FLEXe

Future Energy System

RESEARCH REPORT
NO XX
HELSINKI 2015

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D2.1-2 Smart Grid and Communication Architectures and Plans for Joint Secondary Substation Automation Testbed

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ISBN XXX-XX-XXXX-X
ISSN XXXX-XXXX

CLIC Innovation
Research report no XX

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Preface

This report was done as a part of the Finnish national research project "Flexible Energy Systems" FLEXe, and it was funded by Tekes, the Finnish Funding Agency for Technology and Innovation, and the project partners. The report was written by VTT Technical Research Centre of Finland, Emtele, ABB, Tampere University of Technology and Lappeenranta University of Technology.

For the report, valuable contributions and comments were obtained from Fortum (Marja Englund) and WP2 leader (Jukka Lassila).

Name of the report: D2.1-2 Report on the utilization of 4G and 5G networks in flexible energy

Key words: flexibility, architecture, mobile network, smart grid, secondary substation automation

Summary

Distributed energy generation is one of the main drivers in the evolution of the distribution network from a centralized “passive” grid to a distributed “active” grid. The grid needs to be agile and flexible to respond to various dynamics of future energy systems. It should offer means for more accurate metering and monitoring, higher efficiency, and better load management. One crucial corner stone in flexible energy systems is communications that must be both reliable and secure. The communications should also reflect to different stakeholders’ quality and business requirements.

In this report, we give a short overview to different communications technologies and architecture implementations offered today or proposed for the future grids. According to the literature study and end-users’ feedback, we have compiled a list of requirements for a pilot testbed. Our use case focuses on secondary substation automation taking interaction between energy and communication systems and different stakeholders into consideration. Later, the objective is to apply experimented communication solutions to other types of energy networks belonging to the flexible energy systems.

Our focus is on experimentations and measurements rather than studying theories behind 4G/5G technologies and networks. In this report, we present a joint pilot testbed design to connect three existing testbeds, namely the smart grid testbed in Tampere, communication testbed in Espoo, and (low voltage direct current (LVDC) testbed in Lappeenranta. The goal is to study the performance of 4G networks to support future secondary substation automation by concentrating on reliable and secure communication aspects in remote monitoring and control of energy systems. This is required to enable bidirectional energy and information flow between distributed control centres and distributed energy production, storage, and consumption. The integration of these testbeds is a challenging task. Therefore, integration work is planned to be carried out in four stages, and the performance results and findings will be reported later in form of conference papers.

Espoo, November 2015

CONTENTS

1 Introduction

Large-scale implementation of distributed generation can lead to the evolution of the distribution network from a “passive” (local/limited automation, monitoring, and control) system to an “active” (global/integrated, self-monitoring, semi-automated) system that automatically responds to the various dynamics of the electric grid, resulting in higher efficiency, better load management, and fewer outages. However, distributed generation also poses a challenge for the design, operation, and management of the power grid because the network no longer behaves as it once did. Consequently, the planning and operation of new systems must be approached differently, with a greater amount of attention paid to the challenges of an automated global system [1].

FLEXe program will find out a solution model and concept for flexible energy systems. One crucial corner stone in flexible energy systems is communications that must be reliable and secure, and optimized as to quality and economy requirements (Figure 1).

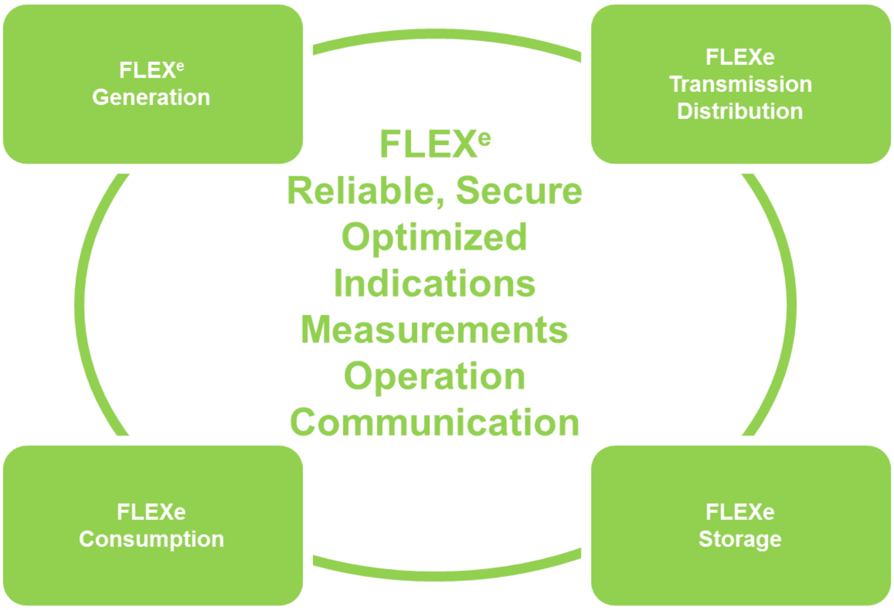

Figure 1. The scope of T2.1.

A strong assumption based on several national and international research results is that the utilization of wireless 4G/5G networks in flexible energy systems will be one good alternative to implement the expected flexibility services.

In this study and report, the focus is on practical issues of applying 4G/5G communications to support flexible energy systems rather than studying theories of 4G/5G technologies and networks, which we leave for the specific standardization bodies and fora.

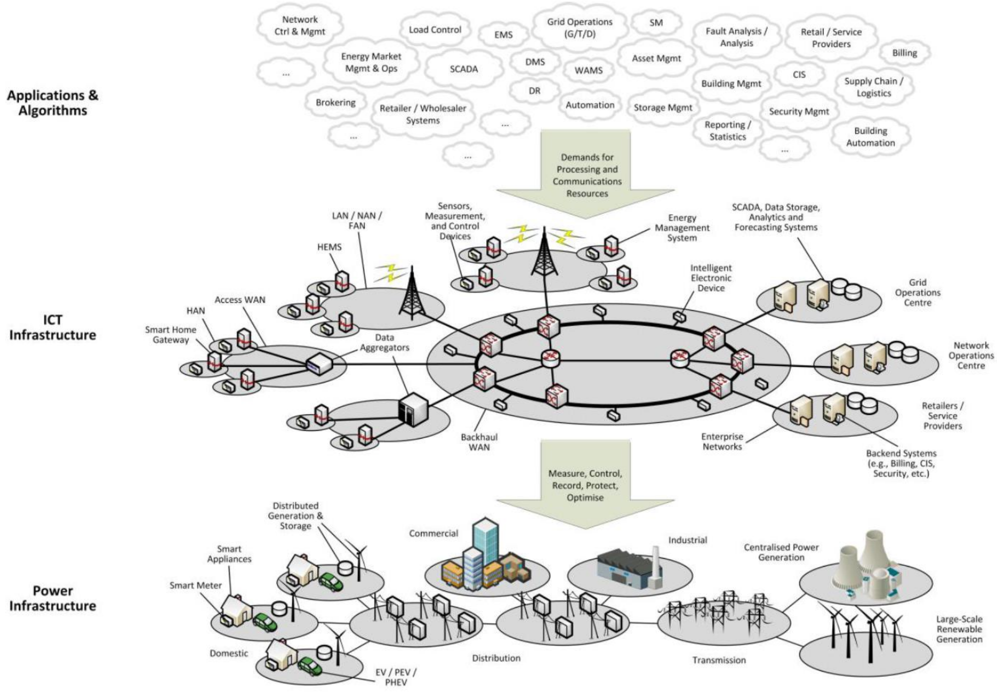

Figure 2. Smart Grid as a system-of-systems [2].

The report is organised in the following manner. Chapters 2 and 3 cover the research goals and focus areas in this report. Chapters 4 and 5 give an overview of existing and forthcoming smart grid and communication architectures and what functionalities they offer to support the secondary substation automation. Chapter 6 concentrates on secondary substation use case and presents how discovered end-user requirements can be fulfilled with existing and forthcoming wireless communication functionalities. The chapter also defines the Proof-of-Concept pilot system that will be used for experimenting and testing developed functionalities. Finally, chapters 7 and 8 conclude and summarise the research results.

Participants of this research were ABB, Emtele, Fortum, Lappeenranta University of Technology (LUT), Tampere University of Technology (TUT), University of Vaasa (UVA), and Technical Research Centre of Finland (VTT).

2 Goal

The goal of our research in task 2.1 is to support the FLEXe program level goals to enable planning and operation of integrated energy networks. This requires novel, high-quality, reliable and secured measurements, telecommunication with consistent level of quality of experience (QoE), data processing.

The task level goals consists of research activities related to sensor and measuring technologies, calibration methods of remote devices and data analysing algorithms, and technical concepts for reliable, high quality and secure measurements including power, voltage and current values, fault detection, protection and control.

This report will concentrate on resilient communication to support secondary substation automation. It is assumed that the same solutions can be applied to other energy systems such as remote heating.

Secondary substation automation was selected due to its importance in flexible energy services. It is possible to have any needed measurement (e.g. energy, current, voltage, and fault) of any electricity network connected major component, energy resource or consumer, through secondary substation.

The communication solution model was studied from the following viewpoints:

- 4G/5G architectures to collect real-time measurement data
- Latency in LTE-networks and find ways to reduce it
- Reliability and quality by using different technologies

The work is done in parallel with cyber security research, whose results are presented in complementary deliverable D2.1-1 (Report on Cyber Security - Requirements for Smart Grid Data Communication).

3 Focus

Our focus is on Smart Grids and 4G/5G networks, since those networks are expected to form a tightly coupled link between communication technologies and energy systems. Communication technology is seen as the central nervous system monitoring, coordinating, and managing activities in the smart grids, whereas the energy distribution technology forms the blood vessels circulating energy through the overall ecosystem and enabling the conversion of natural raw materials into goods and services [3]. Internet of things (IoT) allows us to interconnect households, new renewable power generation options, and external appliances to the energy networks. As a result, the communication and energy flows become bidirectional and end-user's role extends from a consumer to a prosumer.

Interconnecting power and communication networks has been a trend that has been going on for many years. Automated and intelligent network management is seen as a critical component to determine the effectiveness and efficiency of the power systems. The challenge is how to control demand and supply of different power generation options, and distribute it to different types of consumers - people and machines. To meet these requirements, the future power systems (Smart Grids) need to have a variety of new functionalities in terms of digitalization, flexibility, intelligence, resilience, sustainability, and customization [4]. In parallel, we need to develop a fast, reliable and secure communication network to offer Internet of energy (IoE) [4].

The communication network needs to support flexible, time-intensive, and data intensive information exchange for smart grid control and management tasks. The combination of communication and energy networks is essential in creating a fully automated distribution network that ensures two-way electricity and information flow from the power plants down to appliances and all points in between.

The existing 3G/4G communication technologies are not sufficient for fulfilling all the most stringent requirements. Therefore, we need performance measurements in real scenarios to find out what today's networks are capable of fulfilling and what additional is required from the forthcoming 5G networks. 3G/4G networks are not developed for carrying mission critical or massive machine type of traffic or connecting other types of devices than mobile terminals. In 2008, Europe, Asia, and United States started the design of a new generation of worldwide wireless communication systems (5G) that should fulfil speed and reliability requirements. This new mobile communication technology is no longer intended exclusively for human communications. The increasing volume of data and information communicated with and between Things/Machines, which can process information much faster than people can [7]. This new communication technology is also a key for automation needed in future Smart Grids. The defined performance requirements for the future communication system are strict, especially in terms of throughput, latency, reliability, robustness, security and dependability. The potential applications span from traditional voice and video to industrial automation, virtual reality, automated driving, and robotic systems.

Our research focuses on availability, flexibility, quality, and reliability in wireless communications. We will analyse existing 4G and forthcoming communication (5G and sensor network) technologies to see how to utilise them in distributed secondary substation automation. The use case and corresponding components are depicted in Figure 3. The research covers communications for remote control and monitoring of secondary substations including ad-hoc sensor networks, and bidirectional information flow from secondary substations up to the SCADA system. For the research, an integrated energy and communication testbed that will be built in order to obtain concrete performance information. The trials are planned to cover both communication and cyber security aspects within the scope of real-time information exchange to ensure that performance and security aspects are equally taken into consideration.

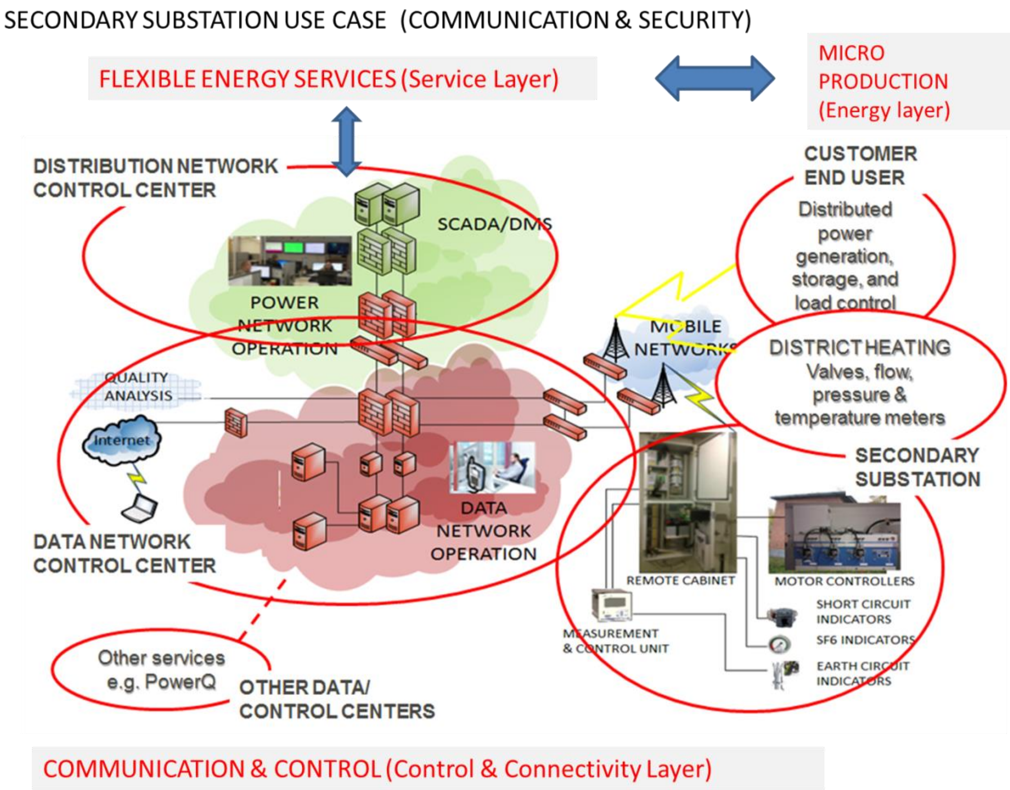

Figure 3. Secondary substation automation use case.

4 Smart Grid architectures

Distribution domain of the smart grid links electricity from Transmission domain to Customer domain of the smart grid. Distribution network includes several elements such as Primary substations, Secondary substations and Control Centre. Traditionally, distribution network management was only based on medium voltage (MV) data without any focus on low voltage (LV) network data. In the smart grid distribution network, role of the LV network data becomes more important because of emerging new application areas such as distributed generation (DG), distributed energy resources (DER), customer automation (DG, demand response (DR) and storage) and electric vehicle (EV) charging. These new topics lead to the new network management model that is called active network management (ANM) in which MV and LV network data is used for dynamic administration of the DERs in the network.

Essential part of the implementation of ANM is distribution automation (DA), which is realized by communication of automation software tools in the control centre with the remote distribution components. The IEC 61850 is now assuming the role of de-facto standard for the DA. Data communication and the interfaces between the automation devices/applications and peripheral devices is implemented using standards such as DLMS/COSEM for smart meters, IEC 61850 MMS messages for intelligent devices and IEC 60870-5-104 for communication of control centre SCADA with remote substations.

Quasi-static information such as the network topologies and network asset information is covered by the common information model (CIM) standard.

Scalability is a critical feature in DA, because of the large number of nodes, substations and DERs. In order to achieve high scalability in DA, a shift is required from the existing centralized automation architecture to the decentralized or distributed automation architecture. Distributed or decentralized architecture requires applying intelligent electronic devices (IEDs) in different parts of the network that work along with substation automation units (SAUs). While there is also some communication with control centre in decentralized architecture, distributed architecture includes only communication between IEDs without control centre intervention.

4.1 Active Network Management

The basic aims of active network management are to enhance the reliability of distribution network equipped with DERs, maintain the power quality in appropriate level and to increase the network hosting capacity that safely operates with DERs. The active network management integrates DERs into the management process instead of connecting them to the network with the "fit and forget" principle. Active network management is based on distribution automation and flexibility services of DERs such as distributed generation, battery storage and micro-grids. Furthermore, the idea of the commercial aggregator collecting DERs data is applied in active network management. Aggregator collects data of small-scale energy resources from multiple customers.

DERs present both challenges and opportunities for grid management. Active network management is obtained with the aid of DA and DERs. DA is applied for monitoring and control of substations (primary and secondary) devices, feeder switching devices and DERs. Direct control and integration of DERs into the distribution network is become possible by the aid of advanced distribution automation, home energy management system (HEMS) and commercial aggregator. HEMS supports advanced information and communication technology (ICT) protocols, and communicates with DERs from one hand and aggregator from other hand. The ANM service computes algorithms for demand side management, power quality measurement and use of controllable energy resources.

The active network management presents new features for the future smart grid:

- Passive management of MV and LV networks.
- Enhancing network monitoring by utilizing smart meter for customer connection point monitoring, remote terminal units (RTUs) in primary and secondary substations and in-field RTUs for filed devices.
- Adding controllability for DERs and LV components.
- Coordination of control actions.

In the active network management, the distribution management system (DMS) at control centre is the centralized place for making control decisions interfacing with the commercial aggregator via market operator. However, new hierarchical automation architecture is required for implementing more effective active network management. This new architecture obtains benefits from coordination of control actions in various distribution network levels. The new architecture can be implemented in decentralized (based on hierarchical system of SAUs) or distributed (based on IED-IED communication) design.

4.2 Distribution Automation Architecture

Currently, centralized automation architecture is utilized in which all the distribution automation decisions are centrally made in the distribution network control centre. However, new approaches in active network management propose distributed intelligence model by shifting simple intelligent functions from control centre to other levels of the distribution network. Electrical utility installs IEDs in primary substation, secondary substation and MV feeders. The installed IEDs communicates with the SAU that is the brain and communication/data hub of the monitoring and control area. Furthermore, the microgrid central controller has interaction with the commercial aggregator for commercial purposes and with utility's SAUs for technical purposes.

4.2.1 Centralized Approach

Figure 4 depicts architecture of the centralized automation in the distribution network.

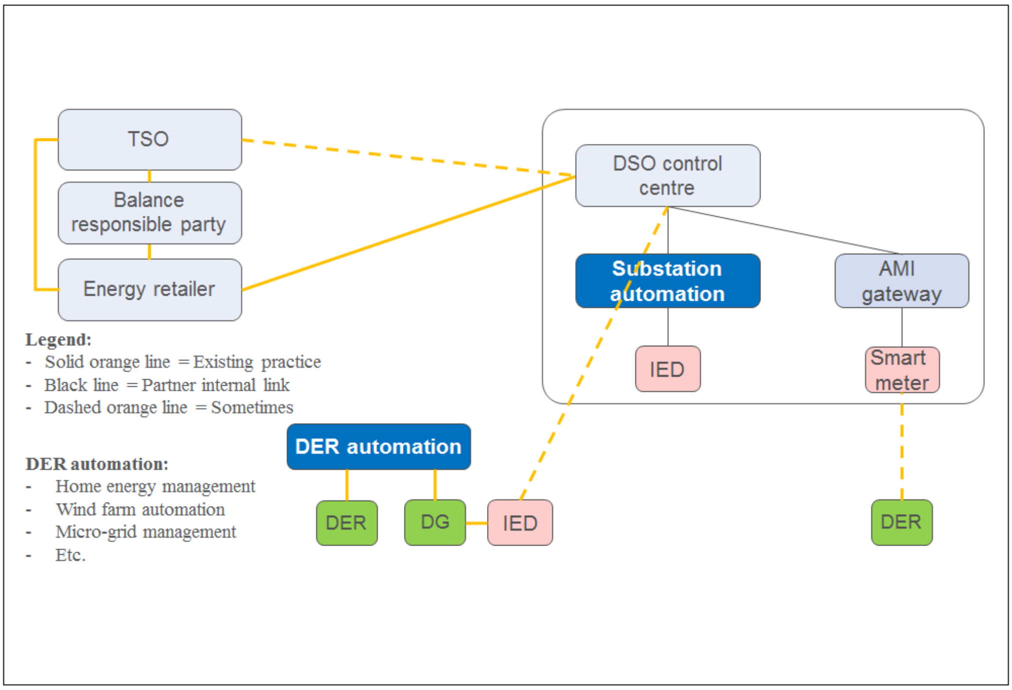

Figure 4. . Centralized automation architecture of today.

In the centralized architecture, IEDs include very simple functionalities for decision making but control center DMS has the main role to manage complex functionalities.

4.2.2 Decentralized Approach

As it was mentioned earlier, scalability is a critical feature in smart grid DA because of the large number of remote substations and customer DERs. The automation architecture must be distributed and modular in order to satisfy the scalability requirements. The control of active distribution network with pervasive monitoring should be designed coherently distributed in which measurements data is also analyzed locally, and remotely coordinated to control over different time horizons and vertical locations within the distribution network in order to harmonize both business and technical decisions.

Decentralization moves the automation system away from “data passing” and close to “know/act here and now”. Decentralization results in iteration of the distribution control/monitoring functions in homologous or complementary manners. In homologous manner, a similar function is replicated in the distribution network levels. For instance, state estimation and forecasting that is distributed to different levels is presented in Figure 5.

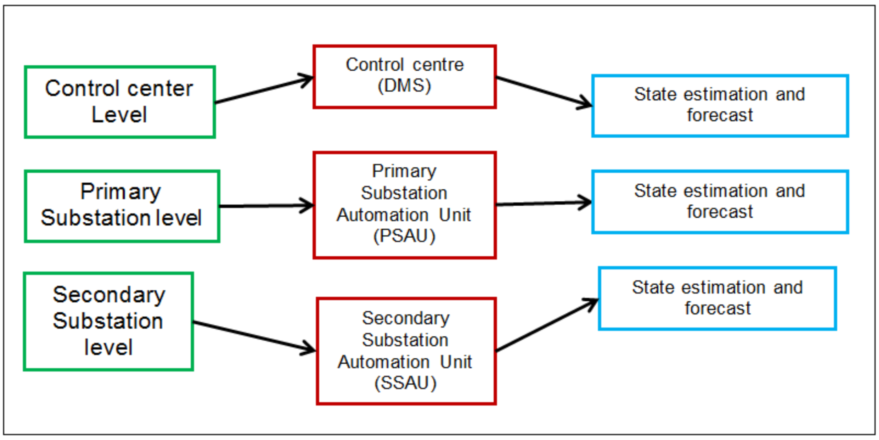

Figure 5. Example of distribution of homologous function.

Additionally, complementary manner such as power control is implemented at all levels i.e. at primary substation, secondary substation and control center levels (Figure 6).

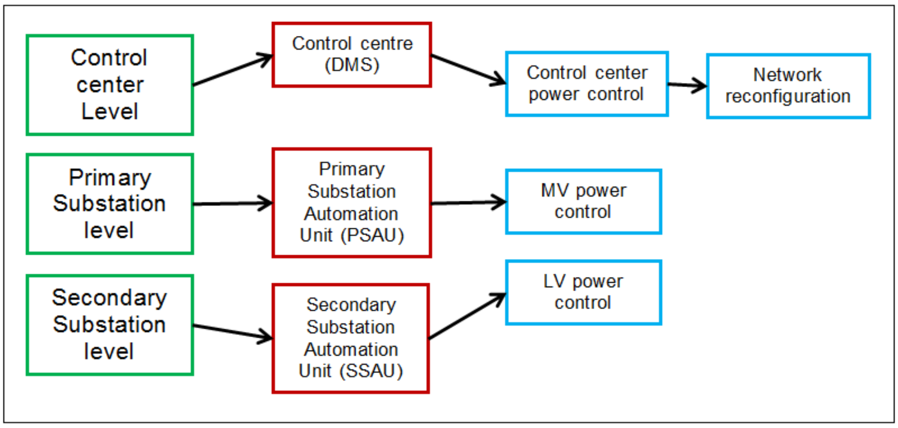

Figure 6. Example of distribution of complementary function.

Distributed data analysis is required in order to decrease the amount of data that is transmitted to the control center. Primary and Secondary substations should be equipped with distributed data storages (for example in SAUs) that locally store and analyze collected data without real-time communication to control center. Figure below displays decentralized architecture of distribution automation.

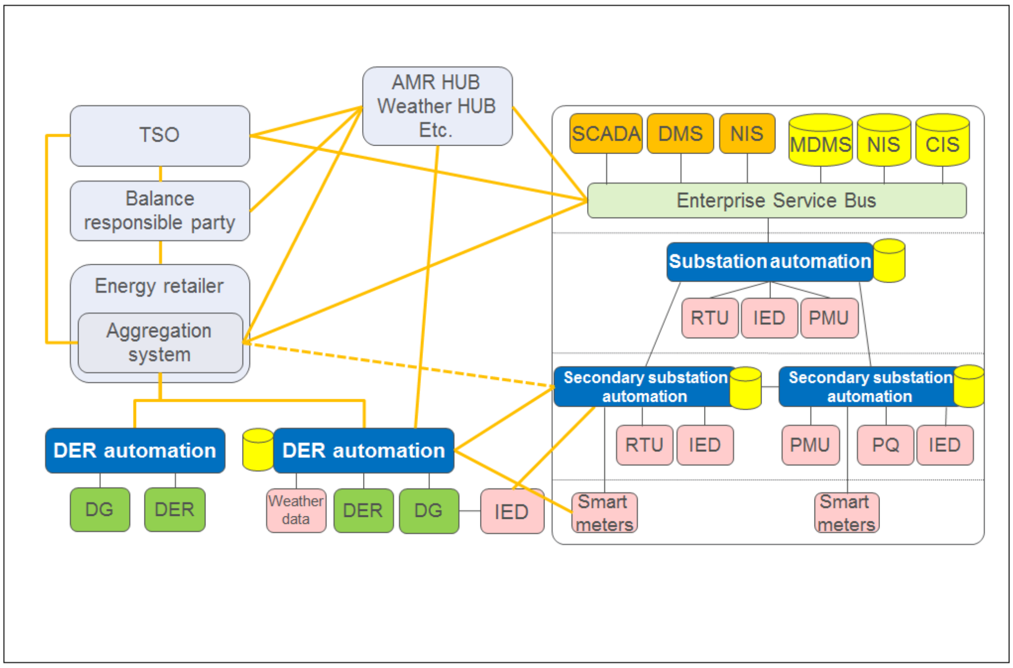

Figure 7. Decentralized automation architecture.

From the actuation point of view, decentralized approach requires IEDs as control units and SAUs to decentralize decision making and shift it from control centre DMS to primary substations, secondary substations and DERs.

4.2.3 DMS/SAU/IED in Decentralized Architecture

In the decentralized architecture [5], intelligent decisions are made in different levels by DMS, SAUs and IEDs. In fact, not all real-time data sent to the control center for making decisions. Instead, only calculated values and alarms are reported to the control center. The following figures (Figure 8 - Figure 10) illustrate characteristics of DMS/SAU/IED in the decentralized architecture.

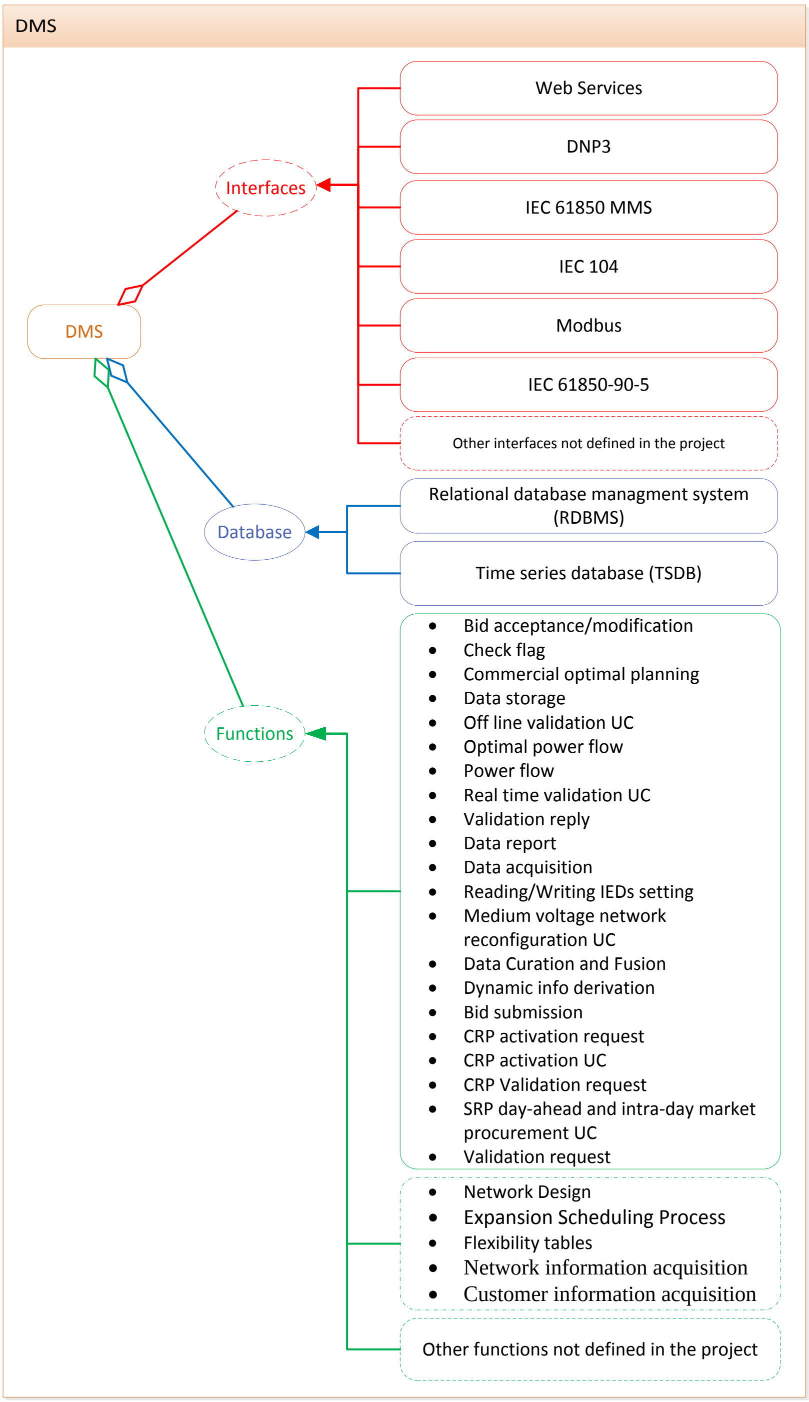

Figure 8. DMS charactristics

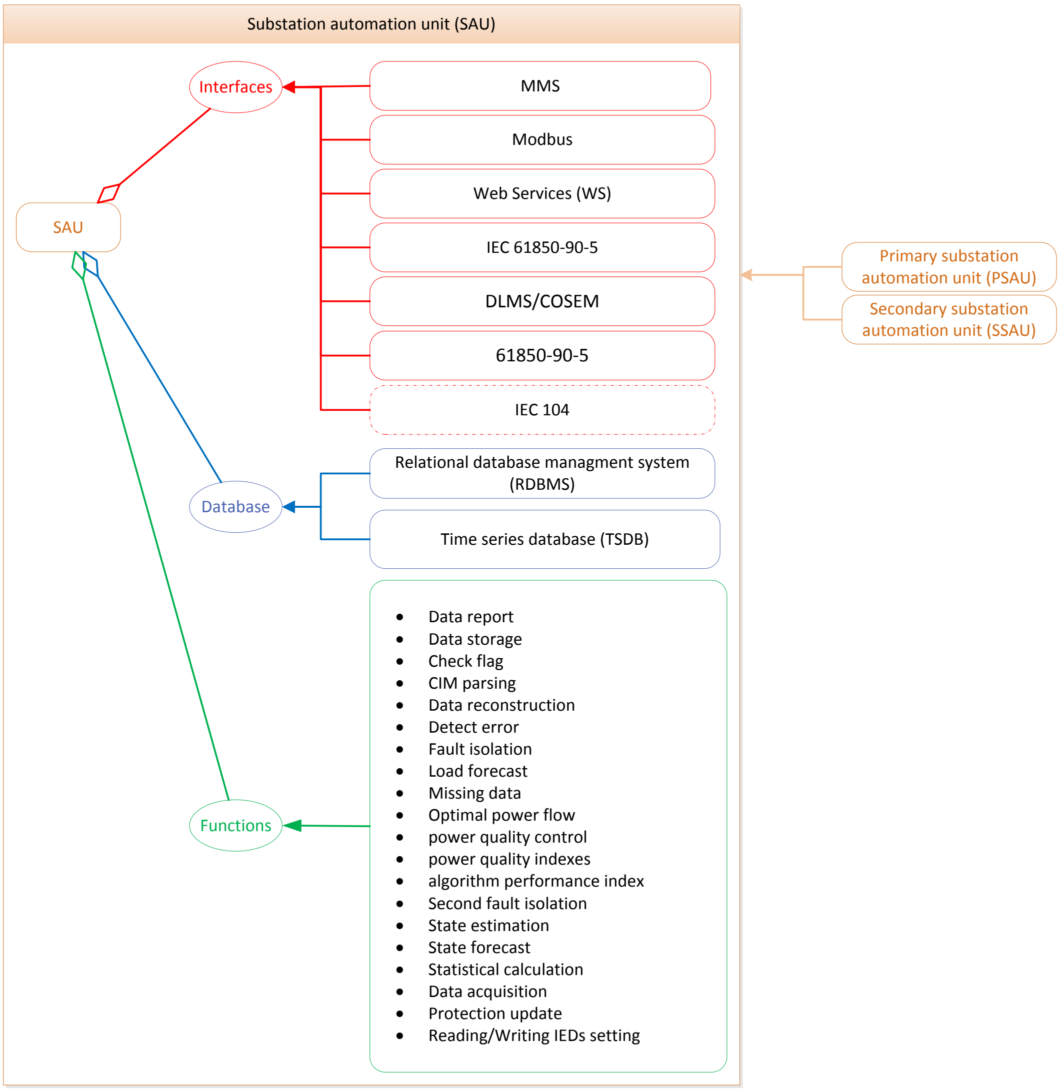

Figure 9. SAU charactristics.

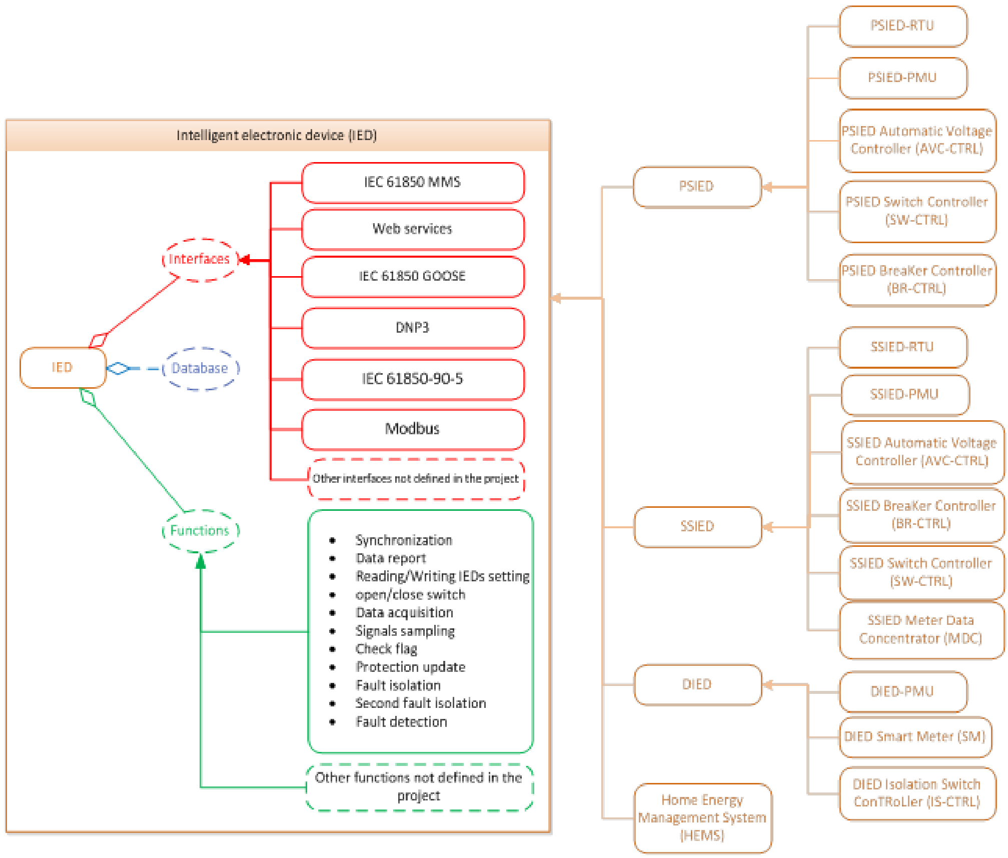

Figure 10. IED charectristics.

4.3 Smart Grid Architecture Model

The Smart Grid Architecture Model (SGAM) framework is a primary importance result of the EU Mandate M/490. The SGAM framework presents graphical demonstration in an architectural way. This framework can be applied for comparing and analyzing of smart grid use cases.

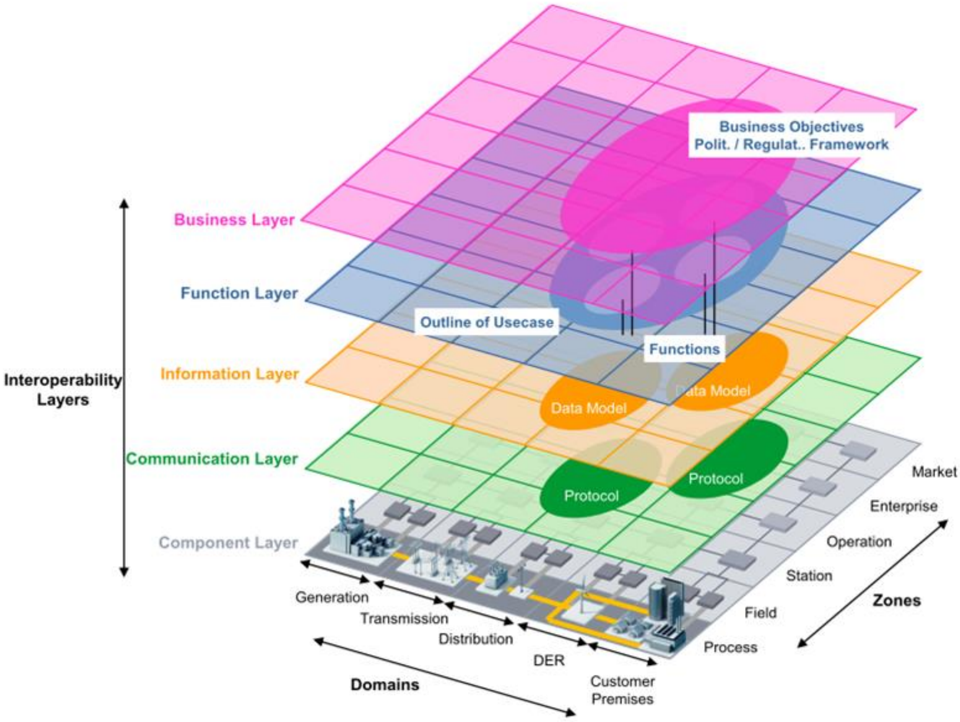

Figure 11. SGAM framework.

The SGAM framework depicted in Figure 11 spans in two dimensions: electrical energy chain and power system management. The electrical energy chain includes Generation, Transmission, Distribution, DER and Customers Premises. The power system management contains Process, Field, Station, Operation, Enterprise and Market. Moreover, the five interoperable layers, i.e. Component, Communication, Information, Function and Business, allow to model both business and technical viewpoints and span on a third dimension. All the use cases within the smart grid distribution network architecture can be constructed with respect to the SGAM framework.

5 Communication Architecture

Advanced metering, DR, and DA M2M applications have different requirements than conventional human-centric applications [10]:

- Some applications have very relaxed latency requirements such as remote meter reading for billing purposes. Other safety or control applications have very strict requirements regarding low latency.
- Some applications require ultra-high communication reliability that is more than today's networks can offer. These applications could be controlling critical parts of electrical grids or industrial process flows.

- Some applications are associated with high volumes of information such as remote video surveillance, while other applications are using very small data payloads like remote metering devices.
- Some applications require very low energy consumption such as battery-powered RTUs or sensors monitoring feeder lines.

In the future, many of these applications will be more cloud based or rely on the content stored in the cloud. Next, we will examine what type of possibilities future communication systems will have. In this short review, we are not limited to MV network automation, but look the system as a whole.

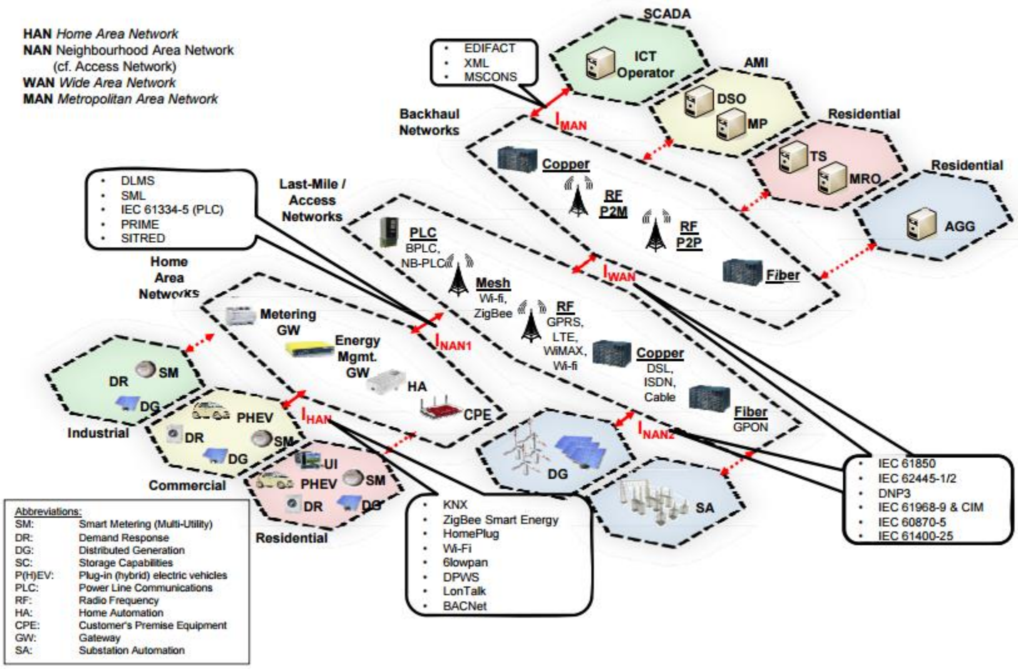

Figure 12. Smart Grid Architecture in Vision 2020 [8].

Mobile communication has a long history. Starting from the 1st generation mobile networks, mobile technology has evolved quickly and offers today versatile broadband mobile services. For example, Global System for Mobile Communications (GSM) aka 2G was primarily developed for voice and circuit switched traffic. As the demand for data services grew, new technologies were added to GSM including e.g. general packet radio service (GPRS) and enhanced data rates for GSM evolution (EDGE).

In the beginning of 1990s, more data services were introduced to universal mobile telecommunications system (UMTS) aka 3G technology. Mobile terminals were designed to support different mobile services and quality of service (QoS) classes: voice, background data, interactive services, streaming, video telephony, short message services (SMS), and multimedia messaging services (MMS). These new services made the system more complex. Later, 3GPP standardization introduced even more technologies e.g. IP multimedia subsystem (IMS), multiple-input and multiple-output (MIMO), high-speed downlink packet access (HSDPA), and high-speed uplink packet access (HSUPA) to enable higher data rates. This added extra overhead in both terminal and network sides.

5.1 4G Networks

Long term evolution (LTE) aka 4G is the most recently deployed technology. In Finland, commercial LTE networks operate in 800 MHz, 1800 MHz, and 2600 MHz frequency bands. In addition to traditional mobile operators, Ukko Mobile offers LTE based mobile services in 450 MHz band. 4G was designed to be simpler than 3G. Its purpose was to speed up broadband mobile services (e.g. video) and deliver better service quality to end-users. The standard promised high bit rates and low end-to-end network delays. The network is all IP based and its architecture is flatter than used in 3G networks. The design does not have any circuit switched components, and all traffic is transmitted through IP packets, even voice.

In LTE, intelligence is distributed among base stations (eNodeB) whereas in GSM and UMTS networks use centralized controllers (radio network controllers (RNCs)). Therefore, a base station can make decisions without consulting with the controller. This shortens the connection setup time and time required for handovers.

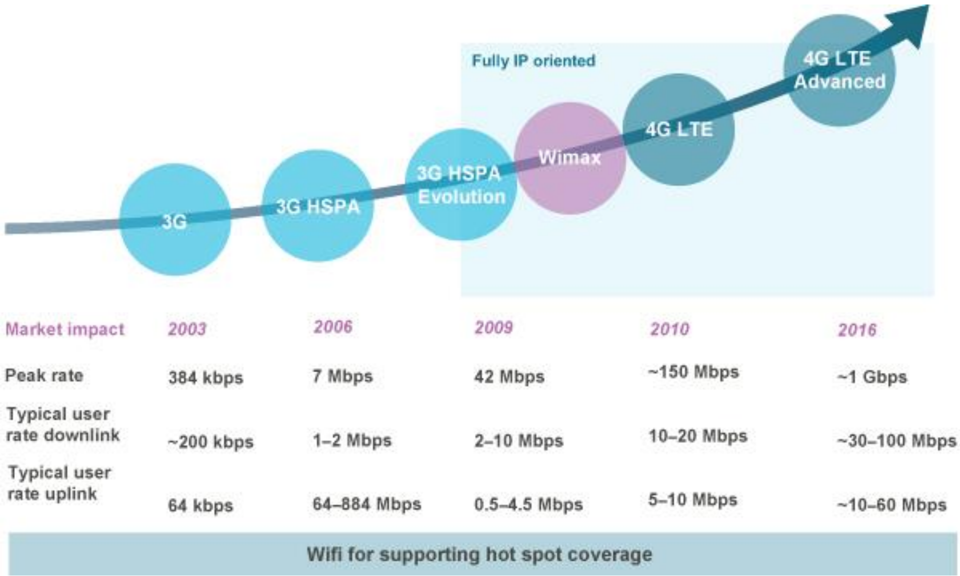

Figure 13. Evolution from 3G towards 4G (source: http://www.3glteinfo.com/lte-vs-hspa-where-is-the-future/).

5.1.1 Flat network architecture

LTE has flat architecture, which is divided into four high level domains: user equipment (UE), evolved-universal terrestrial access network (E-UTRAN), evolved packet core (EPC) network, and services. The architecture is depicted in Figure 14.

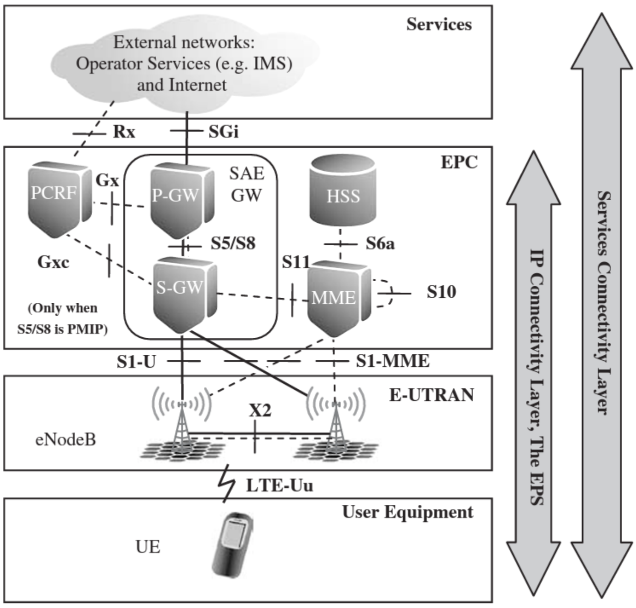

Figure 14. LTE network architecture [11].

E-UTRAN: provides the air-interface between LTE network and user terminal (UE) and constitute the radio access parts of the network. All the radio related protocols for e.g. physical, medium access control (MAC), radio link control (RLC), packet data control protocol (PDCP), radio resource control (RRC) are defined between the UE and E-UTRAN Node B (eNB). The RLC layer provides the reliability services through segmentation and reassembly. The RRC protocol serves to maintain multiple radio bearers services (radio resource management) as well as handle handovers (mobility management) whereas PDCP provides IP header compression service and enables ciphering of data to maintain the integrity of the messages.

Evolved Packet Core Network (EPC): EPC supports E-UTRAN through reduction of network elements, simplification of functionalities which allow seamless connections to other wired and wireless technologies. EPC comprises of multiple logical nodes serving gateway (SGW), packet data network gateway (PGW), mobility management entity (MME), and home subscriber server (HSS). SGW handles routing and forwarding of data packets, which enable mobility of users between eNodeBs and provide compatibility with other 3GPP radio access technologies. PGW is the edge router between an EPC and external packet data networks (PDNs). MME is responsible for mobility management, which tracks the locations of all UEs in its service area, performs authentication for users, and manages subscription profiles of users in the network. HSS is the database server, which maintains records of all subscriber profiles.

Service Domains: The service domain includes various logical nodes, which provide IMS (IP Multimedia Subsystem) or non-IMS based operator services. IMS is an open architectural framework that supports a wide range of IP multimedia services over both private and carrier networks employing both wireless and fixed access technologies.

The 4G technology was designed to support legacy technologies, IMS services, and femtocell networks via well-defined interfaces. These interfaces between network components are shown in Figure 15. 4G/LTE specific network components with short descriptions are presented in Table 1.

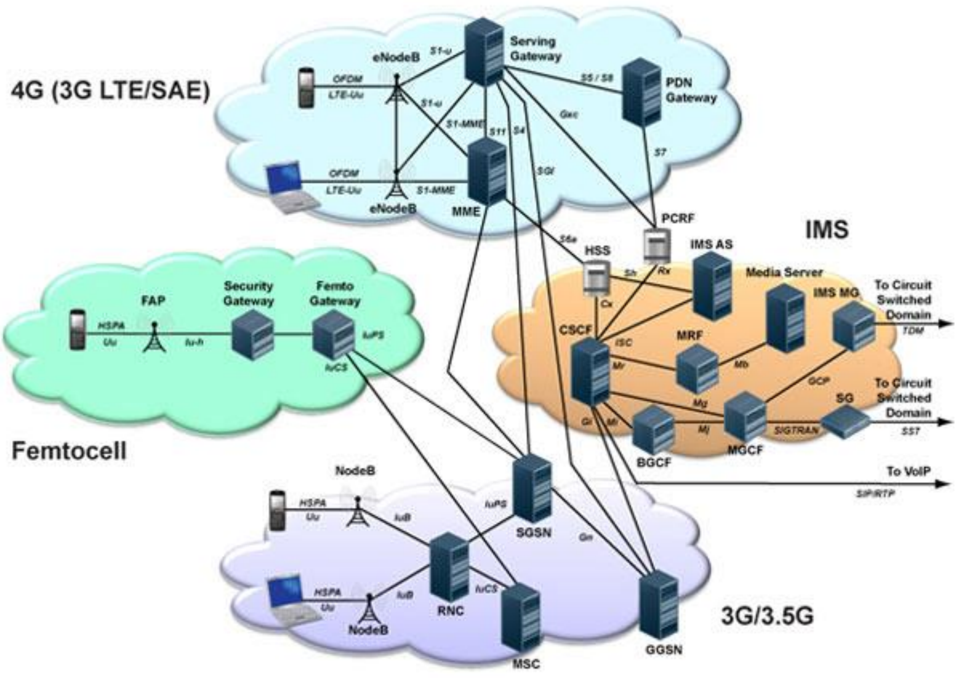

Figure 15. (source: http://www.iphase.com/products/lte_about.cfm)

Table 1. Core 4G network components.

Name	Description
eNodeB or eNB	This is the evolved version of the NodeB (3G) base station, and it is responsible for resource management, scheduling, link adaptation, mobility management, bearer management, error checking, modulation, and demodulation
MME	This is the mobility management entity. MME is responsible for initial user terminal context setup, authentication, initial QoS template management, and location management
HSS	Home subscriber server is responsible for keeping the subscriber profile information, initial QoS templates for initial bearer setup, and location information.
SGW	Serving gateway is handling the user data transmission between eNodeB and PGW. It is responsible to initiate the connection with PGW during the initial UE attachment process. SGW is the mobility anchor for UE.

Name	Description
PGW	Packet data network gateway assigns IP address to the UE, and responsible for bearer establishment, and QoS enforcement with the help of PCRF. PGW receives the QoS information for each bearer from PCRF and enforces these QoS rules in order to make sure that each traffic type is getting its fair share of the network resources.
PCRF	Policy and charging rules function is the QoS database for users. When user connects to the network, specific QoS rules must be applied to the user traffic (bearer). PCRF provides the required QoS profiles via PGW. There are two ways: either PGW requests this information (pull), or PCFR sends the QoS profile to the PGW (push).

5.1.2 Intelligent network management

In telecommunication networks, two key performance indicators are capacity and coverage. In 2G and 3G telecommunication networks, capacity and coverage were almost fixed. Networks were designed to meet particular capacity and coverage targets. Once network was designed, it stayed as it was for a long time. Whenever the coverage or capacity demand increased, mobile operators were forced to deploy more base stations to offer additional radio resources. There were no means to dynamically adjust network capacity or coverage to cope with fluctuating traffic loads and moving subscribers.

In 4G networks, a new concept was introduced called self-organizing networks (SON). This means that base stations are more intelligent and can steer their coverage and capacity based on the changing needs/demand in the network. If demand increases, base station increases its capacity. If more capacity is needed at a particular location, the base station shrinks its coverage to serve those specific locations with more capacity. 4G networks use advanced antenna techniques such as multiple input multiple output (MIMO). A MIMO equipped base station or terminal uses more than one antenna to transmit and receive information over the air. Furthermore, various beamforming techniques can be applied to increase the coverage and to reduce the interference in the specific part of the network.

4G networks are designed to cover large geographical areas. Large mobile operators have thousands of base stations in order to cover their service area. If a group of base stations start changing their configuration based on the changes in coverage or capacity, then this will create a problem to other base stations in close proximity. Consequently, all base stations at a wide area need to collaborate in order to improve the performance of the overall network. For this, base stations are using X2 interface exchange information about current load levels, predicted capacity and coverage levels, etc. Each base station will adjust its configuration to meet the users' demand, and at the same time to minimize the negative impact on the overall network performance. Thus, network optimizes itself to changing traffic conditions.

5.1.3 M2M Communication

Utility companies are looking for communication infrastructure to support remote control, automation, and monitoring. Recent advances (e.g. 3GPP machine type communication (MTC)) in LTE technology have made LTE is a potential candidate for M2M grid communications, sine new features help moving towards low throughput and low latency applications. The new features are depicted in Figure 16.

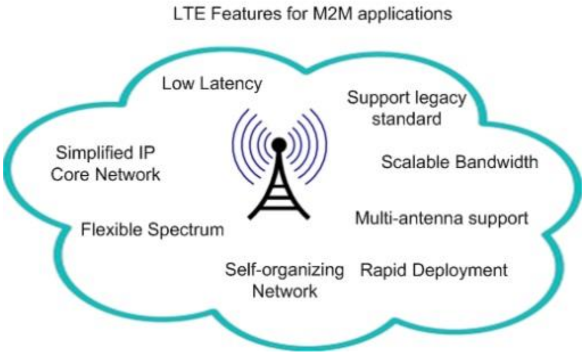

Figure 16. LTE Features for M2M applications,

3GPP uses MTC in LTE to represent machine-to-machine communications, which involves all form of data communication without human intervention. Communicating nodes can be sensors, assets (smart meters, machines, and consumer electronics) or information systems. The complexity of nodes varies from highly mobile vehicles communicating in real-time to simple stationary sensors that sporadically send small amounts of data. M2M networks typically employ Wi-Fi and/or ZigBee, cellular modems (GSM, UMTS, LTE, etc.), or a proprietary network interface to transfer data and control messages between nodes.

Currently, there exist several M2M architecture specifications by different standard development organisations (SDOs). To avoid industry fragmentation, seven SDOs (ARIB, ATIS, CCSA, ETSI, TIA, TTA, TTC have started collaboration to define a common M2M architecture.

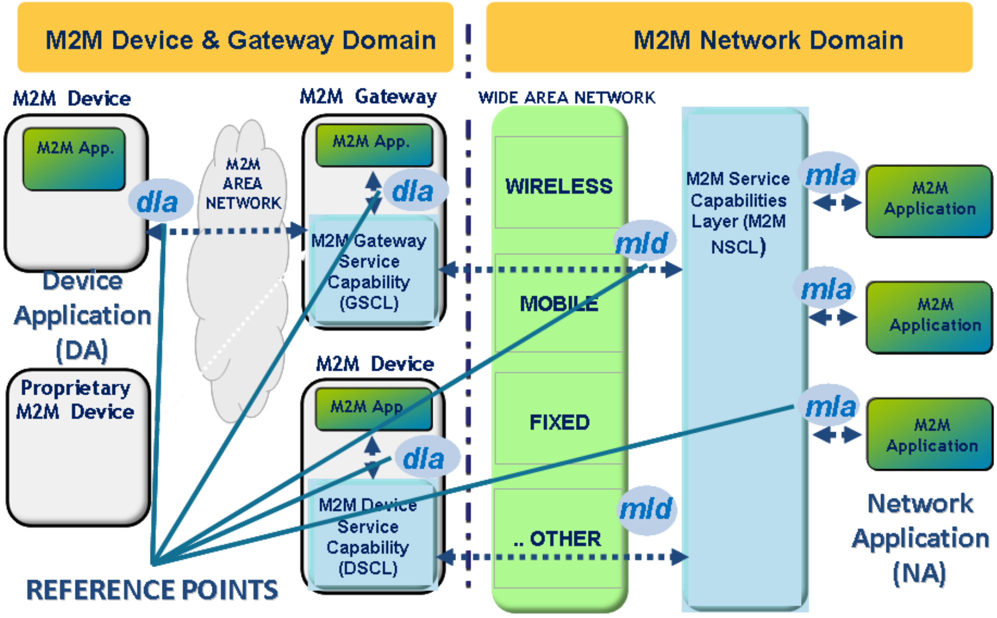

Figure 17. M2M Functional Architecture Overview [12].

In high-level architecture, the system contains Application, Network, and Device domains [12], which all have different responsibilities.

M2M Device domain: it includes M2M area networks, M2M devices, and M2M gateways. M2M area networks provide connectivity between M2M devices and M2M gateways. M2M device can be connected to network domain directly or through a gateway. The M2M device can also provide services to other devices that are hidden from the network domain. The M2M gateway acts as a proxy running authentication, authorization, management, and provisioning functions. A M2M gateway can also run dedicated applications to collect and aggregate information from sensors A M2M device may be connected to the network domain via multiple M2M gateways.

M2M Network domain: it contains access network, core network, and M2M service capabilities. Access network allows the M2M device or gateway to communicate with the core network. Typical access networks are e.g. xDSL, satellite, GERAN, UTRAN, eUTRAN, and WLAN and WiMAX. Core network provides IP connectivity, service and network control functions, interconnections with other networks, and roaming. Core networks (CN) include e.g. 3GPP CN, and 3GPP2 CN technologies. M2M service capabilities provide M2M functions that are shared by different applications. It exposes functions through a set of open interfaces simplifying M2M application development and deployment.

M2M Application domain: it contains M2M applications that run the service logic using M2M Service Capabilities accessible via an open interface. The domain contains also network management functions required to manage access and core networks as well as M2M management functions required to manage M2M Service Capabilities in the network domain.

5.2 5G Networks

5G architecture design addresses six challenges that are not adequately fulfilled with current network deployments. There is need for higher capacity, lower end-to-end latency, massive device connectivity (IoT), reduced operating expenditure (OPEX) and capital expenditure (CAPEX) costs and consistent QoE provisioning.

To overcome these challenges different technology enablers for 5G has proposed. The challenges, enablers, and design principles are depicted in Figure 18.

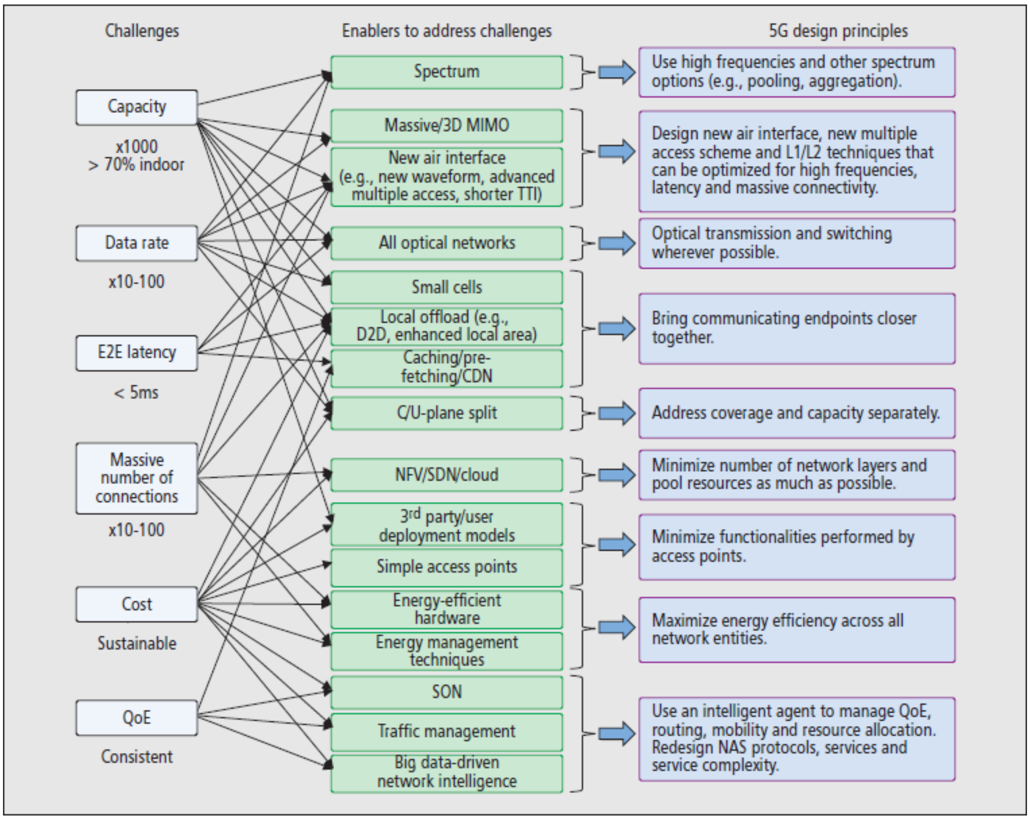

Figure 18. 5G challenges, potential enablers, and design principles [13].

The key elements in the architecture are [13]:

- **Two logical network layers** to split the architecture to radio network that provides only a minimum set of L1/L2 functionalities, and a network cloud that provides all higher layer functionalities.
- **A lean protocol stack** achieved through elimination of redundant functionalities in different protocols and integration of AS and NAS.
- **Deployment of SDN and NFV** Dynamic deployment and scaling of functions in the network cloud through SDN and NFV.

- **C/U plane split** to provisioning coverage and capacity in the RN by use of C/U-plane split architecture and different frequency bands for coverage and capacity.

- **Resource pooling** Relaying and nesting (connecting devices with limited resources non-transparently to the network through one or more devices that have more resources) to support multiple devices, group mobility, and nomadic hotspots.

- **Connectionless and contention-based access** with new waveforms for asynchronous access of massive numbers of MTC devices.

- **Data-driven network intelligence** to optimize network resource usage and planning.

The architecture allows the network cloud to collect user-centric and context-centric information and intelligent algorithms can provide real-time insights for efficient resource management, mobility management, and local offload decisions, QoE management, traffic routing, and context-aware service provisioning e.g. geocasting. The aggregated data could also be used for network planning. By providing application-programming interface to the network cloud, the collected data can be exploited for public (urban planning) and commercial purposes. New business models can be created to information as a service to over-the-top content (OTT) players, which could use this information to improve consistent service quality to end-users.

The challenge is how legacy networks will interface and interoperate with the new network components, and how to determine the optimal physical realisation of network cloud to meet performance and cost targets. Centralisation of resources results in savings from pooling, but can lead to performance bottlenecks, high latency and single points of failure. Centralisation will also need larger processing and transport capacity. The distributing resources lead to performance improvements and reduced latency, but may be costly due to reduced pooling of resources and increased number of data centre locations. Support for local breakouts makes traffic invisible to the network, which affects the intelligent QoE provisioning. Mechanisms to support simultaneous sessions and seamless session mobility across different access networks will also be required to support consistent QoE for end-users.

The network elements and technology enablers are presented in the figure below.

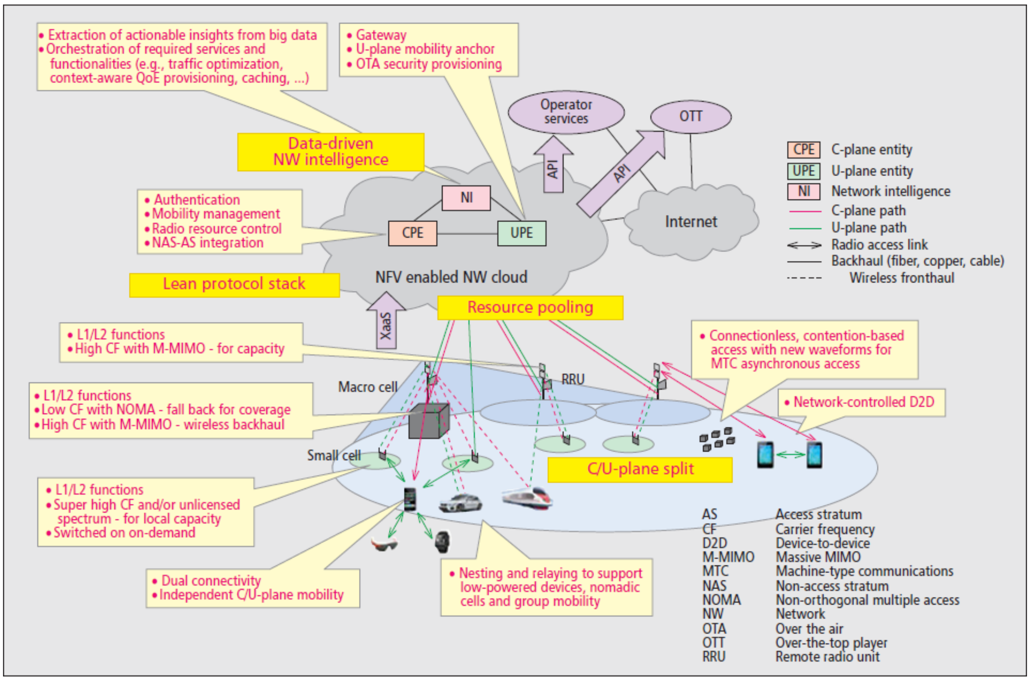

Figure 19. 5G mobile network vision and enablers [13].

5.2.1 Standardisation

Research on 5G has started few years ago and different standard development organisations e.g. 3GPP and International Telecommunication Union (ITU) have strongly driven their ideas for the next generation telecommunication system. Large manufacturers like Nokia, Ericsson, and Huawei have greatly affected to the definition of the 5G architecture. The timeline for the 5G deployment is shown in Figure 20.

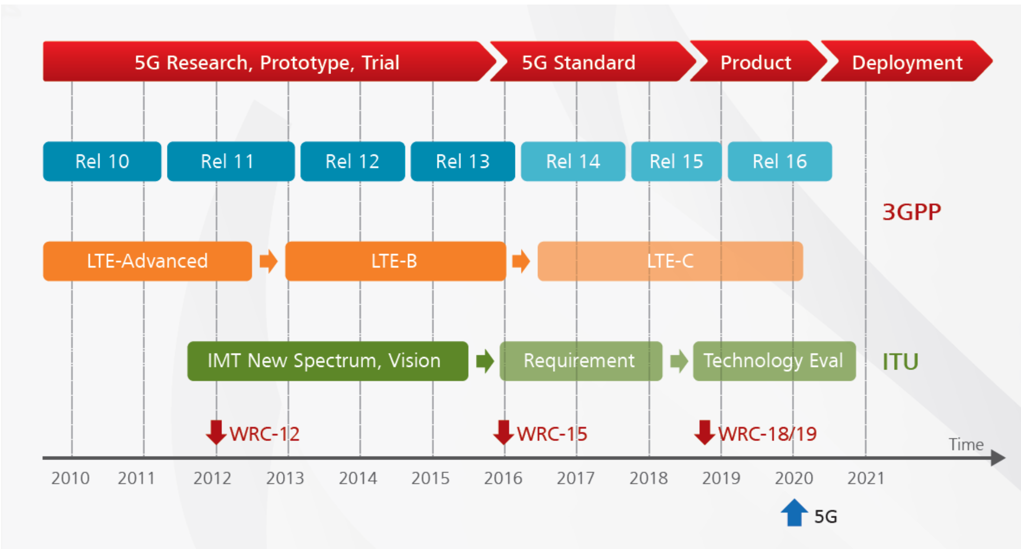

Figure 20. 5G roadmap and timeline [14].

There is a common view that 5G will be a single radio access network (Single RAN) technology that is built upon new radio access technologies and evolved existing ones such as LTE, HSPA, GSM and WLAN [14]. This Single RAN technology will enable operators to simplify their network architecture by operating different radio technologies on a single multi-purpose hardware platform. This platform will exploit both licensed and unlicensed bands. The unlicensed bands are merely used to provide additional capacity in a best effort manner.

Another goal is a unified and programmable infrastructure that should offer a scalable service experience everywhere and anytime. The network should support both human-centric and connected machine-centric networks, since human-centric connected devices are expected to be surpassed between 10- and 1000-fold by communicating machines as the IoT (Internet of things) evolves. Requirements for future applications can be expressed as a 5G HyperService cube depicted in Figure 21. The new services are classified in terms of throughput, latency and number of connections.

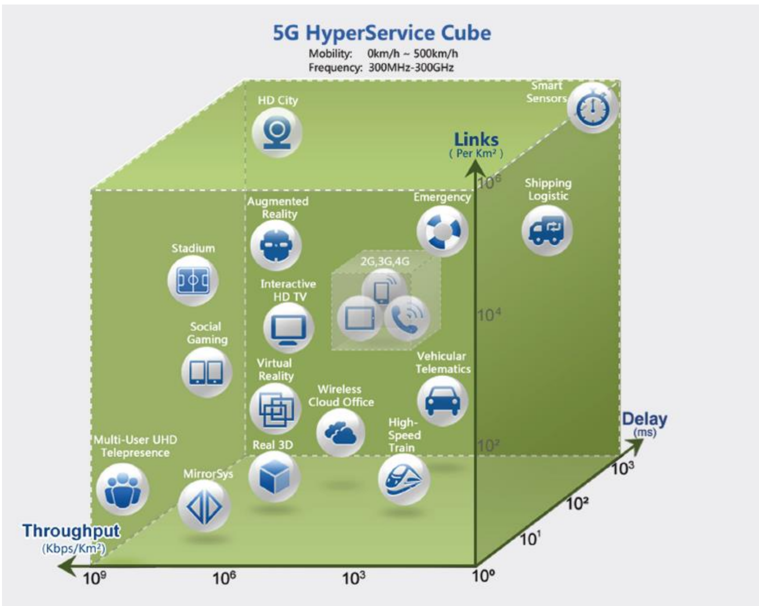

Figure 21. 5G service and scenario requirements [14].

This versatile and partly contradictory demands for new services are associated with end-users' demand for higher capacity, higher data rates, lower end-to-end (E2E) latency, massive device connectivity, reduced CAPEX and OPEX costs, consistent QoE provisioning, and energy efficiency in terminal and base station sides. Expected traffic profiles will greatly vary e.g. high throughput for high-resolution video services, low energy for long–living sensors, and low latency for mission critical services. Although significant improvements have been made in 4G design and implementation, these forthcoming applications consisting of high-resolution video streaming, tactile Internet, expanded IoT, wearable devices, full immersive experience with augmented reality, and vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications will set new requirements that cannot be fulfilled with the evolutionary 4G architecture design. As a result, the 5G architecture design will be revolutionary to make the system extremely flexible and agile to support the diversity of mobile services and new businesses in an efficient and cost-effective manner.

New technologies such as ultra-dense networks (UDN), massive-MIMO (m-MIMO), software-defined networking (SDN), network function virtualisation (NFV), ultra-reliable machine type communication (uMTC), mass machine type communication (mMTC) with new computing and storage solutions will offer the tools for a radical rethinking of the fundamental 5G architecture design. Advanced radio technologies and use of wider spectrum will help to increase the capacity of existing macro cells. To offer high capacity and hyper-connectivity indoors ultra-dense networks (UDN) with small cells are needed. Consequently, the future mobile networks will be heterogeneous networks (HetNets) consisting 10…100x more cells than today's networks. Tera and macro cells will provide wide area coverage and capacity, while smaller micro, pico and femto cells will add high capacity for traffic hot spots and indoor coverage. Applications such as media caching and time-critical cloud services will force data processing and storage to be moved closer to users. For very low latency services and to offload the mobile backhaul, the processing and storage pooling is proposed to be integrated to base station sites.

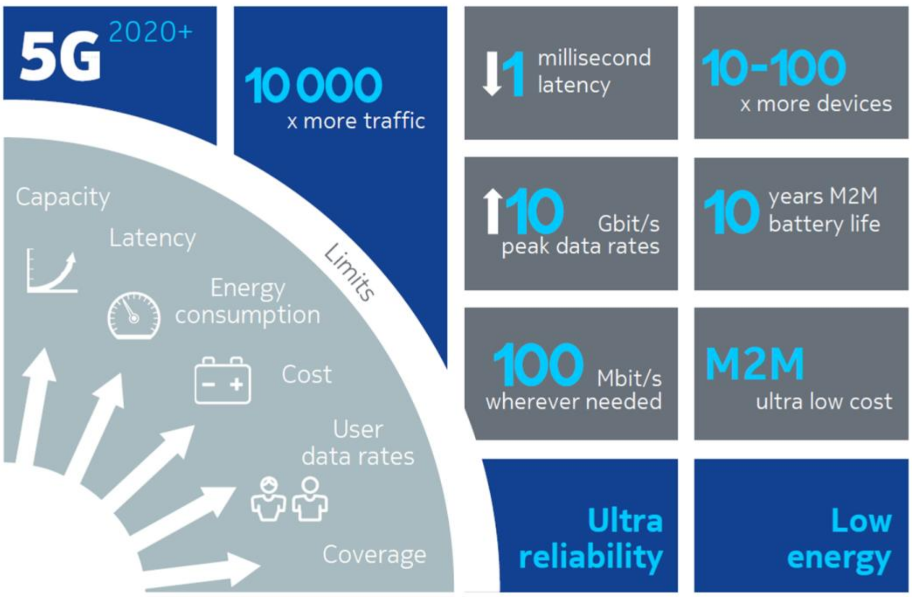

Figure 22. Expectations for 5G technology [15].

5.2.2 Larger and more efficient spectrum

More efficient use of spectrum will be achieved by making base stations and devices to utilize larger and fragmented spectrum. Technologies such as intra- and inter-band carrier aggregation and dynamic spectrum re-farming are essential. Intelligent plug-and-play functionalities will also have significant role in their deployment for both access and backhauling. 5G will have larger spectrum. Re-farming of all 900 and 1800 MHz GSM bands will give additional 220 MHz of spectrum. With the recent 800 MHz and 2600 MHz allocations, the total spectrum can be increased to 600 MHz. By utilising unlicensed 2.4 GHz and 5 GHz bands, the total spectrum can be increased by additional 500 MHz. The disadvantage of using unlicensed bands is the uncertainty due to presence of other devices and services that are not controllable by an operator [16].

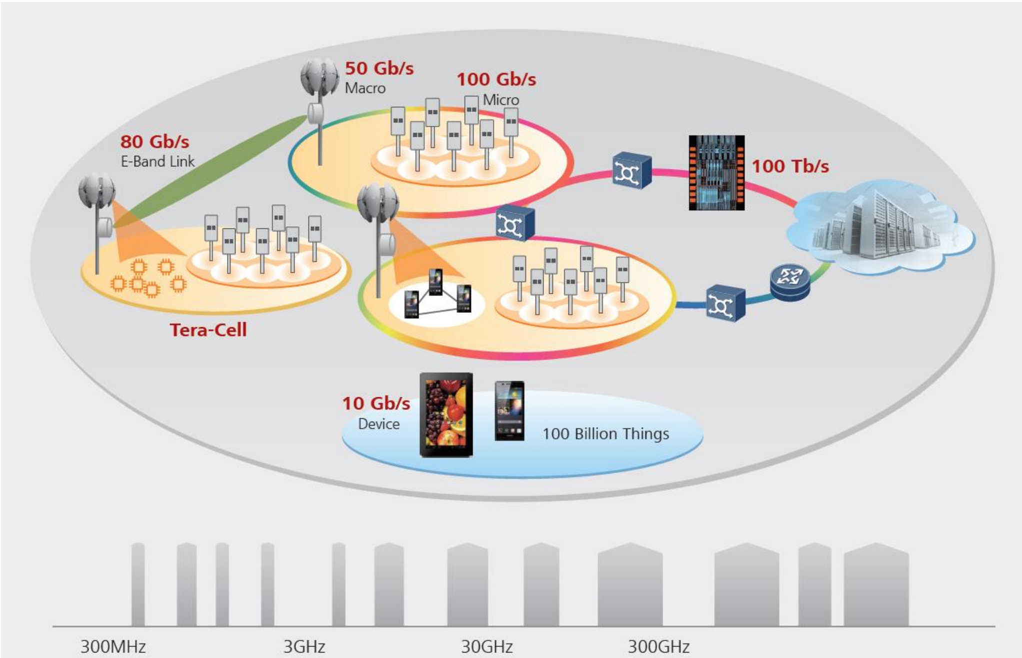

Figure 23. 5G heterogeneous network and broadband spectrum [14].

Better spectrum utilization is designed to be obtained by sharing more bands between network operators, rather than dividing between them. Co-Primary Shared Access models and cognitive radio access procedures enable higher peak data rates as well as higher capacity and coverage. Complementary approach, such as the authorized shared access (ASA) or licensed shared access (LSA), allows fast and flexible sharing of underutilized bands that can't be totally vacated by their primary users [16]. By sharing radio spectrum and radio access infrastructure, mobile operators can reduce their OPEX and CAPEX costs.

More integrated use of time division duplex (TDD) and frequency division duplex (FDD) spectrum assets will also improve the spectrum utilization. FDD based radio access technologies are more popular with traditional mobile operators, who have invested in spectrum, while TDD based technologies are becoming more popular among smaller operators (and non-mobile companies), which have less opportunity to obtain the necessary paired spectrum for FDD. TDD spectrum is often used as a supplement spectrum for FDD configurations, extending either downlink or uplink FDD capacity with available and unused TDD spectrum. Full dimensional and massive MIMO (FD/m-MIMO) with a multitude of small antennas for very fine granular beam steering can be used to reduce the power consumption and provide more dynamic capacity and coverage based on the actual network load.

Enhanced antenna technology will also improve capacity. The future beam forming techniques e.g. massive MIMO systems allow sharply focused pen beams on small spatial regions or individual users. Combination of smart scheduler assigning blocks of spectrum to users every millisecond according to their required QoS and use of multiple spatial paths through coordinated multipoint transmissions (CoMP) can further increase the capacity and reliability of communication links.

5.2.3 Network intelligence

As networks have become more complex, it becomes increasingly difficult to ensure optimal configuration of all network parameters. The future networks need to be self-aware, self-adapting and intelligent. Therefore, future “Cognitive network” aims at automating most of the network tasks. Self-organizing networks (SON) introduced by 3GPP, can be considered as a starting point towards cognitive networks. SON was first focusing only on single or few (radio access) network elements in order to simplify the management of base stations through automated download of configuration parameters, automated optimization of parameters at runtime, and automated recovery procedures in case of failures. In 5G, SON principles are extended to a heterogeneous network environment and to cover also core and transport network parts in order to support e.g. end-to-end traffic steering, load balancing and dynamic allocation of resources where they are needed most. The amount of data to be processed is going to increase dramatically. Big data analytics and artificial intelligence (AI) technologies are seen as core components for future cognitive networks. They are able to interpret rapidly growing amount of data and to perform complex network-optimization tasks even under uncertainty. The high traffic load along the end-to-end path leads to queuing of packets, which increases significantly latency. Application-level QoS differentiation and policy control allow different traffic streams to be treated differently. For example, latency sensitive traffic can take a different path through the network or be prioritized over plain data transfer. Less important data can even be delayed in a case of congestions. Application-level QoS differentiation requires that the network is self-aware in a sense that it has detailed knowledge about its state and used applications. This requires continuous monitoring of network quality and state parameters.

5.2.4 Network virtualization and mobile edge computing

5G will be highly software oriented. Network virtualization aims at decoupling network elements into hardware and software, creating network elements that consist just of applications on top of virtualized IT resources. The hardware will be standard IT hardware, hosted in operators data centres or sourced on-demand from third party cloud service providers. Ultimately, even the gateways and routers in the network could be separated into packet forwarding hardware and software based control logic using SDN architectures. In future, the change of logical network architecture could be done simply by a software update. The integration of SDN and cloud architecture technologies will help to realize this.

The drive forces in 5G networks are network level flexibility, agility, scalability, and service-oriented management. This flexibility can be achieved by upcoming architectural trends like aforementioned network clouds, SDN, NFV, mobile edge computing (MEC), and fog computing (FC) [17]. Network clouds allow resource pooling that reduces overprovisioning and underutilisation of network resources. NFV decouples network functionality from dedicated hardware and promotes software driven implementation of functionality according to a cloud model. SDN decouples control (C) and user (U) data planes of network devices, and provides a logically centralized network view and control. SDN and NFV offer new opportunities for load optimization and resilience by functions re-positioning (e.g. service chaining and/or network slicing) according to network load, service requirements or operational reasons.

New innovation called MEC offers application developers and content providers cloud-computing capabilities and an IT service environment at the edge of the mobile network enabling ultra-low latency, high bandwidth, real-time access to radio network information, and location awareness, which are vital for E2E low latency applications. In addition, associated FC network presents an architecture that uses one or multiple end-user clients or near-user edge devices to carry out storage, communication, computation, and control in a network.

5.2.5 High capacity and hyper connectivity

The mobile data consumption is anticipated to explode due to smart devices (smart phones and tablets), better mobile hardware (improved displays), and better user interface design as well as due to end-users demand for broadband mobile services, and hyper and mass connectivity. Moreover, end-users have multiple devices with different performance to access different types of best effort services. The connectivity is evaluated in terms of how well their applications work regardless of device type, time, or location. For meeting these capacity requirements, a new air interface with shorter transmission interval (TTI) has been proposed to reduce the over-the-air latency to few hundred microseconds. E2E latency can be reduced further by enhancements in higher-layer protocols using context and network-aware admission/congestion control algorithms to replace TCP slow start, bringing communicating endpoints closer (e.g. network controlled D2D and ultra-dense small cell deployments with local breakouts), integrating non-access stratum (NAS) and access stratum (AS) protocols to reduce control signalling, and adding more intelligence at the edge of the networks. The latter can be realized, e.g., through caching and pre-fetching techniques, use of service-dependent location of control plane protocols, and MEC/FC implementations.

Network densification refers to the dense deployment of small cells operating with high carrier frequencies. A split of control (C) and user (U) data among different cells has been proposed to offer coverage and capacity resources independently at critical locations. This allows more U-plane capacity to be provided in critical areas where it is actually needed without the need to provide also co-located C-plane functionalities. For example, macrocells can be used to provide coverage (C+U), and small cells only localized capacity (U). Moreover, simple base stations and remote radio units (RRUs) could be used to perform a minimum set of L1/L2 functions. As a result, these components would also consume less energy. Moreover, in case of time critical services, these base stations or RRUs could be connected to a small nearby data centre whereas in case of no latency critical services, they could be connected to a large one further away. Such flexibility allows operators to deploy different size data centres to meet specific service needs.

5.2.6 Power consumption

The future networks need to support the diversity of devices and service requirements in a scalable and efficient manner. Supporting devices with limited resources (mMTC) such as sensors will require advances in battery and energy harvesting technologies and efficient signalling and data transmission protocols. Contention-based and connectionless access procedures are needed for mMTC applications that only require intermittent connectivity to transmit small packages. In these scenarios, one device could be used as a gateway or rely to aggregate traffic from multiple devices in order to save power and reduce signalling load on the network.

The battery life of devices and seamless experience across multiple devices becomes increasingly important. Especially the IoT adds mass number of new devices to the network. The smaller the cells get and the lower the required RF power, the more power the baseband processing consumes. However, due to the non-homogeneous spatial distribution of traffic in a network, small cells can provide more energy-efficient means to add high capacity in hotspots than large ones. Energy-efficiency of baseband processing can be improved by utilizing centralized-RAN (C-RAN), which pools and shares the baseband processing of multiple sites, allowing more flexible radio resource utilization. The future network can also be taught to be energy-aware through activation and deactivation of parts of the network in response to changing traffic loads. The savings can be significant in those parts of networks where the average utilization of the network is low. Renewable energy sources such as solar power or wind power, and advanced battery technologies or fuel cells will also improve the self-sufficiency of future base stations. These will enable more resilient communication networks to cope with different types of outages.

5.2.7 Operational costs

The future networks cannot generate high OPEX and CAPEX costs to mobile operators. The challenge for the 5G architecture design is that the significant improvements are needed, but end-users are not willing to pay proportionally. Solving the capacity and data rate challenges with network densification would be very expensive in terms of equipment, maintenance, and operations. Therefore, heterogeneous networks using legacy technologies need to be utilised. Energy consumption is a significant OPEX cost. It is estimated that 70 – 80 % of power consumption is from RAN. Therefore, energy-efficient hardware design, low-power backhaul, and intelligent energy management techniques especially in ultra-dense networks dynamically switching small cells on and off can provide significant energy savings without degrading performance. Moreover, use of network clouds is seen as a potential way to reduce OPEX costs. The functionalities in base stations may be reduced by implementing only layers L1 and L2 functionalities and moving higher layer functionalities to a network cloud that services multiple base stations. The resources in data centres can be shifted to support popular application simply by adding additional instances of required software. Spare cloud resources can be lent out when demand is low, whereas additional resource can be rented through infrastructure as a service during peak hours.

5.2.8 Quality of experience

Quality of experience is highly application and user specific and cannot be generalized. Delivering an application with too low QoE leads to user dissatisfaction, whereas too high QoE unnecessarily drains resources on both the user and operator. The challenge is to support applications and services with an optimal and consistent level of QoE anywhere and anytime. Traffic optimisation techniques can be used to meet increasing QoE expectations. Furthermore, installing caches and computing resources at the edge of the network allows operator to place content and services close to the end-users. This can enable very low latency and high QoE for delay-critical interactive services such as high-resolution video, augmented reality, and industrial automation requiring a target of 1 ms E2E latency with high reliability. Big data including sensor information and statistical user data can be used intelligently with such models to assess more precisely the QoE expectations and to determine the optimal resources to use to meet the expected QoE.

5.2.9 METIS architecture

EU funded projects (Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society (METIS)) I and II are defining an overall 5G radio access network design to provide the technical enablers needed for an efficient integration and use of the various 5G technologies and components. The project consortium consists of main players in mobile network market e.g. Ericsson, Nokia, NTT Docomo, Deutsche Telecom, Alcatel Lucent, and Huawei. The project has prepared specifications/recommendations for a 5G RAN design for an optimized support of wireless communication services for industrial, public, and private businesses.

The High-level illustration of METIS 5G multi-facial architecture [18] is depicted in Figure 24.

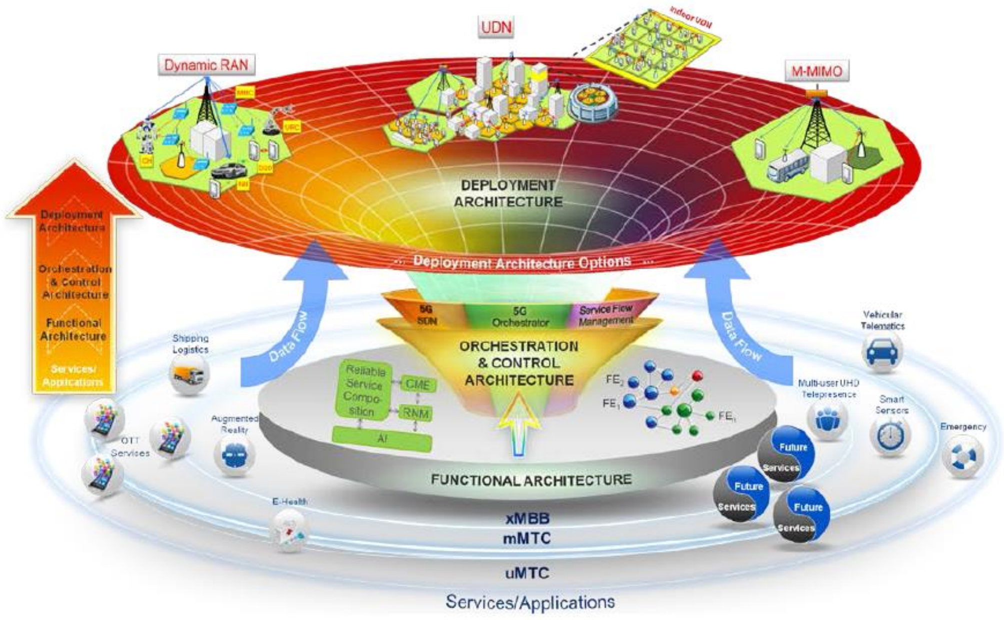

Figure 24. High-level illustration of METIS 5G multi-facial architecture description [18].

METIS proposes improvements in radio access as well as backhaul and fronthaul networks. This requires parallel use of more spectrum, higher spectrum efficiency, network densification, offloading through local area technologies, and integrating various enablers such as small cells (UDN), massive MIMO (m-MIMO), control / user plane (UP) split, NFV and SDN as a part of Dynamic RAN [18]. The design also supports multi-hop connections via fixed or mobile relays (including nomadic nodes) and via other devices, which may e.g. act as a cluster head in a M2M environment or communicate via direct D2D link without incorporation of the network infrastructure. More intelligent network management includes the exploitation of data analytics and big data techniques.

5.2.9.1 Deployment architecture

UDN targets at local ultra-dense deployment of small cells. UDN properties include tight UDN radio node collaboration to support high throughput and low latency, utilization of higher spectrum bands such as mmW, reliance on beam forming, and fast and flexible deployment using wireless backhauling.

m-MIMO provides means to improve spectral efficiency between radio nodes and devices (access) or between radio nodes and the infrastructure (backhaul). Both spatial multiplexing and beam forming are applied.

Dynamic RAN enhances the network's flexibility in terms of adapting its topology to local needs. Demand-driven temporal network densification via nomadic nodes and service provisioning for in-vehicle users via moving relays are two promising enhancements to today's mobile networks. Dynamic RAN uses multiple radio access technology networks to increase resiliency, and it integrates e.g. UDN, nomadic nodes, moving relays, D2D communication, and device duality to enable flexible network deployment to cover the inhomogeneous distribution of traffic demand over time and space. Here, device duality implies that any connected or connectable network element is able to act both as a terminal and as an infrastructure node by temporarily taking over the role of access nodes for other terminals. M-MIMO and UDN are highly complementary. High frequency bands used in UDNs also allow for m-MIMO be used to improve coverage and capacity and mitigate interference by relying on beamforming gains. Dynamic RAN will have a big economic impact, since 5G networks do not have to be designed for peak performance that is only needed for a short period in time.

5.2.9.2 Orchestration and Control Architecture

The service flow management has the responsibility to analyse services and outlining the requirements for data flows of the target services through the network infrastructure. These analyses and requirements are communicated to the 5G Orchestrator and 5G-SDN Controller, which are responsible of realizing the needed functions in the functional deployment architecture. The architecture enables on-demand set-up of customized virtual networks using shared resource pools and allowing effective service-adaptive decoupling of control and data plane in order to optimize routing and mobility management across the whole service transport chain.

5.2.9.3 Services and applications

The extreme mobile broadband (xMBB) services supports the increased traffic volumes and coverage needs foreseen in 5G systems with the aid of dynamic RAN, m-MIMO, and UDN. Improved user QoE in terms of guaranteed minimum data rates and smart content delivery are also considered as part of xMBB functionalities.

mMTC provides connectivity for a large number of devices with constraints in cost and energy consumption. Dual connectivity of terminals to multiple base stations will improve reliability and enable to exploit aggregated spectrum used at different base stations. UDN contributes to required improvements of battery lifetime and m-MIMO to coverage improvements needed for sensors and actuators. In case of highly crowded arrangements, mMTC will support accumulation at group head devices and direct M2M communication.

Ultra-reliable machine type communications (uMTC) addresses the needs for ultra-reliable, time-critical services. For example, V2V and V2I applications require the exchange of information between other vehicles and devices in close proximity with low end-to-end latency and high reliability. As a result, uMTC supports D2D communication for the provision of V2X applications. uMTC will also be applied to the process industry that could use wireless networks to improve operations, product quality, productivity, and reliability. Wireless technology eliminates or mitigates problems associated with wired networks. Advantages of wireless networks are e.g. wear-and tear free data transfer, lower installation and maintenance costs, deployment opportunities in stationary, mobile, and rotating equipment, and fairly reliable communication without expensive connectors.

A wide variety of industrial applications combines uMTC and mMTC requirements by requesting ultra-reliable with the existence of thousands of devices. At the same time, some sensors may require high mobility whereas others are at hidden places where network coverage is difficult to realize. From architectural point of view, these parallel contradictory requirements can only be fulfilled by an extremely scalable and flexible network architecture that adapts available resources to the spatiotemporal requirements. This flexibility will be accomplished by exploiting UDN, m-MIMO, and dynamic RAN.

Industrial uMTC services are associated with periodic data, sporadic data and configuration messages. Periodic data must be delivered within a certain given time (maximum delay and jitter) and with a high reliability and adequate security. Sporadic data, e.g. associated with alarms, must be delivered with a bounded latency (may differ depending on criticality of the alarm). Configuration messages are typically non-real-time having fewer constraints. In general, data packets are short and the bandwidth per node is low. The message order is often more important, since the information about in which order events occur is vital for decision-making applications. The architecture should support mechanisms that ensure delivery in order or single-path routing. The availability of the network is also crucial. Active or passive redundancy measures and multiple paths (where possible) are desirable. At link level, high reliability is necessary. Appropriate measures must be taken to ensure timely packet delivery with (partial) retransmissions or infrequent packet-losses. Appropriate security functions need to be in place, because security, integrity, and authenticity are important in process control applications. Measures against eavesdropping, intrusion detection, and content encryption will strengthen the system.

The traffic coming from machines is topologically and time related. One effective way to tackle the signalling congestion is the context-aware clustering, aka grouping, of machines based on the notion of device duality. There are several approaches. Messages from the MTC devices are accumulated and merged at a selected cluster head before they are relayed to the serving base station (BS). These relays could also be used to support group mobility as all transmissions within the group are aggregated at one or more entities and relayed to the network through wireless backhaul that connects the network to the cloud. The group/cluster head may be selected among a set of available machines or be a dedicated gateway serving as an accumulation point. Another approach of clustering is context-based device grouping and signalling that removes the redundancy in the transmitted messages by either suppressing or compressing the messages with redundant content in a cluster. In this scenario, the cluster head is the one, which has the highest possibility of sending signalling requests when an event occurs within a cluster. Once the message is received from the cluster head, the base station broadcasts the information, and the rest of the machines belonging to the same cluster do not send similar information to avoid redundant messages. The context-based device grouping would also reduce delays in the network.

5.3 Wireless Sensor Networks

Wireless sensor networks (WSN) are infrastructures containing sensing, computing, and communication elements that give the ability to measure, collect, and react to events in a restricted area or space [19]. Possible applications of WSN range from environment sensing, monitoring of structures and smart spaces, emergency response, and remote surveillance. WSNs offer a number of advantages over conventional monitoring systems in terms of quick deployment, high adaptation, and self-configuration, thus reducing the effort required to set up devices and lowering costs of data gathering.

The WSN is defined as a network including any number of:

- source nodes, which generate data, typically sensors measuring specific phenomena,
- sink nodes, which collect the data gathered by source nodes, and
- intermediate nodes that aid the transmission from sources to sinks.

WSN nodes are typically organized in one of three types of network topologies, namely star, tree, or mesh. In a star topology, each node connects directly to a gateway [20]. In a cluster tree network, each node connects to a node higher in the tree and then to a gateway, and data is routed upwards from the lowest node on the tree to a gateway. In a mesh network, mesh enabled nodes are connected to multiple nodes and can pass data through the most suitable path. The mesh link is often referred to as a router.

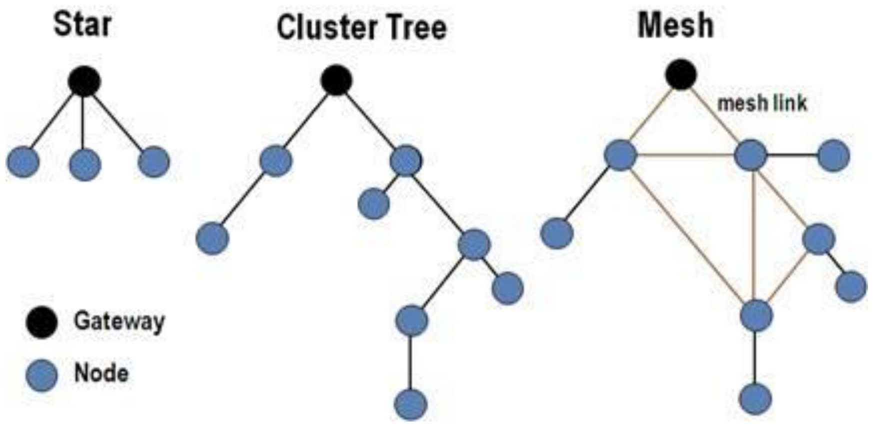

Figure 25. Common WSN Network Topologies [20].

WSN implementation depends on several factors such as deployment type, node mobility, node size, node cost, available energy resources, heterogeneity of nodes, wireless communication technology, network topology, coverage, connectivity, number of nodes, estimated operational time, and quality of service.

The deployment type refers to the method by which nodes are deployed e.g. one time or iteratively replenished. The placement of nodes may be random or specially selected. Topology and architecture specify how sensor nodes are interconnected and routing is organized. Sensor coverage reflects the density of source nodes. In some cases, the sensor coverage may be redundant so that multiple sensors cover the same area in order to increase reliability or the quality of the measurement. The connectivity factor indicates the frequency with which any two nodes communicate. In a connected network, there is always a path between any pair of nodes whereas in an intermittent network, pairs of nodes may be occasionally unconnected. As a special case, the network is said to have a sporadic connectivity when nodes are typically isolated but occasionally come into contact with each other.

WSN applications can be divided into time-driven, event-driven, and query-driven [21]. The classification is based on the network activity. In a time-driven implementation, sensors will transmit their readings periodically. Sampling and communication occurs periodically meaning that the communication times are known beforehand. In an event-driven sensor network, the sensors monitor the area and transmit information only when something meaningful happens. The attempt is to minimize the data traffic and transmission of redundant information. Consequently, scheduled communication protocols are typically used in time-driven and on-demand protocols in event-driven implementations. The last application category is query-driven systems where gathered information is stored locally in the sensor network and specific information is retrieved with queries.

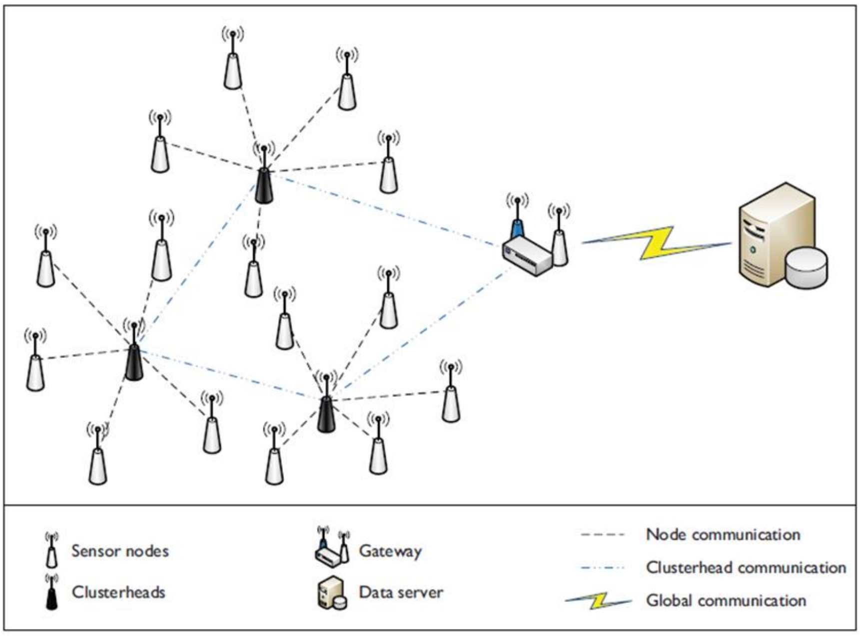

Figure 26. An example of cluster-star topology [22].

Our focus is on WSN architecture used for monitoring a specific region or space in a remote location. A suitable and highly flexible network topology is so called cluster-star. It is a hybrid topology formed from star and mesh network topologies. An example of a network is depicted in Figure 26. In this topology, sensor nodes are divided into normal nodes and clusterheads. Normal nodes are only communicating with their clusterhead whereas clusterheads can also communicate with each other. This structure allows the most of the sensors in the network to be simple, and only a few nodes need to be more intelligent with additional memory and processing capabilities. The communication link between the sensor network and global network is through gateways using licensed or unlicensed radio access technologies. During the first WSN deployments, proprietary radio transceivers were used. They mostly operated around 900 MHz band. Nowadays, most sensor nodes use transceivers according to the 802.15.4 low-rate wireless personal area networks (LR-WPANs) standard and operate in the 2.4 GHz ISM-band, or alternatively use licensed cellular networks.

This cluster-star topology is not perfect. It imposes some disadvantages. The malfunctioning of a clusterhead may affect the sensor network. To mitigate this, sensor nodes initially connected to the malfunctioning clusterhead can be programmed to reconnect automatically to other clusterheads. The problem still exists with border area nodes that are out of the communication range of any other clusterhead. Moreover, a malfunctioning clusterhead may also interrupt data flow from several clusterheads to a gateway. This causes the sub-partitioning of the sensor network. Some of these weaknesses can be overcome by deploying redundancy in communication routes or using backup clusterheads.

Key parameters for sensor networks are sufficient connectivity, coverage, and energy supply. Coverage generally describes the operational area for sensors and connectivity refers to connection with the data sink, rather than the overall connectivity. These two parameters go hand in hand. While coverage certainly is important for gathering sensor data, the connectivity enables the data transmission to the operator. In sensor networks, the energy supply sets additional requirements. Sensor nodes are typically battery powered with limited recharging capabilities. Sensor nodes need to disable their communication whenever possible in order to reduce power consumption. However, waking up in time to receive a packet destined for the node is a fundamental challenge in sensor networks.

Sensor network can be homogeneous or heterogeneous. In homogeneous WSN, all the nodes have same capabilities. The gateway functionality can be implemented in the application level using e.g. a web server. In heterogeneous network, devices that are more capable can be harnessed to carry more of the burden in the network. Those higher capability nodes can be assigned as clusterheads. In heterogeneous sensor networks, each node does not need to be globally addressable. Many wireless sensor applications send only small amounts of data per packet. Sending data without header addressing information significantly reduces the communication overhead and saves energy.

When utilising wireless sensor networks, we need to understand that wireless sensor networks fundamentally differ from traditional IP-based networks in many ways. This needs to be taken into account when applying to energy systems. Main differences between IP-based and sensor networks are presented in the Table 2 [23].

Table 2. Key differences between traditional IP-based networks and large scale wireless sensor networks [21].

Properties	Traditional IP-based networks	Large scale wireless sensor networks
Network mode	Application independent	Application specific
Routing paradigm	Address centric	Data and location centric
Typical data flow	Arbitrary one-to-one	To/from querying sink, one-to-many or many-to-one
Data rates	High (Mbps)	Low (kpbs)
Resource constraints	Bandwidth	Energy and limited memory and processing capabilities
Network lifetime	Long	Short
Operation	Attended, administered	Unattended, self-configuring

Data flow pattern is different between sensor networks and traditional IP-networks. In sensor networks, one-to-many and many-to-one data flows dominate whereas conventional IP-based networks are designed for one-to-one addressable data flows. Moreover, traditional IP-based networks follow layering principles that separate the application level functionalities from network layer functionalities. This is needed for supporting a high number of different IP-network based applications. Contradictory, sensor networks are likely to run a very limited set of applications. In addition to that, the full IP stack implementation on sensor networks is not feasible due to the limited computational and memory resources on nodes. As a result, cross-layer optimization and application-specific functionalities are used to reduce communications and energy consumption. For example, intermediate nodes may be allowed to look at the application-level content of packets in order to filter out irrelevant and redundant information. Moreover, they can aggregate data with information originating from other sources.

5.4 Low-Power Wide-Area Networks

Low-power wide-area (LPWA) networks are opening new M2M use cases where connectivity costs are expressed in dollars per year rather than dollars per month. Technology is under development and within the next 5 years we will see which implementations are winners.

LPWA networks are designed for machine-to-machine (M2M) applications that have low data rates, long battery lives, and that operate unattended for long periods of time. It is an emerging area of the IoT and represents a huge market opportunity as the IoT matures. Analyst firms such as Analysys Mason, Machina Research, and Strategy Analytics anticipate that there will be 2.7 billion LPWA connections by 2022. Moreover, it is anticipated that by year 2025, there will be seven billion connected devices over cellular IoT networks. That is equivalent to the current number of global cellular subscriptions. However, the density of connected devices may not be so uniform. Some cells will have very high numbers of devices connected and others only a few.

Market shares of the main vertical sectors are depicted in Figure 27.

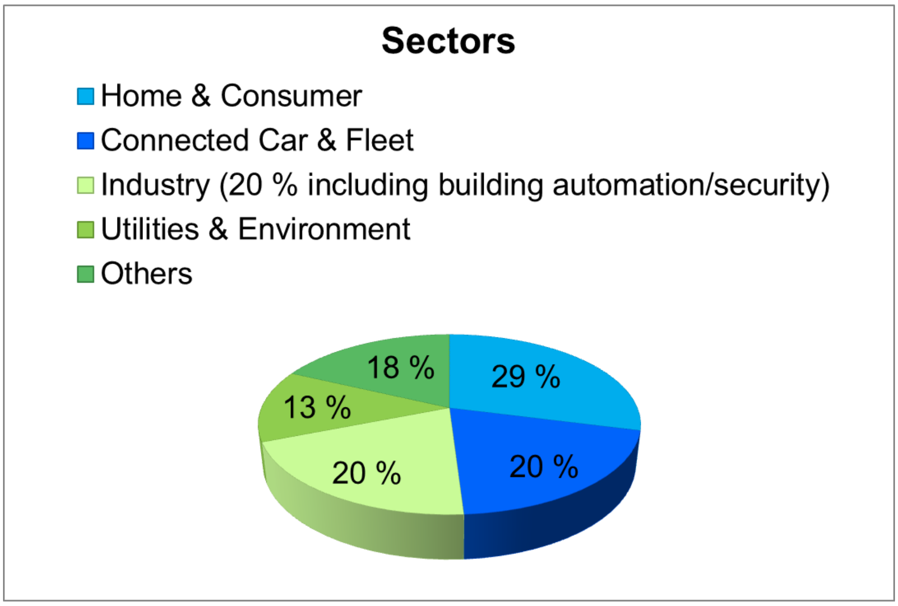

Figure 27. Vertical sectors for cellular IoT connections [34].

LPWA IoT M2M applications and services vary widely in terms of their service requirements, data throughput, latency and connectivity reliability. The key requirements for LPWA networks to support massive M2M deployment are:

- Long battery life (many IoT devices must operate for very long times, often years, and the target is a minimum of 10 years of battery operation for simple daily connectivity of small packages)
- Low device cost (current industry target is for a module cost of less than 5 $)
- Low deployment cost (as to cellular LPWA, target is to avoid any new hardware and site visits, and keeping CAPEX and OPEX to a minimum)
- Full coverage (simple examples are smart meters, which are often in basements of buildings behind concrete walls, and the target for connectivity link budget is an enhancement of 15-20 dB. The coverage enhancement would typically be equivalent to wall or floor penetration, enabling deeper indoor coverage)

LPWA type solutions are particularly well suited for applications presented in Table 3 [34].

Table 3. Applications for LPWA.

Application area	Description

Application area	Description
Water, gas and electricity metering and monitoring[1]	Some smart meter implementations incorporate multiple connectivity options, raising the price of the units, where LPWA can provide near universal coverage from a single radio module. In addition, pipelines and electricity grids have vital equipment in remote locations where GSM may not reach but LPWA solutions could potentially provide detailed monitoring.
Fire alarms	Fire alarms are activated rarely but need to be monitored to check that they are still live and working. This can be achieved with occasional status messages, at a much lower price point than equivalent solutions that use GSM technology.
Intruder alarms	Intruder alarms could have each individual sensor directly connected by LPWA, rather than having all the data aggregated at a hub for wireline or GSM transmission. This would make it much harder for a burglar to disable the alarms and make installation and ongoing maintenance easier.
Facilities management services	Facilities management services can see huge benefits in operational efficiency. LPWA sensors can be used to detect when city bins are full, when rodent traps have been activated or when soap dispensers need to be filled, thus optimising operator workloads and delivering a better quality of service.
Parking space monitoring	30% of congestion in cities is caused by drivers looking for somewhere to park. Monitoring individual parking spaces allows drivers to be directed to space. Such solutions are far easier to deploy when supported by a LPWA network.
Machinery on hire	Only the largest and most expensive equipment justifies the cost of GSM monitoring, but any downtime is costly for both construction companies and the rental firms. LPWA would allow predictive maintenance for lower cost equipment.

LPWA is split into two separate sub-categories. The current proprietary LPWA technologies, such as SigFox and LoRa, operate on unlicensed spectrum, and the forthcoming 3GPP standardized cellular IoT technologies on licensed spectrum [32][33][35][36].

The key LPWA technologies are shown in Figure 28.

[1] Usually meters and devices require software/firmware upgrades. LPWA is not suitable for downloading MBs of SW/FW upgrades to devices. This will set a challenge to utilize LPWA networks in these cases and will require planning of meters and devices to be upgradeable with much smaller SW/FW bundles (or users must have some other ways to manage upgrades).

	SIGFOX	LoRa	clean slate cIoT	NB LTE-M Rel. 13	LTE-M Rel. 12/13	EC-GSM Rel. 13	5G (targets)
Range (outdoor) MCL	<13km 160 dB	<11km 157 dB	<15km 164 dB	<15km 164 dB	<11km 156 dB	<15km 164 dB	<15km 164 dB
Spectrum Bandwidth	Unlicensed 900MHz 100Hz	Unlicensed 900MHz <500kHz	Licensed 7-900MHz 200kHz or dedicated	Licensed 7-900MHz 200kHz or shared	Licensed 7-900MHz 1.4 MHz or shared	Licensed 8-900MHz 2.4 MHz or shared	Licensed 7-900MHz shared
Data rate	<100bps	<10 kbps	<50kbps	<150kbps	<1 Mbps	10kbps	<1 Mbps
Battery life	>10 years	>10 years	>10 years	>10 years	>10 years	>10 years	>10 years
Availability	Today	Today	2016	2016	2016	2016	beyond 2020

Figure 28. The key LPWA technologies [32].

European operators such as Orange, KPN, and Proximus are in the process of using LoRa (Long Range) technology for LPWA services. In Finland Digita and Espotel announced a trial using LoRa. Meanwhile, the GSMA recently launched its own Mobile IoT project designed to address the use of low power solutions in licensed spectrum. Other solutions are Sigfox, Telensa and Weightless.

Sigfox is the most mature technology of those three. Its network covers most of Europe. LoRa WAN / LoRa MAC protocol based network is currently expanding in Europe by LoRa Alliance that includes many telecom operators. Weightless is the latest technology on the market. The final specification of its protocol is still in development.

5.4.1 LoRa

LoRa™ Alliance is an open, non-profit association of members that believe the Internet of Things era is now. The mission is to standardize Low Power Wide Area Networks to enable the IoT, M2M, smart city, and industrial applications. The Alliance members collaborate to drive the global success of the LoRa protocol, LoRaWAN, by sharing knowledge and experience to guarantee interoperability between operators in one open global standard [37].

LoRaWAN network architecture is a typical star-of-stars topology depicted in Figure 29. In the architecture, gateways form transparent bridges relaying messages between end-devices and a central network server.

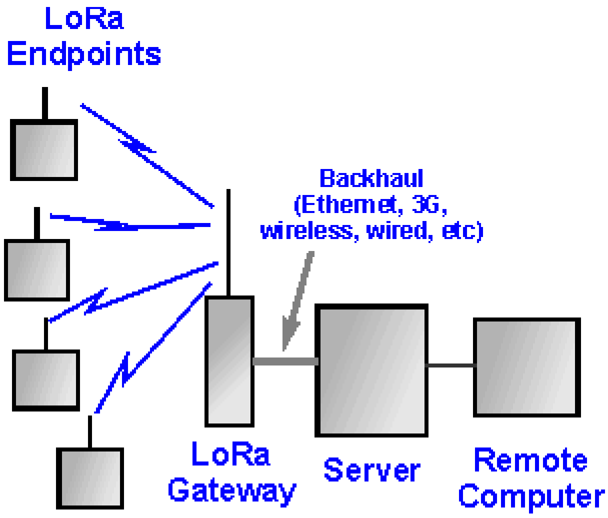

Figure 29. LoRa star architecture [37].

These gateways are connected to the network server via standard IP connections, while end-devices use single-hop wireless communication to one or many gateways. All end-point communication is generally bi-directional. The gateways also support multicasts in order to enable mass message distributions to reduce 'on air' communication time. This can be used e.g. for software upgrades over-the-air.

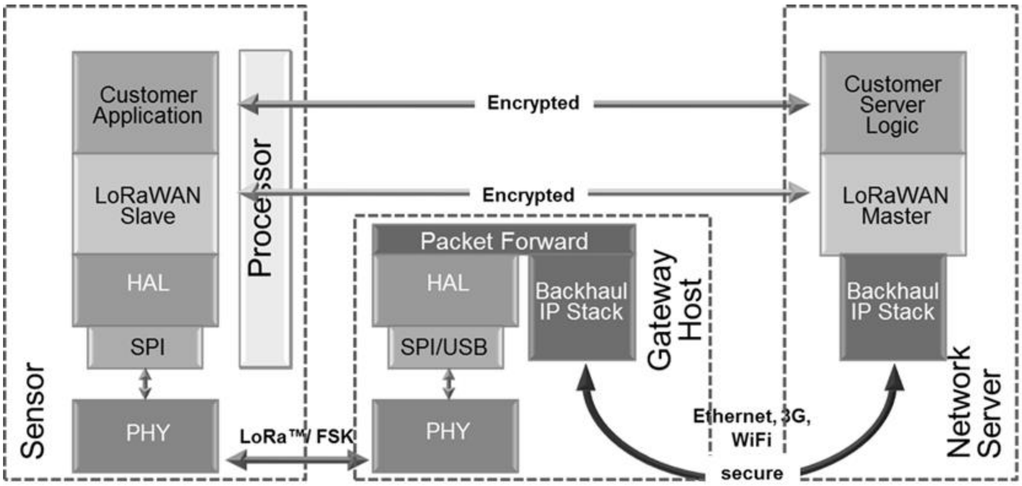

Figure 30. LoRa protocol slayers [37].

Communication between end-devices and gateways is distributed via different frequency channels and data rates. The selection of channel and data rate is a trade-off between communication range and message payload. LoRaWAN data rates range from 0.3 kbps to 50 kbps. To maximize both the battery life of the end-devices and network capacity, the LoRaWAN network server manages the data rate for each connected sensor via an adaptive data rate algorithm (ADR). This unique optimization is based on advanced information such as SNR, RSSI, PER, and channel allocations to ensure optimal performance under the local radio conditions.

LoRaWAN has three different classes, presented in Table 4, to address the very different requirements of IoT applications.

Table 4. Applications for LPWA.

Classes	Description
Class A **Bi-directional end-devices**	End-devices of Class A allow for bi-directional communications whereby each end-device's uplink transmission is followed by two, short downlink receive windows. The transmission slot scheduled by the end-device is based on its own communication needs with a small variation based on a random time basis (ALOHA-type of protocol). This Class A operation is the lowest power end-device system for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission. Downlink communications from the server are queued automatically until the next scheduled uplink.
Class B **Bi-directional end-devices with scheduled receive slots**	In addition to the Class A random receive windows, Class B devices open extra receive windows at scheduled times. In order for the end-device to open its receive window at the scheduled time it receives a time synchronized beacon from the gateway. This allows the server to know when the end-device is listening.
Class C **Bi-directional end-devices with maximal receive slots**	End-devices of Class C have nearly continuously open receive windows, only closed when transmitting.

Regarding to security, national LPWAN's for the IoT have strict requirements in terms of security for each individual user and typically require local or national hosting. To ensure this for each user, the application or the network owner LoRaWAN includes:

- Unique Network key (EUI64) and ensure security on network level
- Unique Application key (EUI64) ensure end-to-end security on application level
- Device specific key (EUI128)

5.4.2 SigFox

Specifically, SigFox sets up antennas on towers in a similar way to mobile phone operators. SixFox base stations receive data transmissions from devices like parking sensors or water meters. The transmission is done over unlicensed frequencies. In US, 915 MHz ISM band is used, which is actually the same than used for cordless phones. Alternatively, in Europe, a narrower band around 868 MHz is used. The rest of the world is using variations of

European and US bands, and they have different rules for governing SigFox networks.

SigFox wireless systems send very small amounts of data (12 bytes) with very low data rates (300 baud) using a standard binary phase shift keying (BPSK) modulation. The long range is achieved using very long and very slow messages. According to information theory, the slower you transmit, the easier it is to “hear” your message.

This technology is a good solution for any application that needs to send small, infrequent bursts of data. Examples of suitable applications are e.g. basic alarm systems, location monitoring, and simple metering. In these networks, the signal is typically sent a few times to “ensure” the message goes through. While this works, there are some evident drawbacks such as shorter battery life for battery-powered applications, and an inability to guarantee that a message is actually received by a tower.

SigFox has not yet deployed any bidirectional connections, although they have announced to be developing it. After bidirectional connections are available, the variety of applications that can utilize SigFox networks will significantly increase, even though communication links will be asymmetrical due to selected underlying technology.

6 Secondary substation monitoring and control (Use case)

6.1 Use case description

“The personnel at SCADA detects that the power quality has decreased and makes corrective actions by sending control commands to the grid.

One remote microgrid starts adjusting its parameters and causes a power oscillation. It has used its functions to respond to the request from the SCADA. Its actions are unsuccessful and the power oscillation escalates and affects also other grid entities. Each grid entity performs its own counteractions, which just keep escalating the problem. The fault events are detected in the control centre. The SCADA system alarms the personnel according to monitoring information. It takes time for personnel to detect the power oscillation problem and its scale. As a result, several adjustments are needed in order to get the network back to balance.”

Through this use case, our objective is to examine how today’s centralized monitoring and control system is used to resolve this types of problems and what are the requirements for the future monitoring and control to support localised network automation. The main aspects are architecture, flexibility, reliability (including security), and response time.

6.2 Approach

The secondary substation use case is approached from the automation model perspective of future energy network. It is anticipated that energy networks will utilize widely self-healing and decentralized local intelligence instead of only one centralized management. The major assumptions for the secondary substation automation architecture are:

- Architecture will support decentralized Smart Grid automation
- Intelligence is distributed into hierarchical levels, where analyses and decisions will be made on local level based on measurement collected locally and case by case supported with remote centralised analyses
- There could be hundreds of thousands substation type nodes in the system.
- Most critical/important local nodes could exchange data with each other to refine processing and decision making
- Data to be transferred and processed may be from few bytes to kilobytes depending on the measurements and aggregation level
- Intra and inter substation communication coexist and the defined architecture should support it

Our architecture design refers to a concept of Open Node Architecture [24], where the secondary substation node (SSN) is a distributed control system in the medium to low voltage distribution network whose objective is to aggregate data from local and remote sources as well as aggregate information from the connected smart meters and local devices at the customer side. Distributed intelligence at stations and data flow between substations are illustrated in Figure 31. The challenge in this architecture is that devices and systems at different hierarchy level can be under different stakeholders.

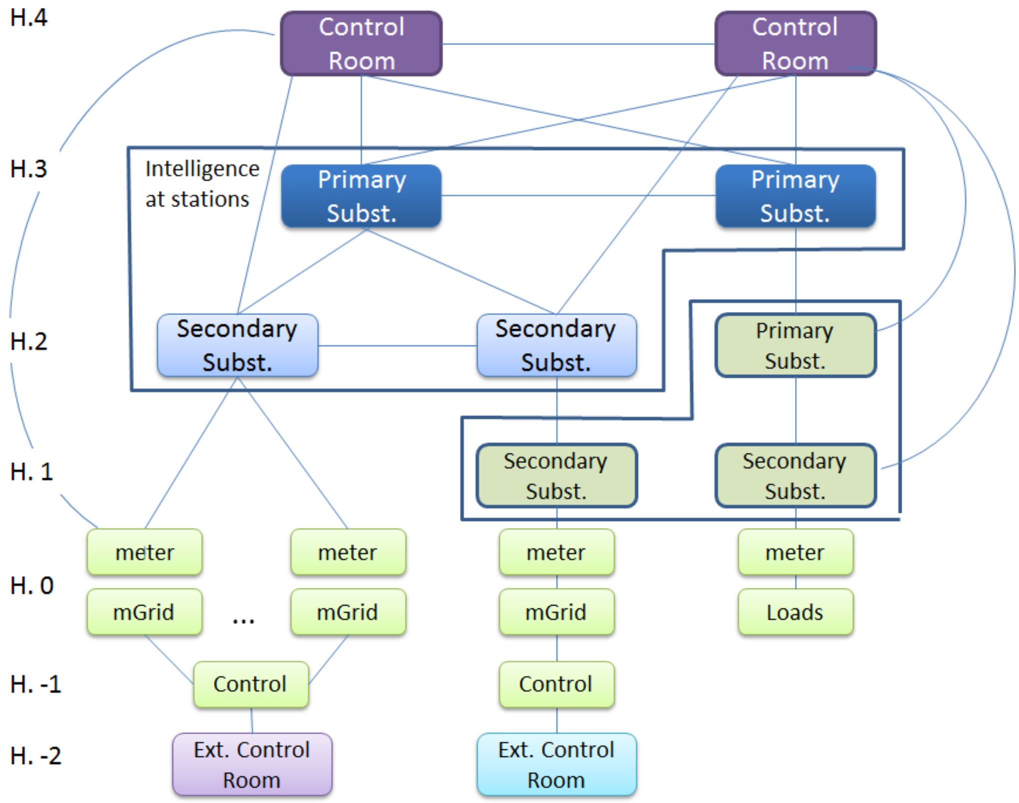

Figure 31. Example about local intelligence and data flow between sub stations.

The main functions of the SSN are:

- Acquisition of customer energy consumption
- Receiving reports on QoS
- Polling smart meter information to determine loss of power or disconnected meters
- Real time monitoring of power quality at the secondary substation
- Status monitoring of local devices in the secondary substation
- Collect information about Outages and their duration
- Perform load shedding/control
- Automatic device operation and remote controlled operation (e.g. switch on-off) via smart meters
- Remote contract management (change of tariffs, change of contracted power, administrative cuts, etc.)
- Demand Side Management through the power control function

The SSN is able to interact with the local devices, sensors, and electrical equipment at the substation in order to send control commands and to acquire real-time periodic data e.g. related to power consumption or voltage. If measurements are lacking elsewhere in the grid (e.g. HEMS or automatic meter reading (AMR) is not widely deployed) the secondary substation is an understandable choice to choose as a hub for measurement, communication, and control functionalities. Moreover, the secondary substation can be considered as a logical place for the local hub in cases, where a MV/LV transformer supplies e.g. a LV microgrid and all the customer data is collected and further relayed e.g. to the remote data bases. Thus, the LV microgrid can have a local communication network controlled by the secondary substation.

End-users relevant to the secondary substation use case are:

- End Users having direct or indirect business relationship with distribution system operator (DSO) or are under the control of DSO
    - **Service Operation Centres** for communication and distribution network control and operation
    - **Subcontractors** for field installation, fault correction and maintenance of primary and secondary electricity and communication devices, sensors and cables
    - **Device and Software Vendors** for communication and electric devices, sensors and their software for secondary substations
- End Users having distribution network connection with DSO (but business relationship could be with energy retailer or aggregator)
    - **DER owners** (could be anyone having legal identity or social security number)
    - **DER Hardware and Software Vendors**
    - **Subcontractors** for field installation, fault correction and maintenance of primary and secondary electricity and communication devices, sensors and cables (of DERs)
- **Energy Retailer or Aggregator** (selling or restricting energy capacity of DER owners)
    - Have only enterprise level connection with DSO for DER control (other possibility is direct DER control through DER SOCs)
    - Have only contractual relationship with DER owners and a licence to control their DERs

6.3 End-user requirements

Our goal is to study selected requirements in order to see how well today's mobile systems are able to fulfil distributed automation requirements and what needs to be left for 5G and wired systems. It is still unclear which communication technologies are best for various grid applications. There is a wide range of requirements from different smart grid stakeholders operating in different parts and layers of the network.

The presented communication requirements differ greatly depending on the literature source. Our approach follows The Integrated Energy and Communication Systems Architecture (IECSA) project's work [26] and an American study [27] that aimed at compiling all communication requirements in the smart grid. In the study, the control and monitoring networks are represented by a hierarchical multi-layer architecture, where network technologies are categorised according to data rates and coverage areas. The categories loosely define set of wireless communication technologies, which can be used in data transmission. The categories are wide area network (WAN), neighbourhood/field area network (NAN/FAN), home/building/industrial area network (HAN/BAN/IAN) and sensor network (SN).

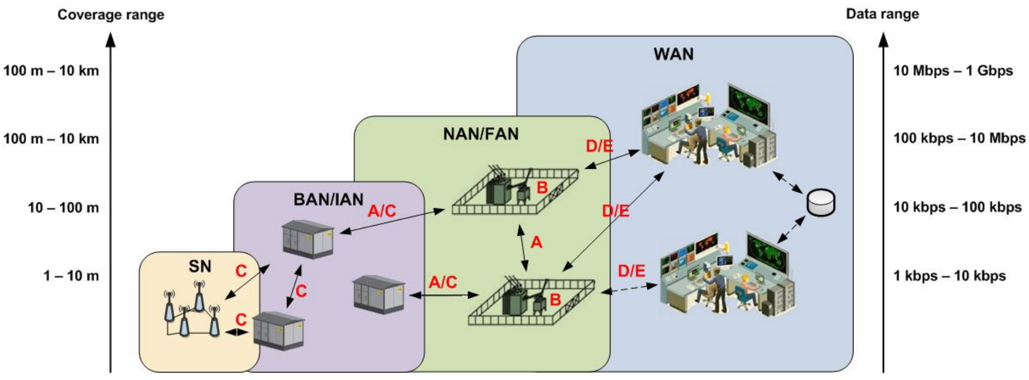

Figure 32. Operation environment specific communication technologies for the smart grid.

According to the architecture, the communication networks are classified as:

- SN: Sensor network to exchange information between a secondary substation and sensors inside or close proximity of secondary substations.
- BAN/IAN: Building area and industrial area networks to exchange information between neighbouring secondary substations.
- NAN/FAN: Neighbourhood and field area networks to exchange information between primary substation and secondary substations/ field patrols.
- WAN: Wide area network to exchange information between a primary substation and control centre (SCADA).

The IECSA project specified Smart Grid Environments and defined requirements for each of them. We have limited the requirements on control, monitoring and protection applications applied for secondary automation by selected end-users. However, the market and legislation related functionalities are excluded from the survey. In the table below, the identified requirements are divided by environment type and functions/applications. The link type and network category identify which type of network technologies can be utilized. The operation environment types are presented in Figure 32.

Table 5. Requirements for communication [26].

Environment Application Link type Network type	**Data size [bytes], Bitrate [Bps/kbps]**	**Sampling period [s]**	**Latency, (internal + comm.) [ms]**	**Jitter [ms]**	**Risk**	**Max. comm. outage**	**Availability [%]**	**Cost requirements**	**Power consumption requirements**
A. Deterministic inter-site – System-wide stability and reliability of the power grid Sending protection, samples, phasor measurements, and process control information between sites in real-time									
Differential protection, time critical protection requiring data from several locations (differential algorithms**)**									
Wired/ wireless, FAN	100 B (500 kbps)	< 1 ms	< 1 ms (10 ms)	50 us when no sync	high	10 ms	99.9999	low	low
Grid automation protection applications (several algorithms utilizing Goose)									
Wireless, FAN	100 - 300 B (100 - 1000 Bps)	1 - 10 s	<100 ms (100 ms)	1 ms	high	1 s	99.999	low	low
B. Critical operations intra-substation – Critical to legal, safe, and reliable power system operations within substation **Substation automation**									
Planned local control operations, responses triggered by protection functions (e.g. interlocking)									
Wired, BAN	100 - 1000 Bps (100 - 1000 Bps)	10 s	100 ms (100 ms)	10 ms	medium	10 s	99.99	low	medium
Intra substation information exchange									
Wireless, BAN, SN	300 B (100 - 1000 Bps)	10 s	100 ms (100 ms)	10 ms	medium	10 s	99.99	low	high
C. Inter-field equipment – Communication between devices outside control centres Mostly, optimization of the network									

Environment Application Link type Network type	Data size [bytes], Bitrate [Bps/kbps]	Sampling period [s]	Latency, (internal + comm.) [ms]	Jitter [ms]	Risk	Max. comm. outage	Availability [%]	Cost requirements	Power consumption requirements
Grid automation control operations, controlled from substation (e.g. load shedding, fault isolation and power restoration)									
Wired/ wireless, BAN	300 B (100 - 1000 Bps)	10 s	100 ms (100 ms)	10 ms	medium	10 s	99.99	low	high
D. Critical operations DAC – Critical to legal, safe, and reliable power system operations between a substation and control centre Monitoring and control of substations, pole-top devices, generation plants or distributed energy resources									
Control operations from NCC towards the grid (normal SCADA communication)									
Wireless, WAN	200 - 1000 B (100 Bps, 9.6 kbps (serial))	1 min - 1 h	100 ms - 3 s (100 ms - 3 s)	1 s	medium	1 min	99.9	medium	high
Disturbance data gathering, from (major) fault situations (normal SCADA communication)									
Wireless, NAN	200 - 1000 B (100 Bps, 9.6 kbps (serial))	1 min - 1 h	100 ms - 3 s (100 ms - 3 s)	1 s	low	1 min	99.9	high	high
Network-wide protection and control operations, triggered by monitoring functions (not in use yet)									
Wireless, WAN	- (100 Bps)	1 min - 1 h	1 - 60 s (1 - 60 s)	100 ms	medium	10 s	99	high	high
E. Non-critical operations DAC – Gathering of less-vital data Mostly, optimization of the network									
Data gathering for network optimization, maintenance and asset management purposes (normal SCADA communication)									
Wireless, WAN	200 - 1000 B (100 Bps, 9.6 kbps (serial))	1 min - 1 h	1 - 60 s -	1 s	low	1 min	99.9	high	high
Maintenance operations, triggered by monitoring functions (normal SCADA communication)									
Wireless, WAN	-	1 d	1 - 60 s (1 - 60 s)	1 s	low	1 d	99	high	high

6.4 Control and monitoring architecture

6.4.1 Architecture design

The pilot system is designed to enhance secondary substation automation by offering more flexible and reliable communication. This is required to enable bidirectional energy and information flows between control centre and distributed energy production, storage, and consumption. Figure 33 depicts different grid components operating in different hierarchical levels (ranging from H1 to H4) and their interactions with mobile networks. In the conventional implementation, the decision-making is centralized in SCADA (H4) and partly in primary substation automation level (H3). Traditionally, communication between these H3 and H4 is mainly established via wired connections. Only limited monitoring and decision-making functionalities are placed at the secondary substation (H2) and metering levels (H1). However, the trend is to move decision-making at the lower levels and utilize more wireless technologies due to their flexibility and cost-effectiveness. Today, wireless technologies are still considered rather unreliable and latency-limited (≤ 1 - 10 s). Therefore, they are merely used for sending and receiving operator commands, events and alarms that are not significantly time-critical.

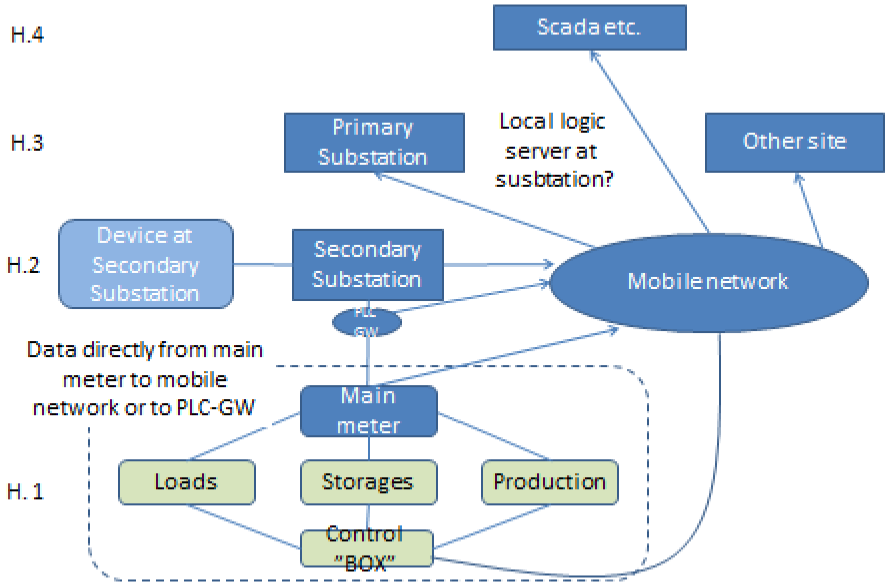

Figure 33. Grid components and their interactions.

The forthcoming 4G/5G M2M technologies are open new possibilities to exploit wireless technologies more excessively to cover slow and fast automatic interactions (< 20ms), releases and status changes (< 10 ms), and possibly even trips and blockings (< 3ms). This enables more precise and more frequent status and fault monitoring in H1 and H2 levels. Consequently, the number of monitored elements is expected to grow significantly, which in turn increases the received data amounts in the SCADA and primary substation levels. Vice versa, the forthcoming demand response will require faster reaction times at the H1 and H2 levels in order to balance the supply and demand.

In order to deal with these changes, more automation will be required in the secondary substation level. It is evident, that a centralized SCADA system cannot filter, aggregate, and analyse fast enough the excessive amount of real-time data generated by the forthcoming grids. In the centralized architecture, the received information contains a lot of irrelevant and redundant information, which is needlessly processed. As a result, huge data amounts and outliers in the data will slow down the decision-making and complicate the detection and discovery of the root causes of faults or problems. The centralized systems are not able to react fast enough – especially over wireless links.

Stemming from this, our goal is to move intelligence and automation to the lower levels in the energy network architecture. Data processing complexity will be divided among distributed more intelligent components. These components will be self-governing, and hence more agile to cope with local situations. The architecture is designed to be a spanning tree-like where the outermost leaves analyse most localised faults or problems. When moving toward the root node, the analysis covers larger geographical areas and problems that are more generic. The advantages of this problem localisation are reduced signalling overhead and faster response time. Moreover, the increased level of secondary substation automation and distributed decision-making ensures that only relevant data is collected at each component and only data required at higher levels is delegated on demand basis. The trend in grid and telecommunication network automation is toward self-healing, self-configuration, and self-optimisation. The distributed intelligence tends to create new types of interdependency challenges. The distributed intelligence in different layers and networks will easily cause situations where localised decision-making components are making contradictory decisions and causing the overall system to oscillate. This is especially problematic if parent supervision is not adequate. To solve decision-making complexity problem, the plan is to study supervised and unsupervised expert systems that aimed at solving problems having no satisfactory algorithmic solution and rely on inferences. They are mimicking human expert's problem solving, diagnosis, and planning activities by exploiting prior experience and knowledge. They have ability to learn and analyse causal time-variant and multivariate data including problematic data characteristics e.g. ambiguity, vagueness, generality, imprecision, uncertainty, and fuzziness.

The goal is to study different expert system implementations and apply them to the hierarchical monitoring and control systems. The similar approach has already been proposed to communication networks by VTT. The concept uses intelligent probes and Network Expert System (NESs). The NESs were designed to be connected to each other in order to form a hierarchical tree (or temporary graph). The probes pre-process the monitored data in order to extract outliers and to remove redundant and irrelevant data. The probe generates both network dependent and independent key performance indicators (KPI), which are sent as events to a NES. Indicators requiring instant response can by-pass NES, and are directly delegated to upper levels. The monitored data is fetched to a NES for autonomous or semi-autonomous decision-making. The decisions are made locally in order to be quick enough to predict or react to performance bottlenecks before end-users experience degraded quality.

6.5 Remote control and monitoring testbed

The pilot testbed will be implemented exploiting existing pilot testbeds at TUT (microgrid), LUT (LVDC), and VTT (communications) premises. The detailed description of each testbed is given in section 6.6.

6.5.1 Testbed implementation

The integrated testbed is designed to enable comparison between traditional centralised and forthcoming distributed monitoring and control system in good, average, and bad communication environments. The communications needs to be flexible and reliable in all radio conditions. The emphasis is put on mobile technologies due to the high expectations set to them. The pilot system will help us to learn in practice how well current and forthcoming wireless technologies can fulfil the requirements of distributed secondary substation automation, and what are realistic expectations for their performance.

The communication architecture design relies on TUT's Monitoring and Control framework. It divides the energy network components into meters/sensors, SSAUs, PSAUs, and Control Centre (SCADA) components. In the FLEXe pilot design, the framework is made a hierarchical spanning tree where monitoring and control connections between components are links (either wireless or wired) and nodes are grid components. The tree structure ensures flexibility and good scalability, since overloaded nodes can be split to new nodes in order to distribute data load and processing work. The hierarchical tree structure is not limited to layers H1 to H4. More detailed aggregators and sensor gateways can be added to the communication and control tree by creating new branches. Moreover, processing of a single SSAU or PSAU monitoring and control data can be split to a parent and several child nodes, which improves the flexibility of the whole system.

Links in the monitoring and control tree is not designed to be static. In abnormal situations, e.g. a parent node loses its communication link, the affected branch need to be re-formed. Establishing new links with wireless technologies is rather easy. The same logic can be applied, if communication capacity is not sufficient for transmitting data from a child node to its parent. In this case, multiple links can be created between child and parent nodes using e.g. different radio access technologies or multiple operators. Nevertheless, the architecture is intended to maintain tree-like structure in order to reduce control signalling and routing table updates, which have been known problems in large-scale mesh networks.

The green arrows in Figure 34 show the focal research points in the pilot system.

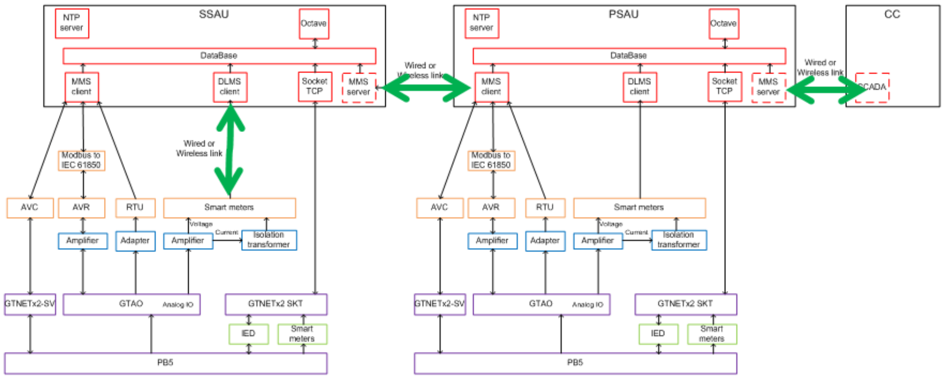

Figure 34. Building blocks of hierarchical monitoring and control system.

6.5.2 Development stages

The proposed control and monitoring architecture requires significant enhancements to the existing testbeds. Therefore, the implementation work is divided into four stages. These stages are presented in Figure 35. After each stage, the design plans are refined and more components are integrated to the pilot testbed. The aim is to accomplish as much as possible with the available resources and time constraints. The stage 4 is considered as a long-term vision, which is beyond the scope of this project.

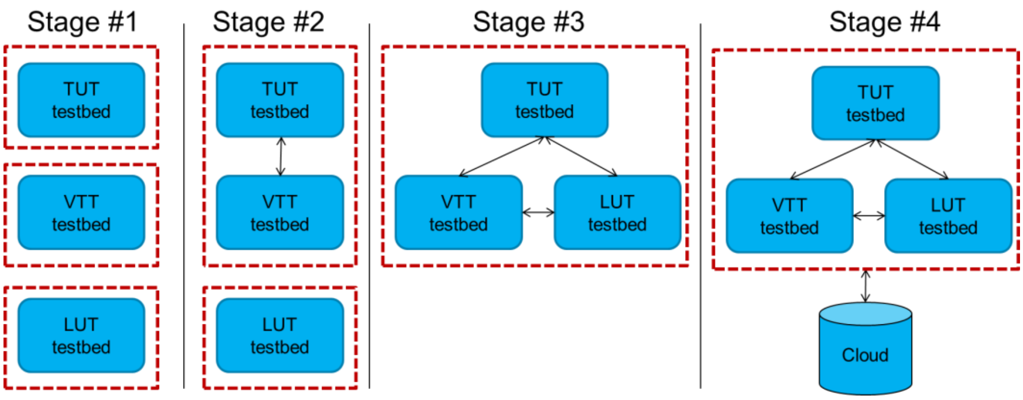

Figure 35. Development stages of integrated energy and telecom testbed.

Stage #1

VTT and TUT will tailor their testbeds for the energy and communication network integration. TUT will focus on security and usability. They will use Ajeco modems to establish a wireless connection between SSAU/PSAU and SCADA over multiple radio access technologies. Furthermore, TUT will tailor the SSAU / PSAU database to manage new types of quality indicators from communication networks. LUT will concentrate on Big Data and Emtele for applying LoRa technology to exchange monitor data among multiple secondary substations.

VTT will tailor their communication testbed to mimic data communication between SSAU and PSAU. The communication link will be built using an Arctic 4G/5G modem and M2M gateway. The goal is to utilise Layer 2 virtual private network (VPN) connections to make the SSAU and PSAU networks appear in the same network and to enable transmitting GOOSE traffic between a SSAU and PSAU. For testing purposes, secondary substation data will be recorded in advance. This recorded data or data generated with a traffic generator will be transmitted over the communication link under different radio conditions and configurations. Moreover, VTT will implement the functionality to enable one-way latency measurements between SSAU and PSAU. This requires software modifications in both SCADA and SSAU sides. VTT will also implement a sensor gateway module that collects context information from simple sensors or actuators that are in the proximity of a secondary substation. The gateway aggregates the data and delegates it to the SSAU. The figure below shows the testbed components. The implementation work concentrates on the section indicated with a green arrow in Figure 36.

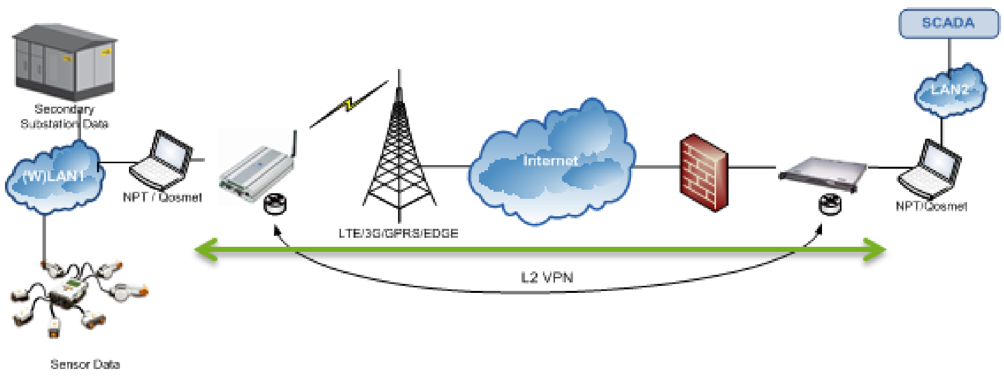

Figure 36. The communication testbed (stage #1).

In this stage #1 testbed configuration, a SSAU component is placed in Micronova building and PSAU in VTT Digitalo depicted in Figure 37. By changing the location of the SSAU inside the building, different radio conditions can be created. The testbed setup is also used for testing QoS and one-way latency with QosMeT software tool using different data transmission intervals and packet sizes.

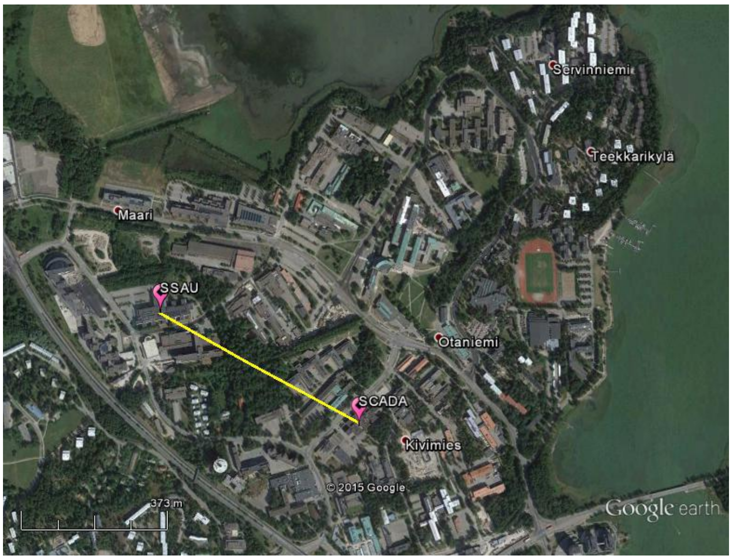

Figure 37. Communication link between SSAU and SCADA.

Stage #2

In this stage, the tailored TUT's microgrid testbed at Hervanta and VTT's communication testbed at Otaniemi will be connected. The integration is not straightforward, since the communication and microgrid components are running on mixed operating systems. In order to establish interfaces between the components, the databases in TUT's SSAU, PSAU and SCADA components will be utilized. The databases will require modifications in order to maintain real-time communication and sensor quality data. Also, database design decisions are needed in order to find balance between database performance and data privacy of different stakeholders. The integration will require tailoring of SSAU and communication components to arrange integrated decision-making in order to handle both energy or communication network related fault events and alarms. The integrated testbed will be used to study the effects of long range monitoring and control of energy system over commercial mobile networks in urban environment. The aim is also to study data aggregation and filtering possibilities in order to reduce the amount of data sent over a wireless link. This is an initial step to increase automation also from communication's viewpoint. The effects of improved security will also be studied using OpenVPN connections where secure point-to-point / site-to-site connections will be created using secure sockets layer (SSL) / transport layer security (TLS). OpenSSL encryption library will be experimented in pilot measurements in order to see in practice how different encryption algorithms affect the communication performance (security vs performance).

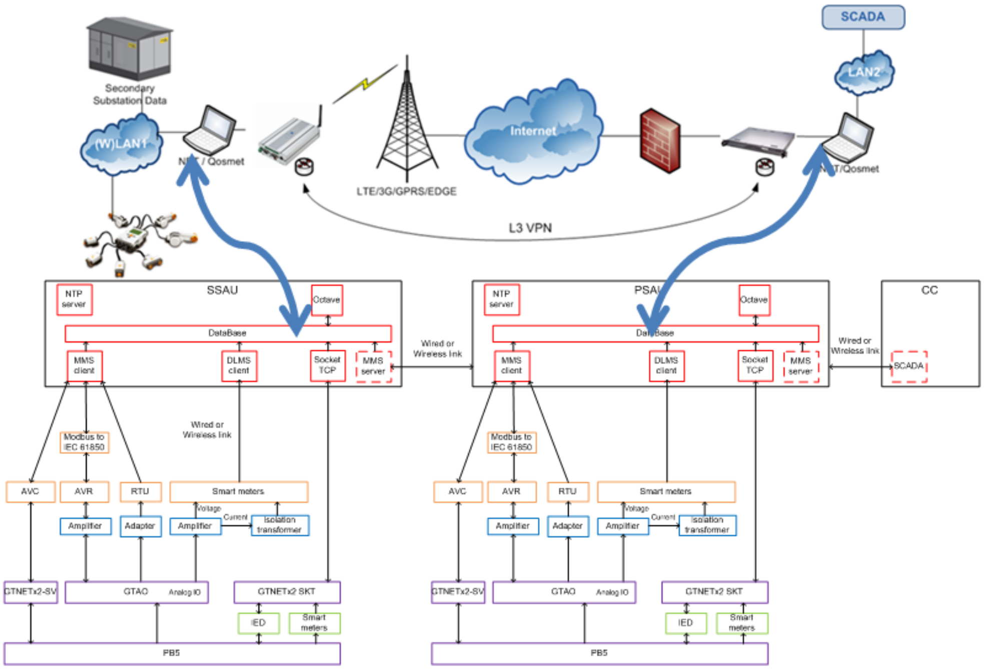

Figure 38. Integrated communication and microgrid testbed (stage #2).

Stage #3

In the third stage, the integrated testbed will be extended to include LUT's LVDC testbed. The LVDC is seen as one additional IED in the TUT's microgrid testbed. However, the distance and functionalities of LVDC set new requirements for the integrated TUT&VTT testbed. The LVDC testbed is located at Suomenniemi North-East from Lappeenranta. This region is rural area with limited mobile network coverage.

The plan is to study differences between urban (Hervanta) and rural (Suomeniemi) secondary substation automation. Moreover, separate field measurements are planned to get more detailed performance information – not only from secondary substations but also concerning communication capabilities offered to repair and maintenance patrols. Figure 39 illustrates the data and communication links that need to be tailored for the integration.

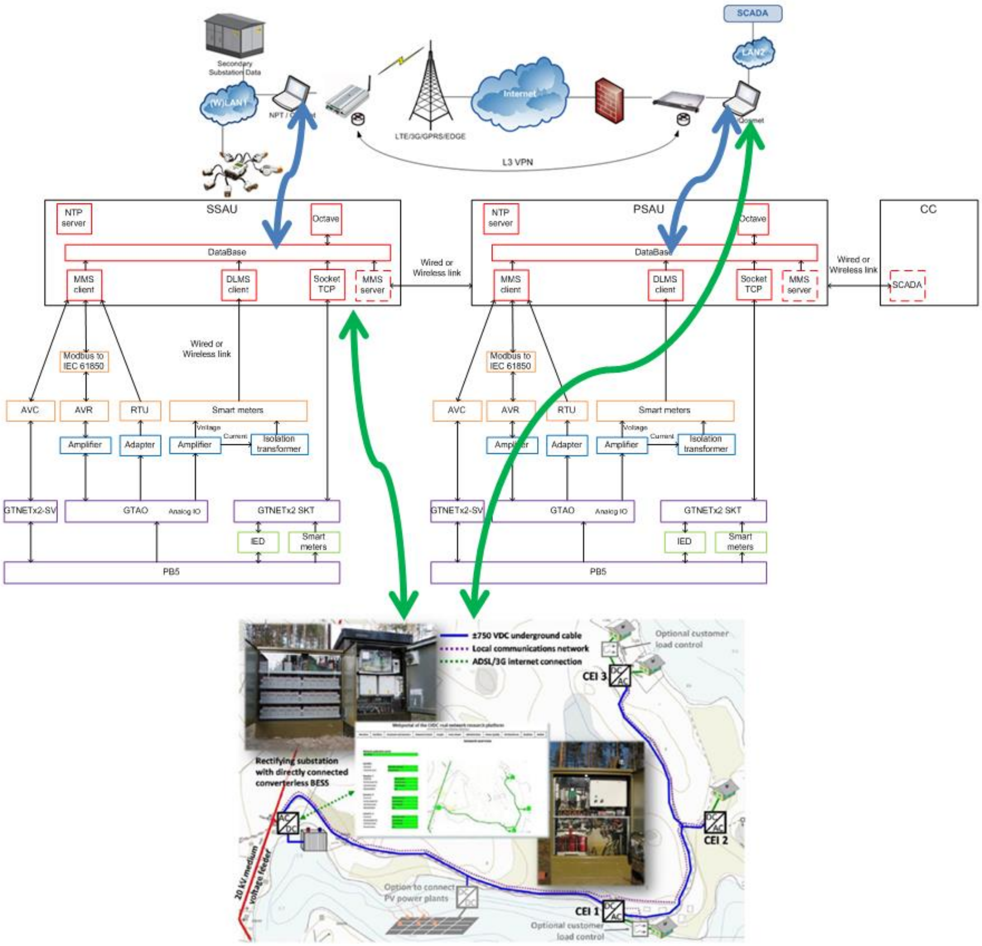

Figure 39. Integrated communication, microgrid, and LVDC testbeds.

The stage 3 pilot system extends the geographical area of testbeds to cover Tampere-Espoo-Lappeenranta. The measurements will enable to discover differences between urban and rural area secondary substation automation. This will offer new information for setting performance requirements for urban and rural area remote control and monitoring.

Stage #4 (Beyond the project)

In the last stage, the pilot system will be connected to a cloud service in order to make pilot system and its data available for simulation and modelling tools. The research extends beyond the physical testbed in order to enable the performance assessment of large-scale hierarchical control and monitoring system using today's and tomorrow's wireless technologies. The main emphasis will still be on security, flexibility, and proactivity. As the tree gets higher, then the data encryption and wireless links themselves may turn out to be the major performance bottleneck. The techniques such as localised security, direct data forwarding, and data aggregation will be analysed. The response time and reliability of remote control depend on the number of wireless and wired links, which all may have different reliability, throughput, and latency characteristics. Inherently hierarchical tree structures are not resilient. To improve resiliency, we need to improve the supervision of parent nodes and techniques to establish alternative control and monitoring routes without disturbing the data traffic. Moreover, use of spatiotemporal sensor information for proactive maintenance will be studied as well as feasibility of LoRa technology to gather information collectively from neighbouring secondary substations. The goal is to lower operational costs and for reduce communication between PSAUs and SSAUs.

The time synchronisation of grid components is critical in order to ensure accurate power and communication quality measurements. For this, the plan is to apply the results from “Enhancing the quality of measurement and monitoring applications” task to the secondary substation level.

6.6 Existing testbeds

6.6.1 LVDC testbed

With the LVDC system, the power transmission capacity can be increased and larger low-voltage networks built compared with traditional alternating current (AC) systems. Accordingly, the MV line branches can be replaced with LVDC system and thus the length of MV feeder lines can be decreased especially in rural areas having a small number of customers, and thus relatively low amount of loads in the LV distribution network.

The LUT LVDC testbed has been built in co-operation with LUT, Suur-Savon Sähkö Oy, and Järvi-Suomen Energia Oy. The LVDC testbed controls the electricity distribution of four customers in the DC network in Suomenniemi. After MV is transformed to low voltage AC, the power is rectified and smoothed to DC (±750 VDC, and 0 V) with a grid converter. Then, the low voltage DC is delivered to customers with the same underground cable network as used with low-voltage AC. Each customer, depicted in Figure 40, is equipped with customer-end inverter (CEI) that produces standardized 230/400 VAC to customer loads. The testbed has been in operation since summer 2012, and the future goal is to extend the grid monitoring and control functionalities to cover also the customer load control inside the customer premises. By this way, the customers and their loads can be integrated to the flexible energy markets. Moreover, the applicability of the DC distribution also inside customer premises is one potential study case in future.

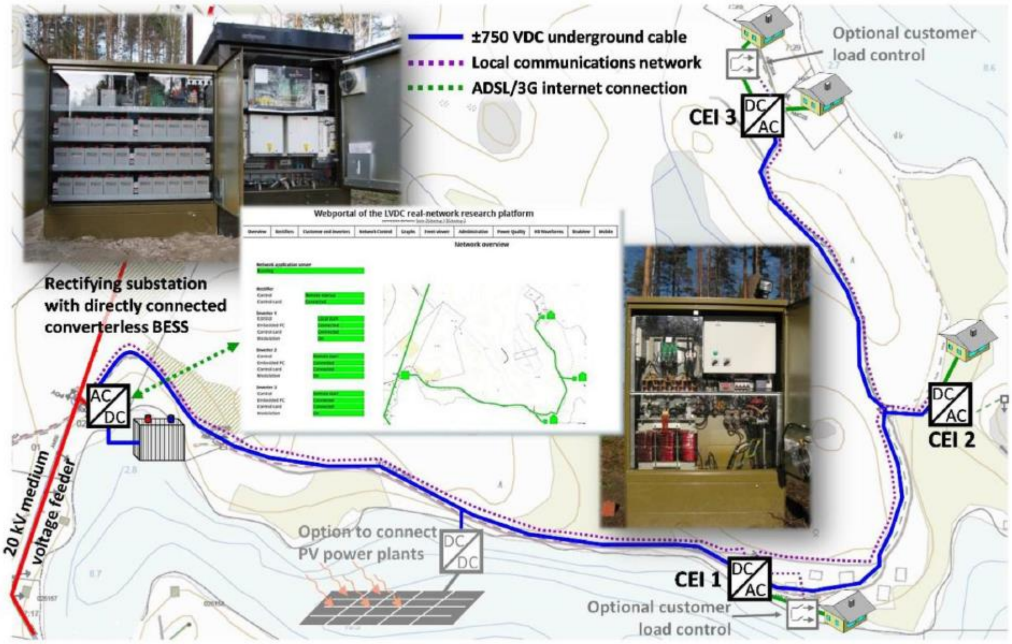

Figure 40. LVDC research site and its components located on the map [30].

The LVDC testbed is managed by a distributed ICT system, which includes IEDs (such as embedded PCs at rectifying substation and each CEI) and local communication network. It uses a proprietary protocol over TCP/IP to enable connections between the IEDs. The communication inside the LVDC system is over multi-core optic fibre. A dedicated manageable Ethernet switch manages single cores at the rectifying substation. In the other ends of the DC grid, single cores are connected via fibre-Ethernet converters to the embedded PCs at each CEI.

Each embedded PC is also connected to a CEI microcontroller and rectifying substation with Ethernet cable. Microcontrollers control the operation of grid-tie converter and CEIs. Similarly, the embedded PCs of rectifying substation and battery energy storage system (BESS) next to the rectifying substation are interconnected. The BESS is controlled via its embedded PC, which again controls the battery management system (BMS) of the batteries. The data connection to remote databases and for wireless research purposes is implemented with asymmetric digital subscriber line (ADSL). The network has also backup connections implemented with mobile 3G modem at the rectifying substation. Thus, the rectifying substation, where also the MV/LV transformer is the interface both to the MV grid and the remote ICT systems. Embedded PC at rectifying substation comprises web-based server, that is, the system supervision portal. The ICT system of the LVDC testbed is illustrated in Figure 41.

The most relevant requirements for secondary substation automation related to monitoring and control in LVDC testbed are listed in the end of Chapter 6.3.

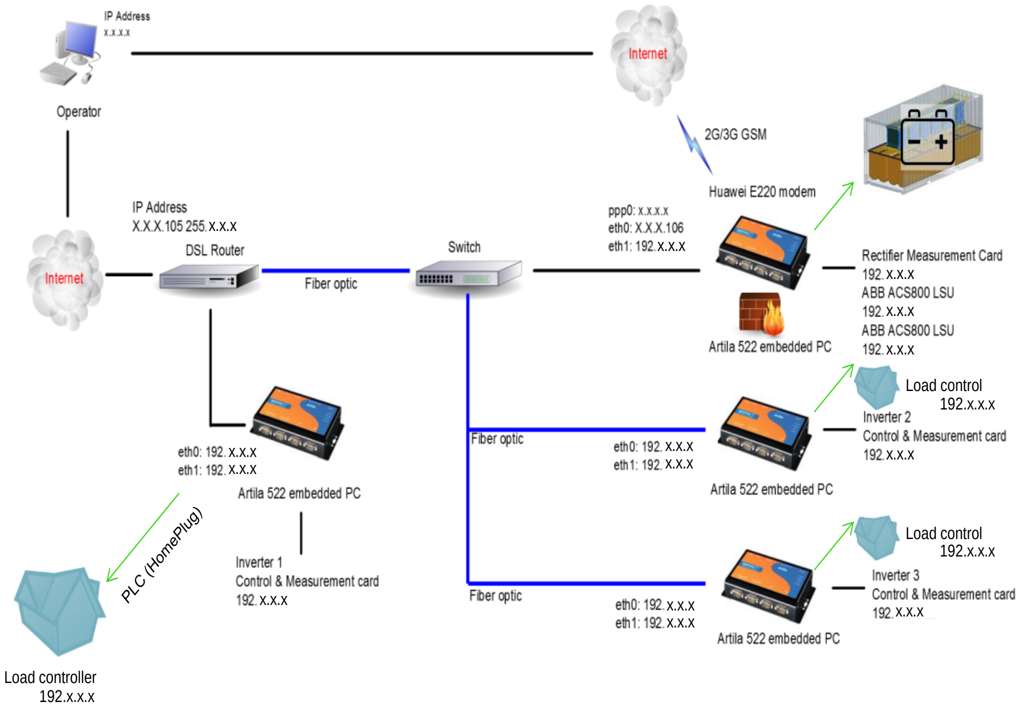

Figure 41. ICT system of the LVDC testbed [31].

6.6.2 Smart Grid testbed

Smart Grid testbed of TUT is located in the premises of Department of Electrical Engineering and Automation Science Engineering departments. The testbed is used for simulating and investigating Smart Grid functions for e.g. protection, monitoring, control, smart metering, and communications in secondary substation, primary substation, and SCADA levels. The testbed consists of various hardware and software components. The core components of TUT Smart Grid testbed are presented in Figure 42.

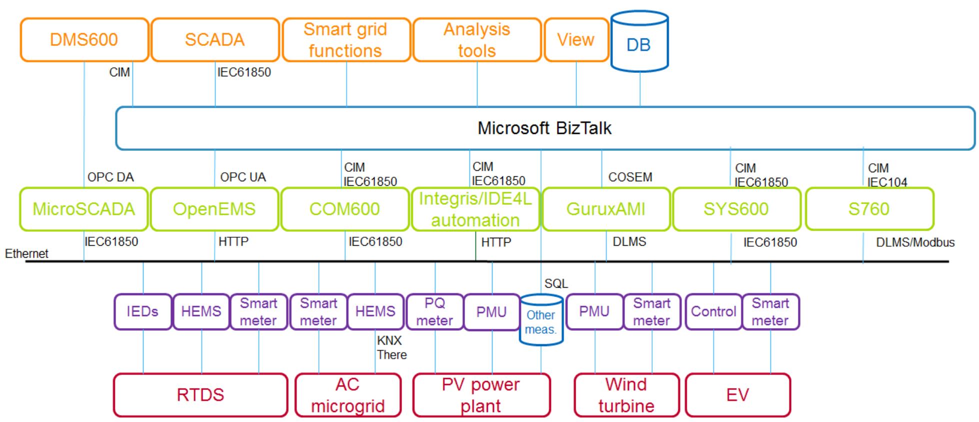

Figure 42. TUT Smart Grid Testbed Components.

Next, the components that are relevant for the FLEXe pilot system are shortly described.

The SCADA module is the topmost component. The testbed SCADA contains all the required components to mimic power system SCADA. It includes several types of RTUs, master terminal unit (MTU), ABB MicroSCADA software, and data communication facilities. Most of the devices are from ABB. MicroSCADA is used for monitoring and control of primary substations, secondary substations, and MV and LV networks. In the current implementation, a RTU receives measurement data either from real-time digital simulator (RTDS) via hardwiring or from IED via Fieldbus. The RTU sends the collected data over Internet to a MTU using protocols such as IEC 61850, OPC UA, DNP3, and IEC 60870-5-104. Also, wireless data communication can be established via GPRS/3G/4G modems. The centralized MTU is connected directly to the ABB microSCADA system at the control centre.

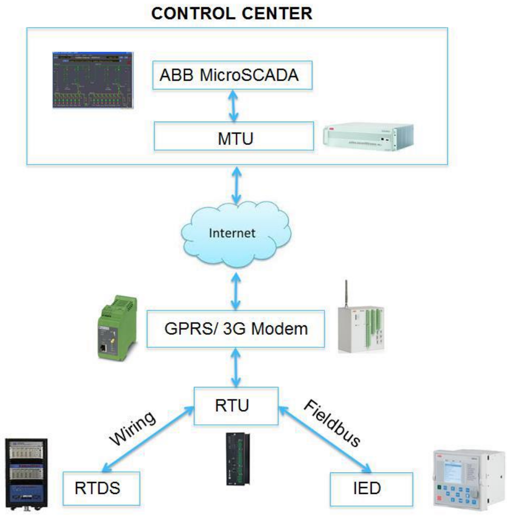

Figure 43. SCADA component.

RTDS can simulate behaviour of real-time power system elements e.g. transformers, generators, and feeders. It also has an external interface to connect real devices to the simulator. RTDS is monitored and controlled by a RSCAD software tool.

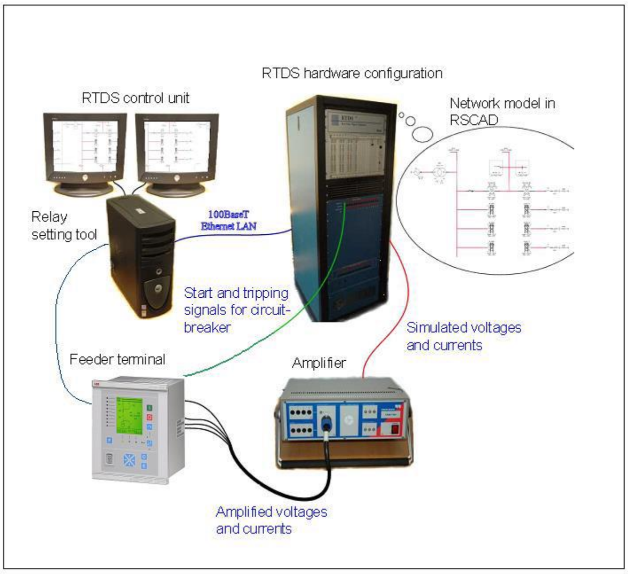

Figure 44. Real-Time Digital Simulator.

There are several IEDs such feeder IED and voltage controller IED that support not only protection and control functions but also latest substation automation standards. All of the mentioned IEDs support IEC 61850 standards in which they are able to communicate via digital data communication. They receive measurement data as sampled values from RTDS. Then, they exchange data in form of GOOSE messages in substation LAN. Additionally, they are able to report substation events to the higher level management applications through manufacturing message specification (MMS). These IEDs also support advanced ICT protocols that make them capable of connection to external TCP/IP networks. Furthermore, there is a substation communication gateway that supports a variety of communication standards. This gateway is considered as the interface between substation network and control centre network that includes SCADA and DMS 600 applications.

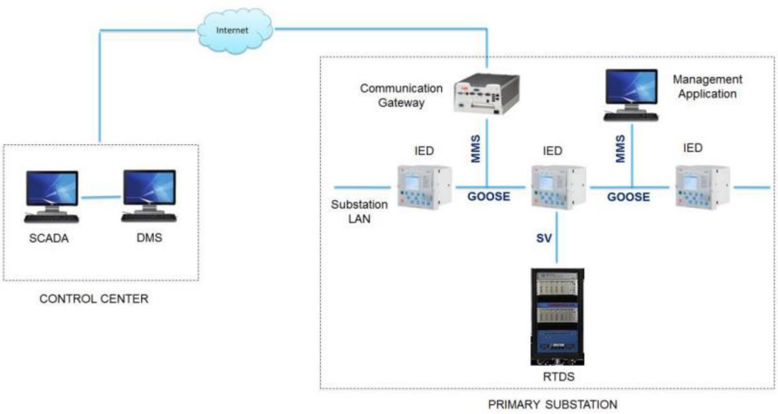

Figure 45. Primary Substation Automation Unit.

SSAU is a software tool that emulates the corresponding device. It is responsible for executing secondary substation automation tasks. SSAU contains sub-components such as DLMS client, MMS client, and IEC 61850 database. The current SSAU implementation controls five smart meters that can emulate AMR, advanced metering infrastructure (AMI), and automated metering management (AMM) applications. The smart meters support DLMS/COSEM protocol over TCP and are remotely accessible via the Internet. IEC 61850 database is used for collecting secondary substation level status information and to trigger fault events via a MMS server.

6.6.3 Communications Testbed

VTT's communication testbed is located in Espoo and Oulu. Espoo network contains the ERVE network that models core network components and management services. This testbed uses OpenStack and SDN functionalities to enable different network configurations with emulated or physical network components.

The radio access network is placed in Espoo and Oulu. In Espoo, the radio access network is called Green Mesh Network (GMN) and it contains several long-range point-to-point links and indoor and outdoor WLAN APs operating at unlicensed 2.4 GHz and 5 GHz bands. This network is built on commercial off-the-self and low-power devices. It offers network virtualization functions for energy-efficient and flexible mesh networking. The main components are a SDN controller and a centralised radio controller. They manage radio resources and are responsible for packet forwarding between wireless backhaul links and connected APs.

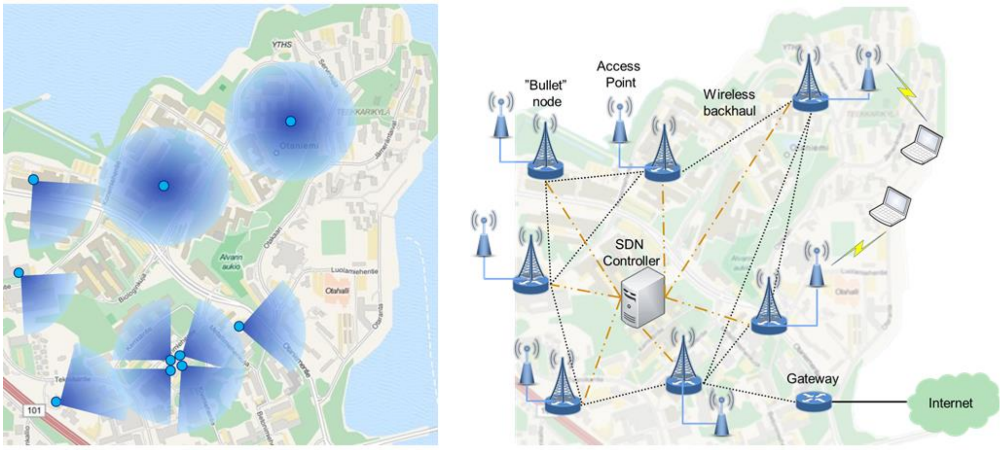

Figure 46. WLAN network for robust and energy-efficient mesh networking and SDN research (Green Mesh Network).

Converging Networks Laboratory (CNL) network is in Oulu and Espoo. It provides a test environment for future convergent communication infrastructures. The CNL consist of different RAN technologies e.g. 2G/3G/4G and WiMAX/WLAN base stations, network management and monitoring tools, virtualized application/cloud servers, and a large variety of different terminals.

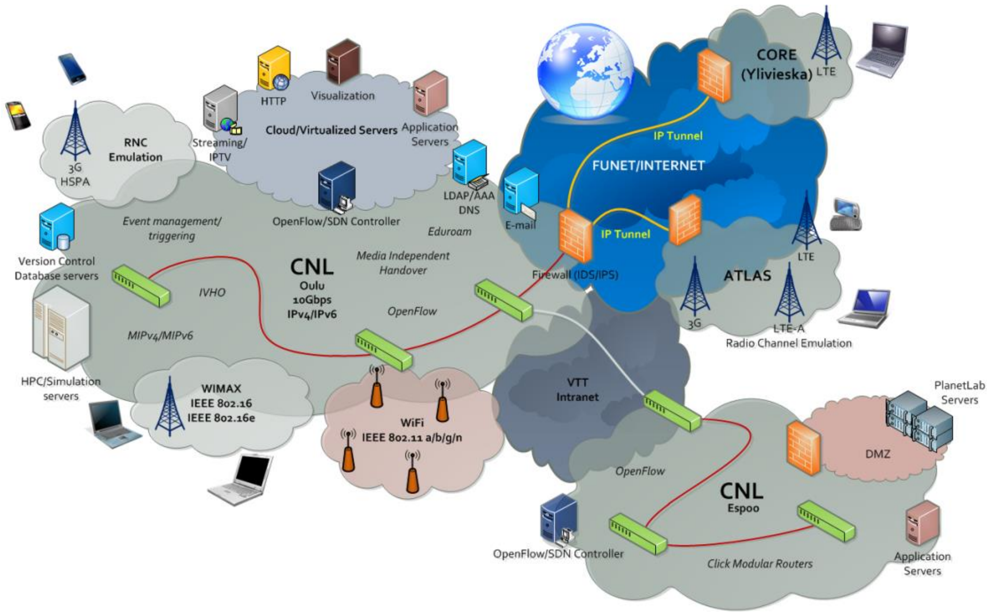

Figure 47. Converging Networks Laboratory (CNL).

In addition to CNL and GMN networks, Nokia's NetLeap LTE test network has been used for communication research. The next step is to extend the network inside VTT premises. The network was built by Nokia and Aalto University for research on radio access and core networks. The NetLeap network is frequently updated with new network components and services that are still in research and testing phase. The base stations of NetLeap are managed and operated by Nokia. This network contains both indoor and outdoor eNodeBs, which are connected with high-speed optical fibre links. The network covers nearly the whole Otaniemi and thus gives a good opportunity to test communication solutions in different radio environments e.g. indoors (stationary) and outdoors (moving). For trials, dedicated Nokia test SIMs are required.

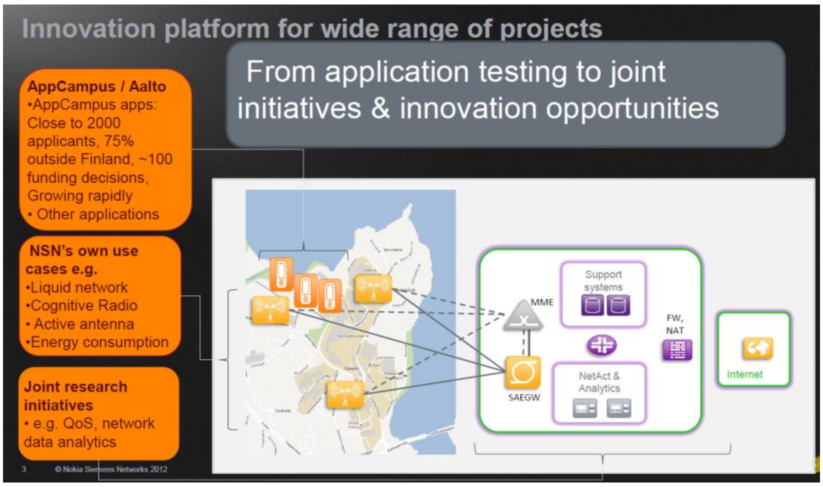

Figure 48. LTE network for research and innovative mobile application development (NetLeap).

To support communication research, VTT has developed a measurement, simulation, and analysis platform that supports mobile network planning and performance assessment. One of the core components is Network Planning Tool (NPT) developed for integrated network planning, measurements, and performance analysis. The tool was implemented to support better the R&D of different communication solutions in multi-operator and multi-RAN environment. The tool supports both indoor and outdoor as well as real-time and offline measurement and analysis scenarios. The tool contains interfaces to different measurement devices e.g. Nemo Outdoor, Viola Systems' Arctic modules, NPT client with QoSMeT and IVHO software tools, and to dedicated monitoring apps on Android phones. Moreover, data from NSN's Clarinet (network side tool), Aalto University's NetRadar and VTT*s Mobiilimittari can also be used as a data source for performance analysis.

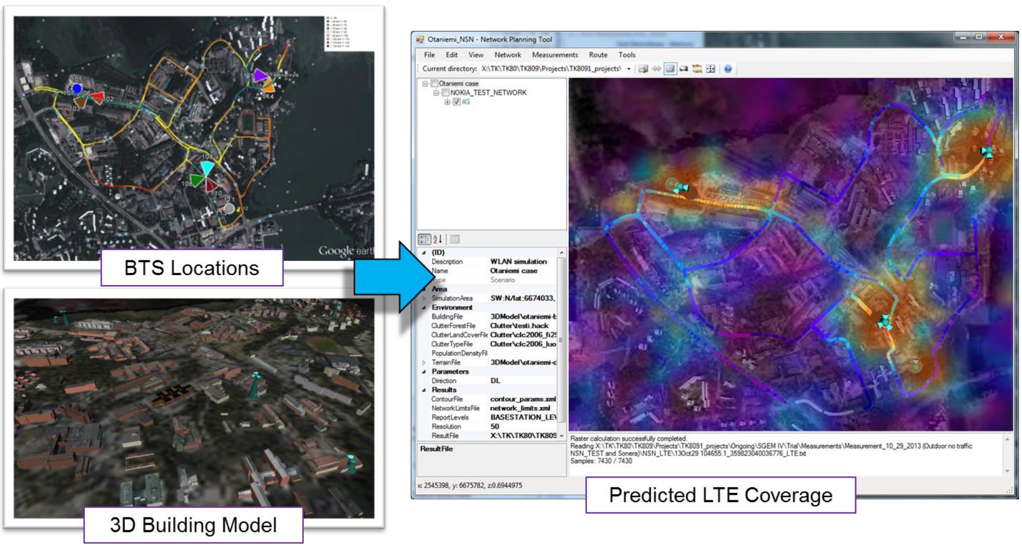

Figure 49. NPT tool used for measuring and analysing the performance of different networks.

The recent development in M2M/IoT communications has made the latency aspects increasingly important. Therefore, the measurement and analysis platform was extended to support configurations where both one-way and two-way delay measurements can be performed [28][29]. The two-way delays (round-trip time (RTT)) are measured with Nemo Outdoor and one-way delays with the Qosmet tool. The latter one is a real-time passive measurement tool that monitors and computes key QoS parameters from ongoing network traffic.

7 Conclusions

This report sums up the work done so far to examine today's and tomorrow's communication technologies applied to remote control and monitoring of flexible energy systems. The report presents a specific but extensible use case that focuses on secondary substation automation requiring secure and reliable communications. According to the prior research results and literature survey, we have defined architecture for remote control and monitoring Proof-of-Concept testbed. Our next goal is to implement the joint testbed by integrating three different types of testbeds located in Tampere (Smart Grid testbed), Espoo (Communication testbed), and Lappeenranta (LVDC testbed). This joint testbed will enable a wide variety of short and long distance measurements to be performed at different radio conditions and data loads.

The joint testbed will require a significant amount of tailoring work. As a result, we have split the pilot integration work into four stages. After each stage, the design plans need to be refined and if needed even altered. In the starting stage, VTT Technical Research Centre of Finland (VTT) and Tampere University of Technology (TUT) will tailor their testbeds ready for the energy and communication pilot integration. TUT will focus on security and usability by implementing a wireless connection between secondary / primary substations and SCADA over multiple radio access technologies. Furthermore, they will tailor the secondary substation database to manage new types of communication network related quality indicators. Lappeenranta University of Technology will concentrate on Big Data, and Emtele for applying LoRa technology to exchange monitor data among multiple secondary substations. VTT will first modify their communication testbed to mimic data communication between secondary and primary substations. The aim will be to utilise Layer 2 VPN connections to enable GOOSE traffic between a secondary and primary substations. Moreover, VTT will implement the functionality to enable one-way latency measurements. ABB will provide technical assistance and devices. Moreover, they will participate in field measurements and provide feedback pertaining to the research results.

The performance results and findings will be reported in conference papers and workshop presentations as well as at technical meetings organized among different FLEXe tasks. The aim is to find out how today's cellular systems are able to fulfil the requirements set by the secondary substation automation and what needs to be left for 5G and other forthcoming technologies. Although our resources will be concentrated on the testbed integration and execution of trial measurements, we will keep the common FLEXe goals in mind in order to offer input to other FLEXe WPs for the design, operation, and management of the global energy system, since a significant driver towards "active" distributed energy system is secure and reliable communications.

8 Abbreviations

2G, 3G, 4G, 5G	2^{nd}, 3^{rd}, 4^{th}, 5^{th} Generation
3D	Three-Dimensional
3GPP	3rd Generation Partnership Project
AC	Alternating Current
ADR	Adaptive Data Rate Algorithm
ADSL	Asymmetric Digital Subscriber Line
AI	Artificial Intelligence
AMI	Advanced Metering Infrastructure
AMM	Automated Metering Management
AMR	Automatic Meter Reading
ANM	Active Network Management
AP	Access Point
ARIB	Association of Radio Industries and Businesses
AS	Access Stratum
ASA	Authorized Shared Access
ATIS	Alliance for Telecommunications Industry Solutions
BAN	Building Area Network
BESS	Battery Energy Storage System
BMS	Battery Management System
BPSK	Binary Phase Shift Keying
BS	Base Station
C/U	Control Unit
CAPEX	Capital Expenditures
CCSA	China Communications Standards Association
CDN	Content delivery network
CEI	Customer-End Inverter
CIM	Common Information Model
CN	Core Network
CNL	Converging Networks Laboratory
CoMP	Coordinated Multipoint Transmission
COSEM	COmpanion Specification for Energy Metering
C-RAN	Centralized-RAN
D2D	Device-to-Device
DC	Direct Current

DER	Distributed Energy Resources
DG	Distributed Generation
DL	Downlink
DLMS	Device Language Message specification
DMS	Distribution Management System
DNP3	Distributed Network Protocol
DNS	Domain Name System
DR	Demand Response
DSL, xDSL	Digital Subscriber Line
DSO	Distribution System Operator
E2E	End-to-End
EDGE	Enhanced Data rates for GSM Evolution
eNB, eNodeB	E-UTRAN Node B, Evolved Node B
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved-Universal Terrestrial Access Network
EU	European Union
EV	Electric Vehicle
FAN	Field Area Network
FC	Fog Computing
FDD	Frequency Division Duplex
FD/m-MIMO	Full Dimensional and Massive MIMO
FLEXe	Flexible Energy System
GERAN	GSM EDGE Radio Access Network
GOOSE	Generic Object Oriented Substation Events
GHz	Gigahertz
GMN	Green Mesh Network
GPRS	General Packet Radio Service
GSM	Groupe Spécial Mobile, Global System for Mobile Communications
GSMA	GSM Association
HAN	Home Area Network
HEMS	Home Energy Management System
HetNet	Heterogeneous Network
HO	Handover
HSDPA	High-Speed Downlink Packet Access
HSS	Home Subscriber Server

HSUPA	High-Speed Uplink Packet Access
IAN	Industrial Area Network
ICT	Information and Communication Technology
IEC	International Electrotechnical Commission
IECSA	Integrated Energy and Communication Systems Architecture
IED	Intelligent Electronic Device
IMS	IP Multimedia Subsystem, IP Multimedia Core Network Subsystem
IoE	Internet of Energy
IoT	Internet of Things
IP	Internet Protocol
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
kbps	Kilobits Per Second
KPI	Key Performance Indicator
LPWA	Low-Power Wide-Area
LPWAN	Low-Power Wide-Area Network
LR-WPAN	Low-Rate Wireless Personal Area Network
LSA	Licensed Shared Access
LTE	Long Term Evolution
LUT	Lappeenranta University of Technology
LV	Low Voltage
LVDC	Low Voltage Direct Current
M2M	Machine to Machine
MAC	Media Access Control
Mbps	Megabits Per Second
MEC	Mobile Edge Computing
MME	Mobility Management Entity
mmW	Millimetre Wave
MHz	Megahertz
MIMO	Multiple-Input and Multiple-Output
m-MIMO	Massive-MIMO
MMS	Multimedia Messaging Services or Manufacturing Message Specification
mMTC	Mass Machine Type Communication
MTC	Machine Type Communication
MTU	Master Terminal Unit

MV	Medium Voltage
NAN	Neighbourhood Area Network
NAS	Network-Attached Storage, Network Access Storage, Non-Access Stratum
NES	Network Expert System
NFV	Network Functions Virtualization
NPT	Network Planning Tool
NSN	Nokia Solutions and Networks
OPC	OLE for Process Control
OPEX	Operating Expenditure
OTT	Over-the-Top Content
PC	Personal Computer
PCRF	Policy and Charging Rules Function
PDCP	Packet Data Control Protocol
PDN	Packet Data Network
PGW	Packet Data Network Gateway
PER	Packet Error Rate
PSAU	Primary Substation Automation Unit
QoE, QoX	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RLC	Radio Link Control
RN	Radio Network
RRC	Radio Resource Control
RRU	Remote Radio Unit
RSSI	Received Signal Strength Indicator
RTDS	Real-Time Digital Simulator
RTT	Round Trip Time
RTU	Remote Terminal Unit
SAE	System Architecture Evolution
SAU	Substation Automation Unit
SCADA	Supervisory Control And Data Acquisition
SDN	Software-Defined Networking
SDO	Standard Development Organisations
SGW	Serving Gateway
SIM	Subscriber Identity Module
SMS	Short Message Service

SN	Sensor Network
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Networks
SSAU	Secondary Substation Automation Unit
SSL	Secure Sockets Layer
SSN	Secondary Substation Node
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TIA	Telecommunications Industry Association
TSL	Transport Layer Security
TTA	Telecommunication Technology Association
TTC	Telecommunication Technology Committee
TTI	Transmission Time Interval
TUT	Tampere University of Technology
UA	Unified Architecture
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UDN	Ultra-Dense Networks
UDNS	Unicast DNS
uMTC	Ultra-Reliable Machine Type Communication
UP	User Plane
UTRAN	Universal Terrestrial Radio Access Network
UVA	University of Vaasa
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	V2I and V2V
VAC	Volts of Alternating Current
VDC	Volts of Direct Current
VPN	Virtual Private Network
VTT	Technical Research Centre of Finland
WAN	Wide Area Network
WiMAX	Worldwide Interoperability for Microwave Access
WLAN, Wi-Fi	Wireless Local Area Network
WSN	Wireless Sensor Networks
xMBB	Extreme Mobile Broadband

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