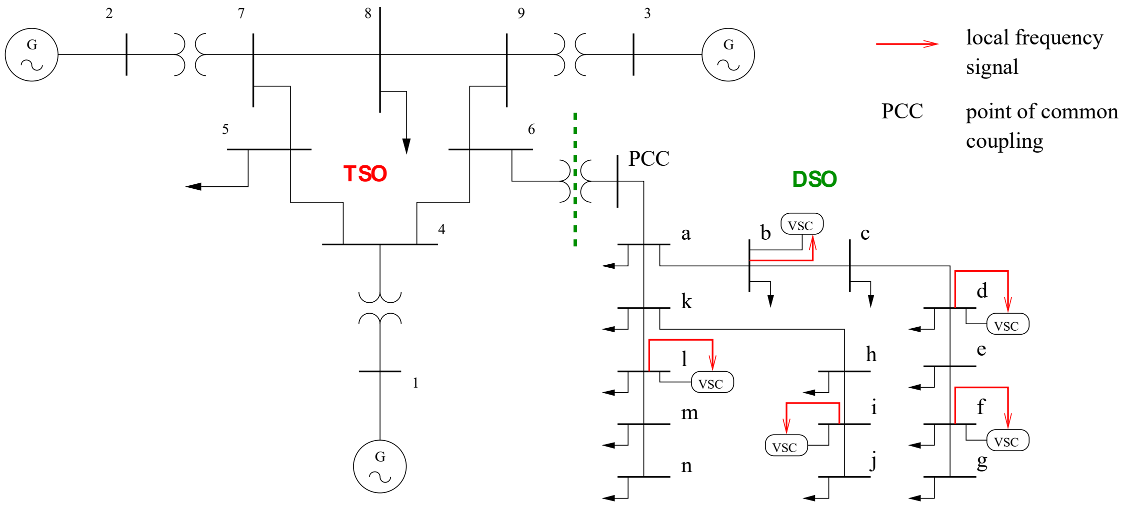

Figure 3-1 Decentralised primary frequency control provided by the Distribution System

S1.1 ICT Communications requirements

The frequency regulation is executed independently by the inverters or VSC devices included in the DER units. Accordingly, there is no need for communications in this scenario and hence there are no requirements.

- S1.2 Low Mechanical Inertia, Sf_A, Primary Control, Centralised

This scenario uses a central DSO **frequency data manager** located at the Point of Common Coupling (PCC) with the transmission system, and data is distributed by means of 5G to all DERs inside the Distribution System (DS). This frequency data manager is shown as a **red box** in the diagram, Figure 3-2.

This frequency data manager is responsible for gathering the measurements from the PCC bus, and then distributing this value to each frequency control device at the distribution system side. This device is the inverter or VSC typically included in DER units. The target frequency value is the frequency measurement taken from the PCC busbar. The DER controllers locally take the needed actions.

The frequency data manager can be part of the Secondary Substation Automation Unit (SSAU) [25]. There are two types of Phasor Measurement Units (PMU) for measuring the frequency at the PCC, as follows.

Types of Frequency Controllers

- **Ideal PMU** – the frequency at the PCC will be measured using an ideal PMU model, i.e., free of latencies and noises. To this aim, the Frequency Divider Formula (FDF) without latency can be used, as described in deliverable D2.1.
- **Real PMU** – the frequency at the PCC will be measured by means of a PMU.

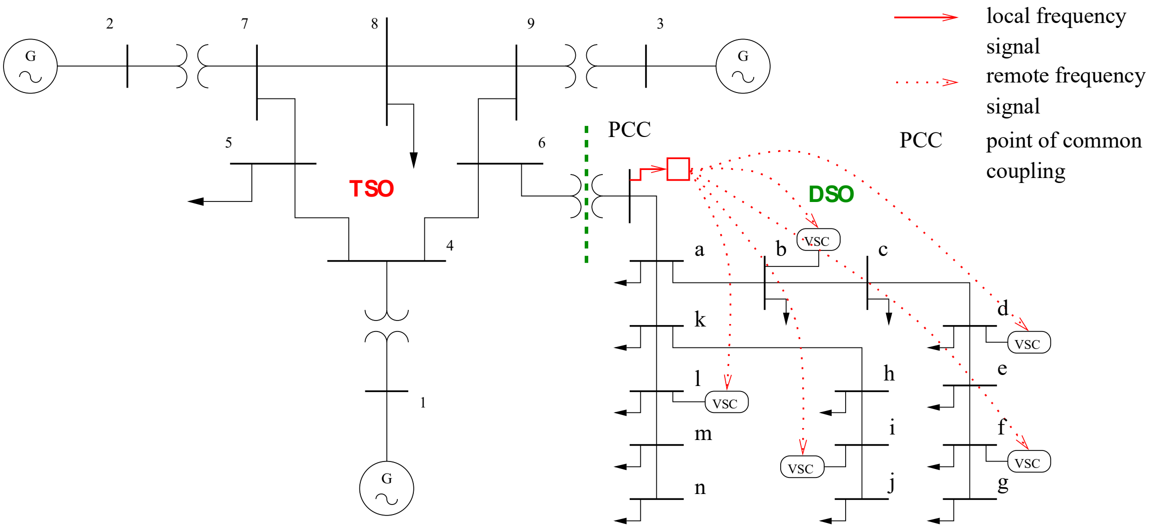

Figure 3-2 Centralised primary frequency control provided by the Distribution system

Table 3-1 shows ICT communications requirements for Scenario S1.2.

The Latency shows transmission time for a measurement or control signal to be sent from point A to point B over the communications network. These times include the end-to-end transport of data over radio interface, processing in base station, transport over backhaul network, and processing in core network.

The Sampling Rate describes the number of data packets per second that are transmitted between sensors and control centres (or vice versa).

The Data Volume indicates maximum size of a standard message between end-points in the distribution network, including overhead for addressing, time stamps, authentication and authorisation, encryption, et al.

Table 3-1 ICT requirements for Scenario S1.2 Low Mechanical Inertia, Sf_A, Primary Control, Centralised

ICT communications requirements	Scenario S1.2 Low Mechanical Inertia, Sf_A, Primary Control, Centralised
Req-S1.2-endPoints	Unidirectional communication takes place from the frequency data manager (located at the Point of Common Coupling (PCC) to the transmission system) to the DERs located in the distribution system. The distance between the end-points ranges from 1 to 5 km. The expected number of measurement devices is between 10's and 100's of devices.
Req-S1.2-latency	The expected signal transmission link latency between the end-points is in the range of 10-20ms.
Req-S1.2-sampleRate	A sampling rate of 50 distributed signals per second is expected.
Req-S1.2-volume	The frequency data manager is responsible for distributing the value the (power) measurements to each frequency control device in the distribution system network. Individual signals are expected to be less than 5kByte in size.
Req-S1.2-reliability	The communication should be reliable (99.99%). If the signal is lost, retransmission is required.
Req-S1.2-security	High resilience and security are required. Device identity management

	is crucial to ensure quality of service.

- S1.3 Low Mechanical Inertia, Sf_A, Primary Control, Distributed

In Figure 3-3, the *frequency data manager* is represented by the **red box** shown to the right of the PCC in the DSO grid. The data manager collects all PLL/PMU measurements, rather than just a single value from the PCC busbar, and then the average of the frequency measurements is computed. The data manager sends the resulting signal back to every VSC controller. The control actions are determined locally by the VSC controllers, such actions depend on the frequency signal sent by the frequency data manager. In that sense, the frequency control is *distributed*, as different sub-areas within the distribution network can use their own *average frequency*.

The central DS frequency data manager computes the average frequency of the PLL signals to reduce noise and spikes from the measurements. The frequency data manager then distributes the average value as common signal to each DER.

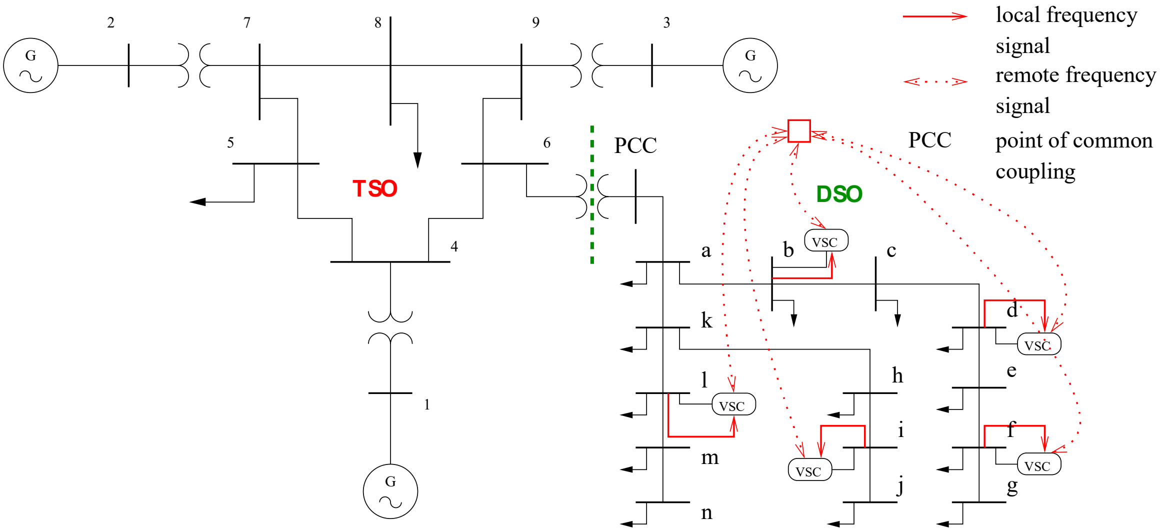

Figure 3-3 Distributed primary frequency control provided by the Distribution system.

Table 3-2 shows ICT communications requirements for Scenario S1.3

Table 3-2 ICT requirements for Scenario S1.3 Low Mechanical Inertia, Sf_A, Primary Control, Distributed

ICT communications requirements	Scenario S1.3 Low Mechanical Inertia, Sf_A, Primary Control, Distributed
Req-S1.3-endPoints	Bidirectional communication takes place between the frequency data manager (located at the Point of Common Coupling (PCC) to the transmission system) and VSC controllers located in the power distribution network. The distance between the end-points is 1 - 5 km. The expected number of VSC controllers is between 10's and 100's of devices.
Req-S1.3-latency	The expected signal transmission link latency between end-points is expected to be 10-20ms.
Req-S1.3-sampleRate	The sampling rate is 50 measurements per second in the uplink to the frequency data manager and 50 distributed control signals per second in the downlink to the VSC controllers.
Req-S1.3-volume	The data manager collects all PLL/PMU measurements (power) from VSC controllers, and then sends the single frequency average signal

	back to every VSC controller. Individual signals are expected to be less than 5kByte in size.
Req-S1.3-reliability	The communications should be reliable. In case of the signal being lost, retransmission is required.
Req-S1.3-security	High resiliency and security are required. Device identity management is crucial to ensure quality of service.

- S1.4 Low Mechanical Inertia, Sf_A, Secondary Control, Centralised

In this scenario, the DSO will participate in the Secondary Frequency Control (2FC) at the transmission system level. This control will be contemporary to the conventional 2FC provided by the automatic generation control by the TSO.

Communication in this scenario is on two levels:

- In the transmission grid, the communication link connects the “secondary frequency controller” in the transmission grid, and the central DSO frequency data manager (red box in Figure 3-4).
- In the distribution grid, the communication link is between the DSO frequency data manager (red box) and the VSC controllers in the Distribution System (shown in Figure 3-4 below).

Note: The “secondary frequency controller” (2FC) is a component of the TSO’s Energy Management System (EMS).

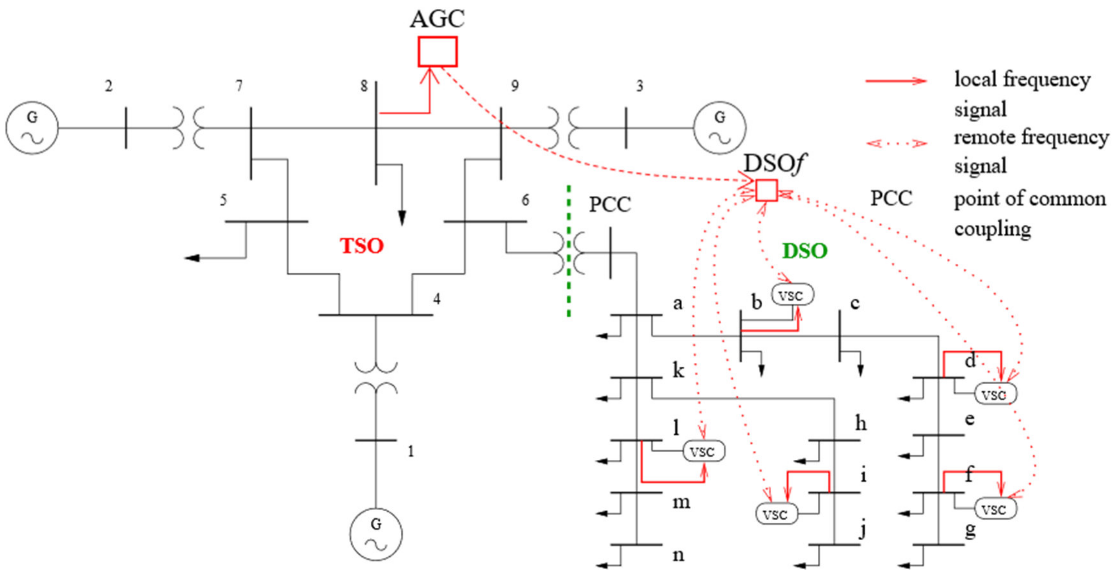

Figure 3-4 Secondary frequency control provided by the Distribution system

Table 3-3 shows ICT communications requirements for Scenario S1.4.

Table 3-3 ICT requirements for Scenario S1.4 Low Mechanical Inertia, Sf_A, Secondary Control, Centralised

ICT communications requirements	Scenario S1.4 Low Mechanical Inertia, Sf_A, Secondary Control, Centralised
Req-S1.4-endPoints	In the transmission grid, the communications link connects the “secondary frequency controller” to the central DSO frequency data manager.

	In the distribution grid, bidirectional communication takes place between the DSO frequency data manager (red box) and the VSC controllers in the Distribution System. The number of VSC controllers is less than 50. The distance between end-points is 1-5km.
Req-S1.4-latency	All the times involving communication between AGC and the VPP controller, as well as for the internal computation and control order, should be smaller than 2 seconds.
Req-S1.4-sampleRate	In the distribution grid, the sampling rate is 2-4 measurements per second and 2-4 control signals per second.
Req-S1.4-volume	The frequency data manager is responsible for gathering the measurements (frequency and power reserve band) from VSC controllers, and then distributing the calculated frequency value to each VSC controller in the distribution system. Individual signals are expected to be less than 5kByte in size.
Req-S1.4-reliability	The communications need to be reliable and lost signals need to be retransmitted.
Req-S1.4-security	High resilience and security are required inside the aggregation. Device identity management is crucial to ensure quality of service.

3.1.1.2 Timescales and preconditions relevant to the commercial scale use of Frequency Control of Distributed Energy Resources in Distribution Networks technique

Network codes and ancillary service need to be regulated and the providers need to be paid appropriately. This can be done within 5 years, but it also could take 10 years. During this work, the following aspects should be considered: measurement equipment (hundreds of thousands of new devices), communications, algorithms running on appropriate platforms, etc.

3.1.1.3 ICT solutions

The systems described in Scenarios 1.2-1.4 need communication connections in the context of the energy system architecture supporting this new model of frequency control to enable its operation.

Many of the communication connections needed, especially those between the older established generation facilities operating within this scenario in the transmission networks will have adequate fixed network connections, provided using fibre optic links or power line communications infrastructure owned by the relevant energy providers. The requirement for new communications links arises in the distribution network because many new devices, requiring communications links, are being added to the power distribution network.

The key issue to the options for using wireless communications as the basis for solutions to the communications requirements within this set of scenarios is the expected **latency** of the system. Latencies of 10-20ms could potentially be provided by an LTE wireless network, but the configuration of the network would need to be checked to enable these low latencies. Such latencies can easily be provided by 5G based wireless networks, which are designed to enable low latency, high reliability connections. Requested communication latencies of this scenario were derived from the tests (D2.6, Appendix A.1.4) on the real-time simulator with the hardware in the loop for the measurement devices and communication systems. The conclusion of the test that, if the overall delay exceeds few tens of milliseconds, the performance of overall system, can be compromised.

The following ICT solutions for Scenarios 1.2-1.4 that are common for several other scenarios are listed here and described in detail in Chapter 4:

- Providing communications links to new end-points in the energy system
- Ensuring End-To-End latency of 10 to 20ms
- Use of communications friendly protocols to maximise the reliability of the communications

- Using Distributed Edge Cloud features to reduce the latency requirements and provide local hosting of algorithms
- Network Slicing for energy provider control of QoS and security features
- Use of public 5G networks without network slicing and public 4G LTE networks
- Use of non-public 4G or 5G networks
- Mobile networks for massive IoT communications

3.1.2 S2 Frequency Makers and Frequency Takers

3.1.2.1 Energy system requirements

This section outlines the ICT requirements for the technical viability of the frequency maker index discussed in Chapter 3 of Deliverables D2.7. This index, which is based on the concept of Rate of Change of Power (RoCoP), is aimed at discriminating between frequency makers versus frequency takers. This approach allows identifying those devices and subsystems that have relevant impact on local frequency variations and, thus, are susceptible to take part in the inertial response, as well as in Rate of Change of Frequency (RoCoF) and primary frequency control of power systems. In particular, applications of the RoCoP include (i) the estimation of local bus frequencies and Synchronous Machine (SM) rotor speeds; (ii) the estimation of the inertia of SMs as well as the equivalent inertia of non-synchronous devices coupled to fast Primary Frequency Control (PFC); (iii) an empirical criterion to differentiate between frequency makers, i.e. devices that have an impact on the frequency at the point of connection based on sufficiently fast and large variations of its active power injection, and frequency takers, i.e. devices that do not have an impact at the local frequency either because they have constant or null power injection, or because such power shows slow and small variations; and (iv) the estimation of the power allocated by a device to regulate the frequency.

The identified ICT requirements are based on results of a case study that considers a real-world dynamic model of the all-island Irish transmission system, which have been presented and discussed in Deliverable D5.7. The model includes 1,479 buses, 1,851 branches, 245 loads, 22 conventional synchronous power plants, and 176 wind power plants.

Based on simulation results, main conclusions and remarks regarding ICT requirements are the following:

- The RoCoP is highly sensitive to fast variations of the frequency signal. Thus, the utility of the index highly depends on the availability of a signal that is as clean as possible, i.e., free of phenomena such as jitter, and other types of signal noise, both external (e.g., electrical disturbances or man-made noise) and internal (such as thermal and/or shot noise).
- Latencies do not prevent the proposed RoCoP index to be accurate. The calculation of the index, in fact, does not need to be in real-time as it is not utilised for control but, rather, for monitoring and a posteriori reward of ancillary services. Since Phasor Measurement Unit (PMU) measurements come with a time stamp and such a time stamp is synchronised with the Global Positioning System (GPS) signal, the evaluation of the index is virtually unaffected by communication delays, packet loss, etc.
- State-of-art PMUs have a sampling rate of up to 120 samples per second which appears adequate for the proposed technique. However, proper techniques to transmit measurement data without saturating the bandwidth need to be thoroughly designed and tested.

Table 3-4 shows ICT communications requirements for Scenario S2.

Table 3-4 ICT requirements for Scenario S2 Frequency Makers and Frequency Takers

ICT communications requirements	Scenario S2 Frequency Makers and Frequency Takers
Req-S2-endPoints	In the order of a few hundred for large grids. Distances are typical of transmission systems (tens-hundreds of kms).
Req-S2-latency	Latency is not an issue. The calculation of the index does not need to be in real-time as it is not utilised for control but, rather, for monitoring

	and a posteriori reward of ancillary services.
Req-S2-sampleRate	PMU sampling rate is 120 measurements per second.
Req-S2-volume	Few measurement signals (2-3 per end-point) are required to be sent to the control/monitoring center (unidirectional).
Req-S2-reliability	High reliability is required to ensure the accuracy of the index.
Req-S2-security	High resiliency and security are required. Device identity management is crucial to ensure quality of service.

3.1.2.2 Timescales and preconditions relevant to the commercial scale use of Frequency makers and Frequency Takers technique

Scenario S2 can be implemented at immediate date. The measurement devices should be installed at the right places and monitored. This could be done within a year. The data processing and communications need to be close to real time. Therefore, computational power and fast communications are needed. Therefore, high computational power and storage capacity, as well as fast communications are required.

3.1.2.3 ICT solutions

The frequency makers and takers need communication connections in the context of the energy system architecture supporting this new model of frequency control to enable its operation. Much of the communication is one directional with packets being sent from the frequency takers to the central control point.

Many of the communication connections needed, especially between the older established generation facilities operating within this scenario will have adequate fixed network connections, provided using fibre optic links or power line communications infrastructure owned by the relevant energy providers.

The following ICT solutions for Scenario 2 that are common for several other scenarios are listed here and described in detail in Chapter 4:

- Providing communications links to new end-points in the energy system
- Use of communications friendly protocols to maximise the reliability of the communications
- Using Distributed Edge Cloud features to reduce the latency requirements and provide local hosting of algorithms
- Network Slicing for energy provider control of QoS and security features
- Use of public 5G networks without network slicing and public 4G LTE networks
- Mobile networks for massive IoT communications

3.1.3 S3 On-line Rotor Speed Estimation

3.1.3.1 Energy system requirements

This section focuses on the ICT requirements for the estimation of the rotor speeds of synchronous machines by means of PMU measurements, concept that is duly presented and discussed in Deliverables D2.6 and D2.7. This estimation, which is aimed at on-line monitoring of electro-mechanical transients and transient stability analysis, falls into the broader concept of Dynamic State Estimation (DSE). DSE is a fundamental tool of energy management systems and control centres of transmission system operators and has become even more important and challenging with the recent development of the smart grid. This, in fact, typically requires faster and system-wider controls than traditional power systems. With the introduction of PMUs, which have a high sampling rate up to 120 measurements per second and accurate synchronization, a fast and accurate DSE is now possible.

In RESERVE, we propose a linear and model-independent rotor-speed estimation problem based on the concept of the Frequency Divider Formula (FDF) [1]-[3]. Model-independent means that generator and load dynamic models and parameters need not to be known. The FDF only requires the bus frequencies measured by PMUs, not voltage and current phasors. The proposed technique is a novel application of the FDF, which, in recent works, has been utilised to estimate bus frequencies [4], and the frequency of the Center of Inertia (CoI) [5].

The proposed estimation technique has been validated by means of simulations based on a case study that considers the dynamic 1,479-bus model of the all-island Irish system described in Section 3.1.2 above and discusses the effect of bad data, noise and latency on the proposed estimation technique.

Based on simulation results, main conclusions and remarks regarding ICT requirements are the following:

- If measurement redundancy is neglected, one only needs a very reduced set of PMU measurements to estimate the rotor speeds of all synchronous machines, even for large systems. For the Irish system, in fact, the minimum set includes 42 PMUs. Bandwidth saturation is thus not considered as an expected issue when using the minimum PMU set. Note: If the traffic is running on public networks, saturation depends on the traffic level locally in the network and on the protocol used in the energy system. Used protocol should not generate unnecessary acknowledgements or bursts of traffic as it is the case with the Generic Object Oriented Substation Events (GOOSE) protocol.
- Bad data can considerably impact on the case without measurement redundancy, in particular if the bad signal is that of the PMU at the machine bus. It is thus required that either
(i) there exists measurement redundancy to increase the robustness of the estimation, thus increasing the risk of bandwidth saturation, or
(ii) ensure the reliability of the signals transmitted at all times. Note that (ii) does not depend only on the communication system involved, but also on the well-functioning of the measurement device itself.
- If no measurement redundancy exists, then the accuracy of the estimation can be compromised in the presence of jitter and/or noise such as that described in Section 3.1.2 above. The communication system must therefore minimize the presence of such phenomena in the transmitted signals.
- Latency can also compromise the accuracy of the estimation. In the simulations, latencies of over 100ms lead to poor estimations of machine rotor speeds in the case where the minimum set of PMUs was used. The latency worsened the impact of the well-known spikes that characterize the PMU measurements in the presence of discontinuous contingencies such as short-circuits or line outages.

Table 3-5 shows ICT communications requirements for Scenario S3.

Table 3-5 ICT requirements for Scenario S3 On-line Rotor Speed Estimation

ICT communications requirements	Scenario S3 On-line Rotor Speed Estimation
Req-S3-endPoints	Less than 100 end-points (PMUs) is expected. Distances are typical of transmission systems (tens-hundreds of kms).
Req-S3-latency	Signal transmission latency between end-points has to be less than 100ms.
Req-S3-sampleRate	PMU sampling rate is 120 measurements per second.
Req-S3-volume	Few measurement signals (2-3 per end-point) are required to be sent to the control/monitoring center (unidirectional).
Req-S3-reliability	Reliable communication is required.
Req-S3-security	High resiliency and security are required. Device identity management is crucial to ensure quality of service.

3.1.3.2 Timescales and preconditions relevant to the commercial scale use of On-line Rotor Speed estimation technique

In Scenario S3, different application is considered but the same conclusions apply as in Scenario S2, i.e., Scenario S3 can be implemented now. The measurement devices should be installed at the right places and monitored. This could be done within a year. The data processing and communications need to be close to real time. Therefore, computational power and fast communications are needed. Therefore, high computational power and storage capacity, as well as fast communications are required.

3.1.3.3 ICT solutions

Although the number of new end-points to be connected in this scenario is low (e.g. 42 PMUs for the all-Island Irish transmission grid), these new end-points will need to be provided with communications links and there may be no existing communications links to the locations of the new end-points.

Meeting latency requirements for packet delivery

For this scenario, signals generated with a frequency of 120 measurements per second imply a required latency of under 10ms if they are to be transmitted in real time to the receiver (control centre operating the algorithm). This level of latency is within the capabilities of a 5G wireless link with a high level of accuracy and reliability in the communications. Such low latencies could not be achieved with LTE or NB-IoT communications features. Once the packets reach a fixed network, such as at the base station which transfer the packets to the mobile backbone transmission network, the determination of the latency in the fixed network connections will depend on the distance travelled and the delays introduction by the processing of packets in mobile and fixed network nodes in the communications path between sender and receiver. The packets are likely to be transferred from the mobile backbone transmission network to the networks of internet providers or communication links providers as part of their communication path to their destination. This delay would need to be investigated for specific solutions in a defined energy system architecture. For frequency control regions spanning hundreds of kilometres, such delays could be relevant.

The following ICT solutions for Scenario 3 that are common for several other scenarios are listed here and described in detail in Chapter 4:

- Providing communications links to new end-points in the energy system
- Use of communications friendly protocols to maximise the reliability of the communications
- Using Distributed Edge Cloud features to reduce the latency requirements and provide local hosting of algorithms
- Network Slicing for energy provider control of QoS and security features
- Use of public 5G networks without network slicing and public 4G LTE networks
- Mobile networks for massive IoT communications

3.1.4 S4 Frequency Control of Grid-Connected Microgrids

3.1.4.1 Energy system requirements

The bulk of papers [6]-[10] discusses the potential impact on frequency control of microgrids (MGs). A detailed summary of such discussions has been provided in deliverable D2.6. Based on simulation results, main conclusions and remarks are the following:

- Without a proper control, MGs can contribute to destabilise the system. In particular, if the MGs only aim at maximizing their revenues, their impact on the system unbalance can be significant [6].
- The effect of the size of the Energy Storage Systems (ESSs) included in the MGs is somewhat counterintuitive. If the MGs aims at maximizing their revenues, then the higher the size of the ESS, the higher is the negative impact on the frequency stability of the system [7][8]. This is consistent as, the higher the capacity of the ESS, the more the MGs are able to “take advantage" of the market, waiting for the right moment to sell energy, i.e., when the electricity price is high, or storing it when the electricity price is low. Small ESSs, on the other hand, makes the MGs more dependent on the system and prone to suffer the stochastic behavior of their renewable energy resources and loads.

- The best approach to control the frequency through the MGs is a fully decentralised control. The work carried out in [9] clearly shows that the Additive Increase Multiplicative Decrease (AIMD) algorithm that has been originally developed for internet connections, is also very effective for MGs. The AIMD approach allow the MGs to both maximize their revenue and provide frequency support to the grid. Interestingly this algorithm works the better the higher the number of the “agents" (the MGs in this case) and, thus, intrinsically, scales very well. Another relevant feature of the AIMD algorithm is that absolutely no communication at all is needed among the MGs and between the MGs and the HV transmission system.
- If an AIMD approach to regulate the frequency is adopted, the impact of the ESSs included in the MGs is higher the higher the capacity of the ESSs themselves [10]. The benefit, however, is not linear and tends to show a saturation. This means that there is an optimal value of the capacity of the ESS beyond which the MicroGrid (MG) does not get any significant additional economical benefit from the ESS. Interestingly, the ESS capacity that is beneficial to the grid in terms of frequency control also saturates, but not at the same value for which it does with respect to the economical benefit for the MGs. This means that MGs might or might not need incentives to install bigger ESS. This depends on several factors, including: network size and topology, loading condition, and number of MGs and conventional generation included in the system.

From the conclusions above, it appears that the implementation of an ad hoc ICT system to communicate among MGs or to connect MGs to the grid is not recommended, at least for what concerns primary frequency control. On the other hand, each MG has to coordinate the devices, namely, renewable generators, storage, load, included within the MG itself. This is done through the Energy Management System (EMS) (see for example [6] and [7]). Typical MGs are relatively small both in terms of energy capacity and spatial dimensions. It is thus auspicious that the EMS is implemented with an efficient and reliable communication system.

S4 ICT communications requirements

Implementation of an ad hoc ICT system to communicate among MGs or to connect MGs to the grid is not recommended, at least for what concerns primary frequency control. On the other hand, each MG has to coordinate the devices, namely, renewable generators, storage, load, included within the MG itself, but it is out of scope of this study.

3.1.4.2 Timescales and preconditions relevant to the commercial scale use of Frequency Control of Grid-Connected Microgrids technique

A fully decentralised, stochastic primary frequency control of MGs can be implemented now. The major requirement is that there is an agreement among the MGs on the implementation of the stochastic control and EMS (e.g., thresholds to enable/disable the control). This could be done within a year. Each MG has to include measurements and an internal communication system to properly coordinate DERs and storage devices. This is assumed to be already in place as per normal operation of the MGs without frequency control. Additional energy storage resources might be needed by MGs to get a full benefit from the electricity market and, at the same time, provide a reliable frequency regulation to the grid. This threshold is network dependent and can be assessed with simulations.

3.1.4.3 ICT solutions

As no communications is required between the MG’s, the focus of communications within this scenario is on the communications within the MG itself to operate its energy management system.

Wireless communications is generally considered to be a beneficial communications solution for MGs as it can be used to easily add new communications end-points to the MG, such as when new energy generation or energy user equipment is added to the network.

Depending on the control algorithm and the physical location of the components of the MG, LTE or NB-IoT communications could provide good solutions, either using private or public networks. If components requiring communications are in very deep basements (more than 2-3 levels below ground, or in rooms with particularly heavy concrete walls, the penetration of the LTE or NB-IoT communications devices may require the deployment of small repeaters, with cabled connections, to ensure reliable communications.

5G networks, public or private, will also provide excellent communications solutions for such MG’s. Repeaters for the indoor use of 5G spectrum will be introduced to the market in coming years ensuring that 5G will operate in deep basements and in buildings hosting critical infrastructures with reinforced walls.

New LTE and 5G based private network solutions, such as the recently launched Ericsson Industry Connect solution, provide cost-effective indoor and limited outdoor communications for use in industrial environments.

3.1.5 S5 Two-level Secondary Frequency Control with Inclusion of Virtual Power Plants

3.1.5.1 Energy system requirements

No changes compared to D2.4. A very reliable communication system is needed for the Energy Management System operating the VPP. This is necessary in order to ensure the Quality of Service.

This scenario is similar to the scenario S1.4 “Low Mechanical Inertia, Sf_A, Secondary Control, Centralised”. The difference is that the VPP’s energy resources are not located in one distribution network, but they can be located geographically dispersed in both the distribution and transmission grids.

The control is performed on two levels. In the first (upper) level, the communication takes place between TSO’s Automatic Generation Controller (AGC) and the control power plants or the VPP controller. One AGC is placed in Load Frequency Block (LFC). One LFC can cover one or several countries. The second (lower, which is faster than the upper one) level exists in the VPPs only; the communication is between the VPP controller and the VPP’s energy resources.

Table 3-6 and

Table 3-7 show ICT communication requirements of the first and second level AGC control in Scenario S5, respectively.

Table 3-6 ICT requirements for the first level AGC control in Scenario S5 Two-level Secondary Frequency Control with Inclusion of Virtual Power Plants

ICT communications requirements	Scenario S5 Two-level Secondary Frequency Control with Inclusion of Virtual Power Plants
Req-S5-AGC-endPoints	Communication is unidirectional from TSO’s AGC to control power plants (either classical power plant like hydro plant or VPP) (those that are connected to the AGC by communication channel). LFC block can cover one or more countries. There are 10s of control power plants. Distance between them is 10s up to 100s kms.
Req-S5-AGC-latency	Latency is not critical requirement in any case what can be derived from the requested sample rate (see Req-S5-AGC-sampleRate).
Req-S5-AGC-sampleRate	Sampling rate of control signal from AGC to control plants is currently 3-5s.
Req-S5-AGC-volume	Data to be sent unidirectionally consists of one variable, which is the power order.
Req-S5-AGC-reliability	Very reliable communication is needed in order to ensure quality of service.
Req-S5-AGC-security	The closed loop operation ensures appropriate security. Stability can be jeopardised only by direct intervention of specialised persons.

Table 3-7 ICT requirements for the second level VPP control in Scenario S5 Two-level Secondary Freqency Control with Inclusion of Virtual Power Plants

ICT communications requirements	Scenario S5 Two-level Secondary Frequency Control with Inclusion of Virtual Power Plants – Second Level VPP Control
Req-S5-VPP-endPoints	Communication is bidirectional between VPP control center and end-points (balancing batteries and individual generation units). There are 100s of end-points. Distance is usually 10's of km, but also can exceed 100km. Communication is bidirectional between VPP control center and end-points (balancing batteries). Distance is usually 10's of km, but also can exceed 100km.
Req-S5-VPP-latency	All the time durations involving communication between AGC and the VPP controller, as well as for the internal computation and control order, should be smaller than 2 seconds.
Req-S5-VPP-sampleRate	Sampling rate of control signal from VPP controller to end-points should be less than the one defined in Req-S5-AGC-sampleRate.
Req-S5-VPP-volume	Data to be sent bidirectionally are: from VPP controller to the regulating energy resources, the variable is the control order; from the regulating energy resources to the VPP controller, the variable is the available power reserve.
Req-S5-VPP-reliability	Very reliable communication is needed in order to ensure quality of service.
Req-S5-VPP-security	Closed system and secured communication between the AGC and the VPP controller ensure appropriate operation.

3.1.5.2 Timescales and preconditions relevant to the commercial scale use of Two-level Secondary Frequency Control with Inclusion of Virtual Power-Plants technique

Scenario 5 can be quickly adopted if the regulator or TSO is open to do it. They need to be open to technical changes. There are no regulations in this field at present, but the concept is well known.

To implement the changes, modified and updated network codes are needed. The network code for storage could come within 2 years. It is being discussed intensively by TSOs. European Network of Transmission System Operators for Electricity (ENTSO-E) Commission has been formed for the battery storage. This is the first step in issuing a new network code. The network codes should be commercial and technical.

Adaptation of the market mechanisms is needed to accommodate VPPs for Frequency control and measurements of quality of service.

As for Scenario S1, this frequency control technique could be implemented within 5 years, but it may take 10 years. It must be assured that control signal is implemented as expected using the measurements. Accordingly, new measurement points and new algorithms are needed.

All energy systems have already measurement devices, but they are not equipped with the communications. However, fast response is not needed for the communications.

3.1.5.3 ICT solutions

As the components of the VPP are geographically widely dispersed, a secure and reliable wide-area communications solution is needed. The backbone of such a wide-area system will be formed by public or private fixed line communications networks. However, the final few kilometres to the end-points requiring communications could well be cost-effectively provided by a wireless network, such as public or private LTE or 5G networks.

The requirements of the Energy Management System used to implement the VPP will determine the choice of wireless networks. If low latency, high reliability communications are needed, 5G will be the clear choice. For less stringent requirements, LTE may offer a good alternative.

The following ICT solutions for Scenarios 5 that are common for several other scenarios are listed here and described in detail in Chapter 4:

- Providing communications links to new end-points in the energy system
- Use of communications friendly protocols to maximise the reliability of the communications
- Network Slicing for energy provider control of QoS and security features
- Use of public 5G networks without network slicing and public 4G LTE networks
- Mobile networks for massive IoT communications

3.2 Scenarios without Mechanical Inertia

The following two scenarios are examples of the frequency control in transmission networks. They study zero mechanical-inertia power systems i.e. grids with no rotating masses, where all power generation is based on renewable energy sources controlled by power converters. Moreover, in these scenarios the Linear Swing Dynamics (LSD) based Virtual Synchronous Generator (VSG) control is used to achieve synchronization, provide virtual inertia and preserve stability in the absence of synchronous machines. The LSD concept is duly presented and discussed in Deliverables D2.3, D2.6 and D2.7.

3.2.1 S6 LSD and Virtual Inertia, Inertial Control, Decentralised Topology

3.2.1.1 Energy system requirements

In this scenario, inertial control and primary control are achieved in a decentralised manner at the transmission level. Similar to S1.1 'Low Mechanical Inertia, Sf_A, Primary Control, De-centralised' means that there is no central unit for gathering the frequency signals from the different converters and the frequency control is carried on independently by the LSD-based VSG at the device level using only local measurements. Therefore, there is no need for any advanced communications network.

In contrast, to S1.1, Scenario S6 considers transmission systems and not distribution systems. In transmission systems, given the long distances and the reliability of measurements, decentralised primary control and decentralised inertial control are deemed to be more meaningful to inhibit de-synchronization and ensure system stability.

However, in distribution systems where measurements are characterised by higher levels of noise and other inaccuracies due to harmonics and unbalances etc., distributed control as described in S1.3 "Low Mechanical Inertia, Sf_A, Primary Control, Distributed" would give better performance.

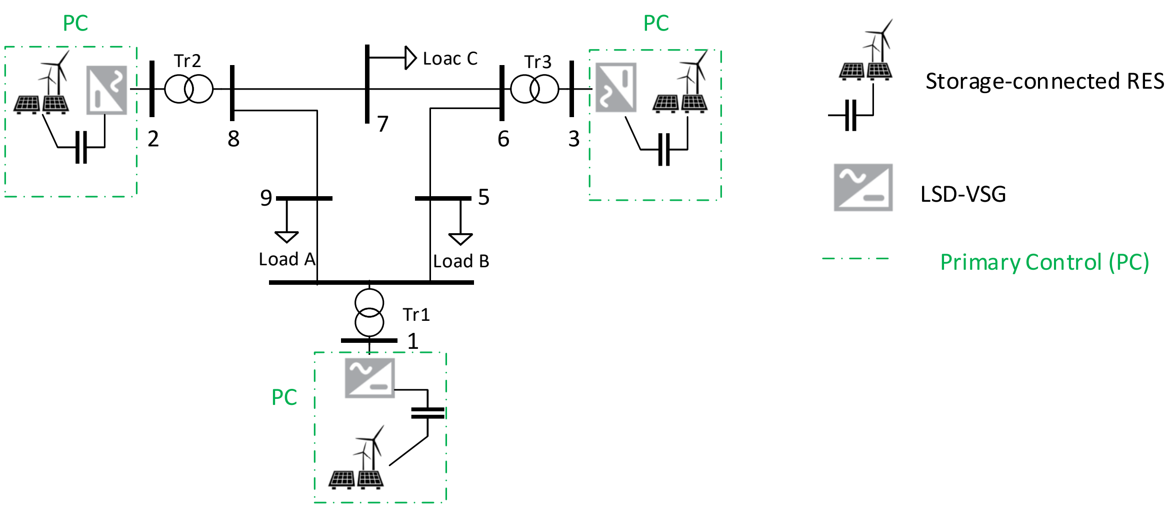

Figure 3-5. LSD-VSG in 9-bus system

S6 ICT communications requirements

In S6, the control is executed in a decentralised manner on the device level. Accordingly, there is no need for communications in this scenario and hence there are no communication requirements.

In distribution networks, in contrast to the system under study, distributed/coordinated primary frequency control would enhance the performance. In such case, 5G network would be used.

3.2.1.2 Timescales and preconditions relevant to the commercial scale use of LSD and Virtual Inertia, Inertial Control, Decentralised Topology technique

Network codes and ancillary service need to be regulated and updated for inertial control provision. Timescale of 5-10 years is possible. As for the LSD concept, it is not yet fully mature for large scale systems and it would require new network codes concerning voltage control and reactive power sharing as mentioned in Deliverable D2.7.

3.2.1.3 ICT Solutions

In Scenario S6, there is no need for communications, and therefore ICT solutions were not provided.

3.2.2 S7 LSD and Virtual Inertia, Secondary Control, Distributed Topology

3.2.2.1 Energy system requirements

The goal of secondary control is to restore the frequency back to the nominal value. Also, restore the power tie-line exchanges among different areas back to their scheduled values. The secondary control is centralised in conventional power systems and usually involves the transmission level. At this level, the communication only takes place between the control center and the resources. Due to the long time frames and the goal of this control, fiber optics and conventional solutions will still be valid for secondary control.

In the wake of the increased integration of inverter based-distributed energy resources, the communication among the new components can be used to enhance the performance of secondary frequency control.

In this scenario the secondary control is carried on in a distributed manner at the transmission system level. As shown in Figure 3-6, neighbouring converters communicate with each other and exchange control signals.

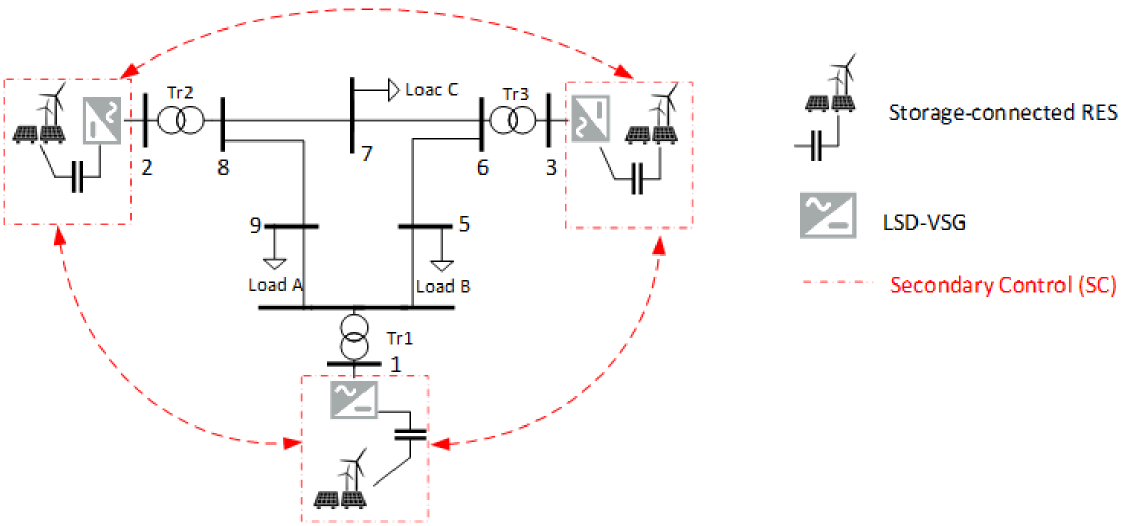

Figure 3-6 Distributed Secondary Control in the 9-bus System

Based on simulation results, presented in Deliverable D2.7, the main conclusions and remarks regarding ICT requirements are the following:

- The results show that the proposed distributed secondary control strategy at transmission network level shows a good performance in restoring the system frequency to the nominal value.
- The distributed secondary control is scalable and only requires sparse communication. Hence, it is more reliable in comparison to the centralised approach.
- The distributed secondary control has shown good robustness and performance under noise as well as communication delays up to 200ms. However, larger delays increase the oscillations in the frequency and could destabilize the system. Hence, fast communication would be needed.
- At transmission network level, due to long geographical distances, fiber optic links would be used for communication. However, the last few kilometres to the end-points, communications could be provided by a wireless network, such LTE or 5G networks, for cost effectiveness.

Table 3-8 shows ICT communications requirements for Scenario S7 LSD and Virtual Inertia, Secondary Control, Distributed Topology.

Table 3-8 ICT requirements for Scenario S7 LSD and Virtual Inertia, Secondary Control, Distributed Topology

ICT communications requirements	Scenario S7 LSD and Virtual Inertia, Secondary Control, Distributed Topology
Req-S7-endPoints	Bidirectional communication will take place between neighbouring power generating units that are geographically distant from each other. It will be few communication end-points.
Req-S7-latency	Signal transmission latency between end-points has to be less than 200ms.
Req-S7-sampleRate	Sampling rate is 50 distributed signals per second.
Req-S7-volume	Data to be sent bidirectionally consisting of one variable between neighbouring converters.
Req-S7-reliability	Very reliable communication is needed.
Req-S7-security	High resiliency and security are required. Device identity management is crucial to ensure quality of service.

3.2.2.2 Timescales and preconditions relevant to the commercial scale use of LSD and Virtual Inertia, Secondary Control, Distributed Topology technique

The distributed secondary control can be implemented today at the scale of microgrids. Network codes concerning energy storage and ancillary services need to be regulated and the providers need to be paid appropriately for providing active power reserves. Moreover, communication links between the units participating in the secondary control need to be provided.

However, the implementation of distributed secondary control at the transmission level, would require a 100% power-electronics driven power system, which is a goal many European countries has set to achieve by 2050 according to the European Commission's 2050 climate plan.

3.2.2.3 ICT solutions

In Scenario S7, the communications will take place among few devices (converters) over a long distance (hundreds of kilometres). The messages will be exchanged sporadically with maximum allowed latency of 200ms. Accordingly, 4G/5G mobile or fixed networks can be utilised.

The following ICT solutions for Scenario 7 that are common for several other scenarios are listed here and described in detail in Chapter 4:

- Providing communications links to new end-points in the energy system
- Reliability of the communications and loss of measurements:

- Use of communications friendly protocols to maximise the reliability of the communications
- Network Slicing for energy provider control of QoS and security features
- Use of public 5G networks without network slicing and public 4G LTE networks
- Mobile networks for massive IoT communications

3.3 Summary of ICT Requirements for Frequency Control

Table 3-9 shows the scenarios for frequency control and their ICT requirements. The most relevant parameters for the scenarios both energy (architecture and time aspects) and communications (end-points, latency, sampling rate, volume, reliability and security) are shown in the table.

Scenarios S4 and S6 do not require communications, and therefore ICT requirements for these scenarios were not shown in the table.

Table 3-9 ICT requirements for frequency control scenarios

Energy Scenarios	**S1**			**S2**	**S3**	**S5**	**S7**
Mapping to scenarios as defined in D2.4	**S1.2 (S2 of D2.4)**	**S1.3 (S3 of D2.4)**	**S1.4 (S4 of D2.4)**	**Not considered in D2.4**	**Not considered in D2.4**	**Not considered in D2.4**	**(S11 of D2.4)**
Architecture	Centralised	Distributed	Centralised	Distributed	Distributed or Centralised	Centralised	Distributed
Time Aspect	Inertial/ Primary	Inertial/ Primary	Secondary	Inertial/ Primary	Inertial/ Primary	Secondary	Secondary
Number of End-Points	<1000	<1000	<50	<1000	<100	<1000	<10
Distances between End-Points	1-5km	1-5km	2-3km	10’s-100’s km	10’s-100’s km	10’s-100’s km	10’s-100’s km
Latency [1)]	10-20ms	10-20ms	1-2s	NA	<100ms	<1000ms	<200ms
Sampling rate [2)]	50 per second	50 per second	1 per second	120 per second	120 per second	1-5 per second	50 per second
Data Volume [3)]	5kByte	5kByte	5kByte	5kByte	5kByte	5kByte	5kByte
Reliability [4)]	High (99.99%)	High (99.99%)	High (99.99%)	High (99.99%)	High (99.99%)	High (99.99%)	High (99.99% to 99.999%)
Security [5)]	High	High	High	High	High	High	High

From the table, it is seen that higher concentration of the devices is foreseen to be used in distribution networks (Scenario S1) than in transmission networks (Scenarios S2-S7). In distribution networks, up to 1000 devices in area of 1-5 km in diameter, whereas in transmission networks up to 1000 devices in areas of 10’s-100’s of kilometers in diameter is foreseen to be used. Requested communication end-to-end latencies in distribution networks are smaller than in transmission network. In Scenario S1, requested unidirectional latency is going down to 10ms. The volume of the transmitted data is relatively small in all scenarios. The message size is foreseen to be maximal 5kByte. Measurement data takes several hundred bits of the overall message size. The rest of the message size is used for the protocols overhead, time stamps, etc. Reliability is a critical requirement in all scenarios. Four-nines availability is requested in majority of the cases meaning that maximal allowed communications system downtime per month is 4 minutes and 23 seconds, or 52 minutes and 36 seconds per year. High communication security is requested in all scenarios.

4. Relationship between 5G ICT Solutions and Frequency Control Scenarios

This section describes 5G ICT solutions for the frequency control scenarios described in the previous section. Relationship between 5G ICT solutions and the frequency control scenarios is indicated in Table 4-1. Note that scenarios S4 and S6 do not require communications and therefore 5G solutions were not provided.

Table 4-1 Relationship between 5G ICT solutions and frequency control scenarios

Energy Scenarios / 5G ICT Solutions	S1	S2	S3	S5	S7
Providing communications links to new end-points in the energy system	X	X	X	X	X
Ensuring End-To-End latency of 10 to 20ms	X				
Use of communications friendly protocols to maximise the reliability of the communications	X	X	X	X	X
Using Edge Cloud features to reduce the latency requirements and provide local hosting of algorithms	X	X	X		
Network Slicing for energy provider control of QoS and security features	X	X	X	X	X
Use of public 5G networks without network slicing and public 4G LTE networks	X	X	X	X	X
Use of non-public 4G or 5G networks	X				
Mobile networks for massive IoT communications	X	X	X	X	X

In further text, 5G solutions listed in Table 4-1 are described in detail.

Providing communications links to new end-points in the energy system

Wireless communications systems, such as 5G, will offer cost-effective and easy to deploy solutions to supply communications over shorter distances to connect individual new assets which are part of the frequency management scenario to fixed networks. In a mobile wireless network, it is normal to have a fibre optic cable connecting each base station and antenna to the backbone of the 5G and general communications transmission system. This means that only the distance between the sending device (communications module or gateway) at the new asset (E.g. a wind turbine) and the nearest 5G base station antenna is actually communications over the air. Once the signal reaches the base station, it is transmitted further within the 5G and other communications networks to the intended receiver over fixed communications links.

Ensuring End-To-End latency of 10 to 20ms

To achieve end-to-end latencies under or equal to 10ms 5G wireless links or fixed cabled connections are very likely to be required as a solution.

Latencies of under 20ms can be achieved by 4th Generation LTE wireless networks. The configuration of the network in the exact locations would have to be investigated to check that the network in question could provide these latencies for each individual link.

Use of communications friendly protocols to maximise the reliability of the communications

The packets to be transmitted are of small size, of the order of magnitude of several hundred kilobits of information. The protocols used by the energy systems should preferably be chosen so that they optimise the efficiency of the use of the wireless communications channel. Examples of commonly used energy protocols which make efficient use of wireless communications channels include Message Queuing Telemetry Transport (MQTT) and Advanced Message Queuing Protocol (AMQP) and other Transport Control Protocol (TCP) based protocols. The use of the Sampled Value protocol is not appropriate as this protocol does not confirm the arrival of packets. Other energy protocols, such as 61850 Generic Object Oriented Substation Events (GOOSE) can generate communications problems as it produces bursts of traffic which can suddenly overload wireless channels and cause delays in transmission.

Using Distributed Edge Cloud features to reduce the latency requirements and provide local hosting of algorithms

In order to reduce the requirements on latency over the wireless link, so that an LTE or slower wireless link could be used, and also potentially, to enable hosting of the frequency calculation algorithm close to the assets, 5G Edge Cloud could be included in the architecture of appropriate communications solutions.

Network Slicing for energy provider control of QoS and security features

Additionally, if the energy provider wants to ensure the quality of service of the communication and the security of the communications on an end to end basis, they could use Network Slicing features of 5G networks to set their own priorities for communications resources reserved for their slice and to use whatever communications security mechanisms they consider appropriate. The 5G networks used could be privately owned by energy providers or could be public 5G networks, or any combination of the two.

Use of public 5G networks without network slicing and public 4G LTE networks

In a public 4G/5G network, the bandwidth available is shared between many users without reservation of network resources resulting in the situation that if there is very heavy traffic load on the network, it is possible that network congestion may result in reduced reliability and increased latency of the communications. Complete loss of individual packets is possible in such rare circumstances.

Use of non-public 4G or 5G networks

A non-public (sometimes also called private) cellular network could be deployed by a DSO or Transmission System Operator (TSO) to provide part or all of the communications links required to use the scenarios defined above. Non-public networks offer the advantage that the owner has complete control of the priorities, security, configuration and access to the network. Public networks can be used to completement the use of no-public wireless networks, for example, enabling single remote locations to be reached by public networks.

Solutions such as the recently introduced **Ericsson Industry Connect** solution[1], based on 5G, provide cost-effective indoor and limited outdoor communications for use in industrial environments and could contribute to communications solutions for this use case if the devices to be connected are located indoors. The solution acts as an indoor repeater enabling 4G and 5G communications to be used indoors in situations where the 4 or 5G signal is too weak to be used without a repeater. This enables a single type of communications network with a single definition of its security and other characteristics to be used for a complete solution giving economy of scale to the operation and maintenance of the communications.

Mobile networks for massive IoT communications

When communication latency is not critical requirement, besides 5G other network technologies for massive IoT type communications can be utilised like: EC-GSM-IoT, LTE-M and NB-IoT. 4G and 3G mobile networks can also be considered if the requirements can be fulfilled in such cases.

[1] See https://wcm.ericsson.net/en/internet-of-things/industry4-0

If components requiring communications are in very deep basements (more than 2-3 levels below ground, or in rooms with particularly heavy concrete walls, the penetration of the LTE or NB-IoT communications devices may require the deployment of small repeaters, with cabled connections, to ensure reliable communications.

5G networks will also provide excellent communications solutions for such scenarios. Repeaters for the indoor use of 5G spectrum will be introduced to the market in coming years ensuring that 5G will operate in deep basements and in buildings hosting critical infrastructures with reinforced walls.

5. Conclusions

Applicability of ICT communication aspects were thoroughly considered through all frequency control scenarios. The following key ICT communications aspects, among many, were identified and considered: number of end-points, communication latency, reliability and security.

Wireless communications systems, such as 4G and 5G, will offer cost-effective and easy to deploy solutions to supply communications over shorter distances to connect individual new assets which are part of the frequency management scenario to fixed networks. The number of devices in the frequency control scenarios that need to be connected is moderate. A higher concentration of the devices that would be used for the frequency control in distribution networks than in transmission networks is foreseen.

Latency of the communication in the frequency control scenarios varies over a wide range. However, in distribution networks the smallest latencies are requested (end-to-end latency of 10-20ms). Nevertheless, the latency smaller than 10ms will improve quality of the frequency control. To achieve end-to-end latencies under or equal to 10ms, 5G wireless links or fixed cabled connections are very likely to be required as a solution. Latencies of under 20ms can be achieved by 4^{th} Generation LTE wireless networks.

In majority of analysed cases excluding those requesting very low latency of 10 to 20ms, wireless networks for critical IoT type communications as EC-GSM-IoT, LTE-M and NB-IoT can be used. These networks have improved outdoor coverage and significantly improved indoor signal penetration to reach deep indoors. Other LPWA network technologies (LoRA, Sigfox) were not considered in this study. Usage of other LPWA network technologies could be the topic for future research. The research should focus on the following aspects: performance, reliability, security, coverage and economics.

Reliability is critical component of the frequency control. 5G brings new features like network slicing and distributed cloud computing ensuring reliable functioning of the frequency control. Private networks that are getting more and more on popularity provide to owner full control over the communication infrastructure including reliability. Furthermore, TCP based protocols like MQTT and AMQP provides reliable data transmission by design.

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9. List of Abbreviations

4G	Fourth Generation Mobile Network Technology
5G	Fifth Generation Mobile Network Technology
AES-CMAC	Advanced Encryption Standard Cipher-based Message Authentication Code
AES-CTR	Advanced Encryption Standard Counter
AGC	Automatic Generation Control
AIMD	Additive Increase Multiplicative Decrease
AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
CAT-M	Category M
CSIG	Constant-Speed Induction Generator
DER	Distributed Energy Resources
DFIG	Doubly-Fed Induction Generator
DMS	Distribution Management System (DSO domain)
DS	Distribution System
DSE	Dynamic State Estimation
DSO	Distribution System Operator
E-UTRAN	Evolved UMTS (Universal Mobile Telecommunication System) Terrestrial
EC-GSM-IoT	Extended Coverage - Global System for Mobile Communications - Internet of
ECIES	Elliptic Curve Integrated Encryption Scheme
EIR	Equipment Identity Register
EMS	Energy Management System (TSO domain)
ENTSO-E	European Network of Transmission System Operators for Electricity
ESS	Energy Storage System
FDF	Frequency Divider Formula
FWA	Fixed Wireless Access
GOOSE	Generic Object Oriented Substation Events
GPS	Global Positioning System
GSMA	GSM (Groupe Spéciale Mobile) Association
HMAC-SHA	Hash-based Message Authentication Code Secure Hashing Algorithm 256-
ICT	Information and Communication Technology
IMSI	International Mobile Subscriber Identity
IoT	Internet of Things
KPI	Key Performance Indicator
LFC	Load Frequency Control block
LPWA	Low Power Wide Area
LSD	Linear Swing Dynamics
LTE	Long-Term Evolution

LTE-M	Long-Term Evolution for Machines
MBB	Mobile BroadBand
MG	MicroGrid
MQTT	Message Queuing Telemetry Transport
MTC	Machine Type Communications
MV	Medium Voltage
NB-IoT	Narrowband Internet of Things
NESAS	Network Equipment Security Assurance Scheme
NR	New Radio
NSA	Non-Stand-Alone
PCC	Point of Common Coupling
PFC	Primary Frequency Control
PLL	Phase-Locked Loop
PMU	Phasor Measurement Units
RES	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
RoCoP	Rate of Change of Power
SA	Stand-Alone
SBA	Service Based Architecture
SCAS	SeCurity Assurance Specifications
SIM	Subscriber Identity Module
SM	Synchronous Machine
SNOW 3G	Word-based synchronous stream cipher with name SNOW
SSAU	Secondary Substation Automation Unit
TCP	Transport Control Protocol
TMSI	Temporary Mobile Subscriber Identity
TSO	Transmission System Operator
URLLC	Ultra-Reliable Low Latency Communications
VNF	Virtual Network Function
VPP	Virtual Power Plant
VSC	Voltage-Sourced Controller
VSG	Virtual Synchronous Generator
WP	Work Package
ZUC	Cryptographic algorithm with name ZUC