Enabling LTE for Control System Applications in a Smart Grid Context

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Abstract

The next generation electric power system, known as Smart Grid, is expected to alleviate the energy shortage problem by exploiting renewable energy resources. The Smart Grid communication network, with its diverse structure, constitutes an indispensable component in the new power system. In terms of power industry standards, the International Electrotechnical Commission (IEC) 61850 framework is of particular note. Originally defined to cover the stringent requirements for automation within the substation, IEC 61850 is proving to be a versatile standard that can also be applied to the medium- and low-voltage networks while facilitating control applications. Long Term Evolution (LTE) appears as a remarkable candidate for supporting remote automation tasks in the electricity grid, offering low latency, high throughput and quality of service differentiation in a single radio access technology. In the context of the thesis, a performance evaluation of the integration of LTE technology with IEC 61850 communication services is carried out. A characterization of the network architecture and the performance requirements for intelligent power system management is performed and an analytical model for the scheduling framework is proposed. Emphasis is given on the development of optimal prioritization schemes and techniques in order to ensure control data scheduling in situations when LTE background traffic coexists in the network. In addition, realistic communication scenarios specifically designed to emulate real network operations are considered and extensive simulations are performed with the use of Ericsson’s radio system simulator platform. The results have demonstrated that LTE networks successfully meet the performance requirements for wide-area automation tasks within a Smart Grid context. Given the size of the LTE ecosystem, such an evolution constitutes an attractive path for future wireless communication.
Acknowledgements

As with any endeavor, the present research project could not have been completed without the assistance and support of many others.

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In addition, I would like to thank Dr. Fiona Williams, Research Director of Ericsson, for her mentorship and support during my entire tenure at Ericsson Eurolab. Working as an intern for the EIT research activity 'LTE for Smart Energy' while simultaneously pursuing my academic endeavors, greatly added to the quality of my work as a student.

Throughout my Master studies, I had the opportunity to work with and learn from many talented fellow students. Thank you all for the precious knowledge exchange. A special acknowledgement also goes to all my friends for making my stay in Stockholm memorable.

This work is dedicated to my beloved family. I would like to thank my parents for encouraging me to pursue my dreams and supporting me whenever I needed it, despite the distance. I would also like to thank my sister, Georgia, for her unconditional kindness.
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<td>3rd Generation Partnership Project</td>
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<tr>
<td>4G</td>
<td>4th Generation</td>
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<tr>
<td>ACSI</td>
<td>Abstract Communication Service Interface</td>
</tr>
<tr>
<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
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<td>AMI</td>
<td>Advanced Metering Infrastructure</td>
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<td>AMR</td>
<td>Adaptive Multi-Rate</td>
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<td>ARQ</td>
<td>Automatic Repeat reQuest</td>
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<td>BSR</td>
<td>Buffer Status Report</td>
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<td>CAPEX</td>
<td>Capital Expenditure</td>
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<td>CDC</td>
<td>Common Data Class</td>
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<td>CP</td>
<td>Cyclic Prefix</td>
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<td>CQI</td>
<td>Channel Quality Information</td>
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<td>DAP</td>
<td>Data Aggregation Points</td>
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<td>DER</td>
<td>Distributed Energy Resources</td>
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<tr>
<td>E-UTRAN</td>
<td>Evolved UMTS Terrestrial Radio Access Network</td>
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<tr>
<td>EIT</td>
<td>European Institute of Innovation and Technology</td>
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<td>EMS</td>
<td>Energy Management System</td>
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<td>EPC</td>
<td>Evolved Packet Core</td>
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<td>EPS</td>
<td>Evolved Packet System</td>
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<td>FAN</td>
<td>Field Area Network</td>
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<td>FDD</td>
<td>Frequency Division Duplex</td>
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<td>FTP</td>
<td>File Transfer Protocol</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>GBR</td>
<td>Guaranteed Bit Rate</td>
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<td>GOOSE</td>
<td>Generic Object Oriented Substation Event</td>
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<td>GSM</td>
<td>Global System for Mobile communications</td>
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<td>GSSE</td>
<td>Generic Substation Status Event</td>
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<td>HAN</td>
<td>Home Area Network</td>
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<td>HARQ</td>
<td>Hybrid Automatic Repeat reQuest</td>
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<tr>
<td>HTTP</td>
<td>HyperText Transfer Protocol</td>
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<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
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<td>IED</td>
<td>Intelligent Electronic Device</td>
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<td>ISO</td>
<td>International Organization for Standardization</td>
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<td>LAN</td>
<td>Local Area Networks</td>
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<td>LTE</td>
<td>Long Term Evolution</td>
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<td>MAC</td>
<td>Medium Access Control</td>
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<td>MCAA</td>
<td>MultiCast Application Association</td>
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<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<td>MME</td>
<td>Mobility Management Entity</td>
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<td>MMS</td>
<td>Manufacturing Messaging Specification</td>
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<td>NAN</td>
<td>Neighbor Area Network</td>
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<tr>
<td>NAS</td>
<td>Non-Access Stratum</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
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<td>OPEX</td>
<td>Operating Expenditure</td>
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<td>P-GW</td>
<td>Packet Data Network Gateway</td>
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<td>PAN</td>
<td>Premises Area Network</td>
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<tr>
<td>PAPR</td>
<td>Peak-to-Average Power Ratio</td>
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<tr>
<td>PDCP</td>
<td>Packet Data Control Protocol</td>
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<td>PDN</td>
<td>Packet Data Network</td>
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<tr>
<td>PHY</td>
<td>Physical layer</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>PLC</td>
<td>Power Line Communications</td>
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<td>PLR</td>
<td>Packet Loss Ratio</td>
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<td>PMU</td>
<td>Phasor Measurement Units</td>
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<tr>
<td>QCI</td>
<td>Quality of Service Class Identifier</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>RB</td>
<td>Resource Block</td>
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<td>RE</td>
<td>Resource Element</td>
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<td>RLC</td>
<td>Radio Link Control</td>
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<td>ROHC</td>
<td>Robust Header Compression</td>
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<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
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<td>S-GW</td>
<td>Serving Gateway</td>
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<td>SC-FDMA</td>
<td>Single Carrier Frequency Division Multiple Access</td>
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<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
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<td>SCL</td>
<td>Substation Configuration Language</td>
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<td>SNTP</td>
<td>Simple Network Time Protocol</td>
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<td>SV</td>
<td>Sampled Values</td>
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<td>TC</td>
<td>Technical Committee</td>
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<td>TDD</td>
<td>Time Division Duplex</td>
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<tr>
<td>TPAA</td>
<td>Two Party Application Association</td>
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<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
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<tr>
<td>VoIP</td>
<td>Voice over IP</td>
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<tr>
<td>WAN</td>
<td>Wide Area Network</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
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Chapter 1

Introduction

In the next-generation electric power systems, automated and intelligent power management is a critical component that determines the effectiveness and efficiency of the overall system. The management automation and intelligence are envisioned to offer a variety of advantages over the current systems in terms of digitalization, flexibility, resilience, sustainability, and customization, which entitles the name Smart Grid to the next-generation power systems. The realization of the Smart Grid applications requires a rigorous interplay between several knowledge fields and the enhancement of the existing networks and standards, inheriting crucial benefits from these systems [1].

1.1 Background

As one of the enabling technologies, a fast, reliable and secure communication network plays a crucial role in the achievement of the potential advantages of the Smart Grid. The current communication capabilities of the existing power systems are limited to small-scale local regions that implement basic functionalities for system monitoring and control, such as Power Line Communications (PLC) [2] and the Supervisory Control and Data Acquisition (SCADA) [3] systems, which do not yet meet the demanding communication requirements for the automated and intelligent management in the next-generation electric power systems. A Smart Grid is composed of a diversity of electric generators and power consumers that are located distributively over remote areas and mutually connected into the same management network. Real-time and bidirectional communication between Intelligent Electronic Devices (IEDs) and systems is enabled. This constitutes the key to support control and automation tasks which, in certain cases, require time-sensitive and data-intensive information exchange.

The International Electrotechnical Commission (IEC) is the world’s leading organization that prepares and publishes International Standards for all electrical, electronic and related technologies. IEC has published several standards for various applications within the Smart Grid. Of particular importance is IEC 61850, which constitutes the standard for the design of electrical substation automation. IEC 61850 is extended to support inter-substation, control centers to substations and Distributed Energy Resources (DER) communications. It also enables interoperability by defining abstract models and services to support communications between IEDs in the electricity grid [4].
Chapter 1. Introduction

1.2 Motivation

Various communication technologies have been considered for implementing the communication network, such as optical communications, PLC, Ethernet etc. In the context of the thesis, the integration of 3GPP Long Term Evolution (LTE) technology [5] with control system applications within a Smart Grid context is examined.

LTE represents the significant advances in the cellular technology. It is initially designed to support high-speed multimedia unicast and broadcast services. LTE appears as a promising option to support control system applications in the Smart Grid, providing the main advantages of low latency, high capacity, ubiquitous coverage and use of the existing public LTE infrastructure. Scalability, reliability and security constitute also important factors that enhance the suitability of this particular cellular technology.

However, LTE was not initially intended for Smart Grid applications [6]. Moreover, Smart Grid data traffic characteristics are not the same as those generated by commercial and enterprise communication networks in use today, therefore LTE network needs to be optimized for data flows related to power automation applications.

The present thesis project is conducted as a part of European Institute of Innovation and Technology (EIT) research activity "LTE for Smart Energy" [7, 8, 9] with specific innovation objective to evaluate and demonstrate how LTE technologies enable smart energy applications, making the delivery of Smart Grid services realisable using public LTE infrastructures.

1.3 Outline

The remainder of the thesis is organized as follows.

Chapter 2 presents the problem to be addressed by the thesis. In addition, the main research questions that the thesis aims to answer, are stated together with the relevant work in this particular area.

Chapter 3 provides a technical overview for LTE. Emphasis is given on the system and protocol description and the LTE scheduling framework is presented in detail.

Chapter 4 describes the distribution automation applications within a Smart Grid context. The communication network architecture is discussed while the specific features and requirements of IEC 61850 standard are provided.

Chapter 5 proposes the scheduler design through a theoretical analysis and an analytical model for the characterization of the LTE scheduling policy is presented.

Chapter 6 describes in detail the simulation experiments and provides an evaluation of the simulation results with the use of relevant network performance metrics.

Finally, Chapter 7 outlines the conclusions of the thesis providing suggestions of further research related to this area.
Chapter 2

Problem Formulation

The study on the novel communication architectures for automated and intelligent system management is still at a primitive stage. Many technical challenges are awaiting solutions. This chapter describes the problem that is addressed in the present Master thesis and the research questions that are posed.

2.1 Problem Statement

IEC 61850 standard was initially defined for internal substation automation and its services use Ethernet as the communication network technology in the data link layer [4]. Ethernet is implemented extensively in power systems to provide real-time monitoring and control through Local Area Networks (LANs).

In the next-generation Smart Grid systems that incorporate diversified renewable energy resources, intelligent control centers are expected to remotely control electric devices separated in large geographical distances. In addition, the transmission infrastructures are expected to employ new technologies in order to enhance the power quality and the smart substations are expected to coordinate their local devices self-consciously. Enabled by the significant advancements in system automation and intelligence, IEC 61850 is proposed to be extended for supporting remote control applications and communication between substations, control centers to substations and DERs [10].

Ethernet, a non-routable protocol, was not initially designed for wide-area communications. Moreover, as the number of DERs and electric vehicles in the Smart Grid communication network increases, Ethernet is rendered insufficient in terms of scalability and installation cost. Under this perspective, LTE, as the latest mobile communication network, appears as a promising solution to map IEC 61850 communication services. Using the existing cellular infrastructure and, consequently, reducing the installation cost, Smart Grid can exploit the important advantages LTE offers in terms of latency, capacity, adjustable cell size, security and reliability. However, LTE has been designed for broadband applications and human-to-human data traffic while most control applications in the Smart Grid applications require sporadic, small amount and time-critical data exchange, leading to non-optimized transmission protocols [11].
2.2 Research Questions

In the context of the thesis, several research questions are posed concerning the enablement of LTE technology for control system applications in the Smart Grid.

1. Which are the basic communication requirements and challenges for supporting remote control communications and IEC 61850 services over LTE?

2. What is needed in order to ensure Smart Grid traffic data scheduling without jeopardizing the conventional LTE traffic in network resources-limited situations?

3. Which is the proposed solution for overcoming these challenges in terms of latency and throughput?

4. Which are the potential limitations and bottlenecks in the LTE network structure that occur while satisfying the performance requirements imposed by IEC 61850?

The theoretical research and simulation results conducted in the context of the present Master thesis aim to answer the above mentioned questions. The thesis performs an overall evaluation of LTE communication technology for remote control communications in electricity distributed grid.

2.3 Relevant Work

The traffic requirements for communication within a Smart Grid are introduced in related literature. In [12], the major types of traffic that a Smart Grid communication network is anticipated to carry are studied along with their QoS requirements. In [4, 13, 14], concepts such as Advanced Metering Infrastructure (AMI) networks (two-way communication networks that interconnect smart meters) and IEDs (example of which are the Phasor Measurement Units (PMUs)) are discussed. The communication requirements for substation automation systems are defined in IEC 61850-5 standard [4]. In specific, the standard describes the performance classes and transfer time upper bounds for the different message types.

Utility based adaptive resource allocation mechanisms with channel dependent information have been previously studied in [15, 16]. While several works have dealt with the uplink scheduling in LTE, the literature is limited in addressing the scheduling of Smart Grid traffic in LTE-based cellular systems [17]. Schedulers designed for LTE cannot be directly applied for Smart Grid, mainly because of the assumption for a limited number of different services and QoS requirements. LTE scheduler schemes are proposed in [18, 19, 20] for common user equipments i.e. mobile phones, which have different requirements with respect to Smart Grid components. In [21] a new LTE scheduler is proposed for Smart Grid based on the distribution of the latency and attempts to guarantee the above mentioned requirements.

In [22], the integration of Wireless Local Area Networks (WLAN) technology with substation automation applications is examined. This particular approach reveals the disadvantages of limited coverage of WiFi technology for remote control communications. Furthermore, at the time the research is conducted, there is no previous study on how
cellular technologies and, in particular LTE, can be used for supporting IEC 61850 communication services. The latency and throughput constraints that energy automation tasks introduce in the scheduling process, when coexist in the same network with LTE conventional traffic, is the principal research objective. As the research and development of this area are currently on progress and closely related to the standardization efforts for 5G technology, the present research activity provides an innovative approach for the current status and future expectation of cellular technologies for control system applications in a Smart Grid context.
Chapter 3

Long Term Evolution: A Technical Overview

In the present chapter, the basic principles of Long Term Evolution (LTE) standard are presented. Its key features are described along with the scheduling framework which constitutes an important concept for the integration with control system applications in Smart Grid.

3.1 Introduction

The 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) represents the global standard for the 4th generation of mobile networks (4G). LTE constitutes the latest standard in the mobile network technology tree that previously realized the Universal Mobile Telecommunication System (UMTS) and the Global System for Mobile Communications (GSM) network technologies. 3GPP work on the evolution of the 3G mobile system started in November 2004 and was finalized in December 2008, standardized in the form of Release 8 document series.

3GPP summarizes the motivation to develop LTE network:

- Ensure the competitiveness of the 3G system.
- User demand for higher data rates and Quality of Service (QoS).
- Packet Switch optimized system.
- Continued demand for cost reduction (Capital Expenditure, CAPEX and Operating Expenditure, OPEX).
- Low complexity.
- Avoid unnecessary fragmentation of technologies for paired and unpaired band operation.
3.2 Key Features

LTE is designed to support high-speed multimedia unicast and broadcast services. Its main goal is to provide high data rate, low latency and packet optimized radio access technology supporting flexible bandwidth deployments. The LTE specification provides downlink peak rates of 300 Mbps, uplink peak rates of 75 Mbps and QoS provisions allowing a transfer latency of less than 5 ms in the radio access network. The user plane latency achieved in LTE is less than in existing 3G technologies providing a direct service advantage for time-critical and interactive application environments.

LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz and uses both Frequency Division Duplex (FDD) and Time Division Duplex (TDD) mode to separate downlink and uplink communications. In FDD, uplink and downlink transmission use different frequencies, while in TDD, both uplink and downlink use the same carrier and are separated in time [23].

The LTE physical layer presents significant efficiency in handling both data and control signaling and employs advanced technologies like Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO). In the downlink, LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) and in the uplink, Single Carrier Frequency Division Multiple Access (SC-FDMA). LTE allows resource allocation on a subcarrier-by-subcarrier basis for a specified number of OFDM symbols. In addition, all LTE devices have to support MIMO transmissions allowing the base station to transmit several data streams over the same carrier simultaneously.

3.3 System Description

LTE architecture is organized in a way that minimizes the overall complexity. As depicted in Figure 3.1, LTE is characterized by a flat architecture which is divided into four main high level domains: the User Equipment (UE), which is usually a device that provides authentication and the interface to the end user, the Evolved-Universal Terrestrial Access Network (E-UTRAN), the Evolved Packet Core Network (EPC), and the Services Domain. In the following subsections, the basic characteristics of E-UTRAN and EPC are presented.

3.3.1 Evolved-Universal Terrestrial Access Network

The E-UTRAN is the air interface of LTE and constitutes the access part of the Evolved Packet System (EPS). E-UTRAN network side is composed only of base stations, eNodeBs, that are equipped with all radio interface-related functions. In particular, the eNodeB hosts the PHYSical (PHY), Medium Access Control (MAC), Radio Link Control (RLC), and Packet Data Control Protocol (PDCP) layers that include the functionality of user-plane header-compression and encryption. It also offers Radio Resource Control (RRC) functionality corresponding to the control plane. Other functionalities include radio resource management, admission control, scheduling, enforcement of negotiated uplink QoS, ciphering/deciphering of user and control plane data, and compression/decompression of downlink/uplink user plane packet headers [25].
In E-UTRAN, there is no centralized intelligent controller, and the eNodeBs are normally inter-connected via the X2-interface and towards the core network by the S1-interface. The reason for distributing the intelligence amongst the base-stations in LTE is to speed up the connection set-up and reduce the time required for a handover.

### 3.3.2 Evolved Packet Core Network

The Evolved Packet Core (EPC) network architecture supports the E-UTRAN through a reduction in the number of network elements, simpler functionality and improved redundancy. It also allows for connections and hand-over to other fixed line and wireless access technologies, giving the service providers the ability to deliver a seamless mobility experience [25]. The main components that exist in a typical EPC are:

- **The Serving Gateway (S-GW):** The S-GW routes and forwards user data packets. It is the node that terminates the interface towards E-UTRAN and acts as the mobility anchor for the user plane during inter-eNodeB handovers and for compatibility between LTE and other 3GPP technologies.

- **The Packet Data Network Gateway (P-GW):** The P-GW provides connectivity to the UE to external Packet Data Networks (PDNs) using the SGi interface. The UE may be simultaneously connected with more than one P-GWs for accessing multiple PDNs. The interface between the S-GW and P-GW is known as S5/S8. This has two slightly different implementations, namely S5 if the two devices are in the same
network, and S8 if they are in different networks.

- The Mobility Management Entity (MME): The MME is the key control-node for the LTE access-network controlling the high-level operation by means of signaling messages. It is responsible for user authentication and for regulating security parameters. It is also involved in the bearer activation/deactivation process.

A key feature of the EPS is the separation of the network entity that performs control-plane functionality (MME) from the network entity that performs bearer-plane functionality (S-GW) with a well defined open interface between them (S11). E-UTRAN and EPC functionalities for an LTE network are summarized in Figure 3.2.

### 3.4 Protocol Layer Architecture

The radio protocol architecture for LTE can be separated into user plane and control plane architecture. Figures 3.3 and 3.4 illustrate the user and control plane protocol stacks respectively.

Concerning the case of the user plane, the application creates data packets that are forwarded to underlying protocols such as TCP, UDP (Transport layer) and IP (Network layer). Next, the information is processed successively by the PDCP, RLC and the MAC protocol, before being passed to the physical layer (L1) for transmission. In particular,

- The PDCP layer is responsible for compressing/decompressing the headers of IP packets using Robust Header Compression (ROHC) to enable the efficient use of the air interface bandwidth.
• The RLC layer is used to format and transport traffic between the UE and the eNodeB. Using the outer Automatic Repeat reQuest (ARQ) method, RLC ensures reliability by handling residual errors.

• The MAC layer schedules the different UEs and their services in both uplink and downlink depending on their relative priorities, and selects the most appropriate transport format. It is also responsible for retransmissions using the Hybrid Automatic Repeat reQuest (HARQ) method.

While inserting the core network (EPC), packets are encapsulated in a specific EPC protocol and tunneled between the P-GW and eNodeB. Different tunneling protocols are used depending on the interface. GPRS Tunneling Protocol (GTP) is used on the S1 interface between the eNodeB and S-GW and on the S5/S8 interface between the S-GW and P-GW.

For the control plane, the Non-Access Stratum (NAS) protocol, running between the MME and the UE, is used for control purposes such as network establishment, authentication, bearer enablement and mobility management. The signaling messages are produced by the RRC protocol and the information flows to the lower layers as in the case of the user plane. The only difference lies on the fact that there is no header compression function for the control plane. RRC protocol is also responsible for the establishment and maintenance of the radio bearers [25].
3.5 LTE Bearer Architecture

An end-to-end and QoS class-oriented architecture has been defined for LTE. Since EPS is a connection-oriented transmission network, it requires the establishment of a virtual connection between two endpoints (e.g. UE and S-GW) before any traffic can be sent between them [26].

The QoS approach adopted for LTE is significantly simpler than the QoS methods defined for 3G/HSPA. The mechanism is based on the concept of data flows and bearers. EPS bearers provide one-to-one correspondence with RLC radio bearers. In particular, data flows are assigned to bearers and, as illustrated in Figure 3.5, three individual bearers (Radio, S1 and S5/S8) are successively combined in order to provide a virtual end-to-end QoS connectivity.

A bearer can be considered as a set of multiple QoS requirements which are indicated by the QoS Class Identifier (QCI). Each QCI describes the type of service that makes use of the virtual connection (e.g. conversational voice, streaming video, signaling, best effort, etc). In specific, each QCI is further characterized by a specific priority, maximum delay and acceptable packet error rate. The QCI label also indicates whether the bearer has a Guaranteed Bit Rate (GBR) or not (non-GBR) and determines the way it is handled by the eNodeB.

3.6 The LTE Scheduling Framework

The scheduler constitutes a key component for the achievement of an optimal and efficient utilization of the available radio resources. Its role is even more significant in situations of limited network resources when different users, associated with various performance requirements, are competing simultaneously for network access. The scheduling activity needs to accommodate the broad range of air interface features whilst simultaneously optimising the system capacity and ensuring QoS to users.

The physical layer at the eNodeB is responsible for protecting the information against
channel errors using Adaptive Modulation and Coding (AMC) schemes based on the channel conditions. QPSK, 16QAM and 64QAM are the available downlink and uplink modulation schemes in E-UTRAN [24]. Channel Quality Information (CQI) is collected by the eNodeB and used to determine the modulation and coding scheme for each user in the cell.

In order to achieve high radio spectral efficiency as well as enable efficient scheduling in both time and frequency domain, a multi-carrier approach for multiple access is chosen by 3GPP. For the downlink, OFDMA is employed while for the uplink, SC-FDMA is employed. OFDM is a multicarrier technology subdividing the available bandwidth into a multitude of mutual orthogonal narrowband subcarriers. In OFDMA, users are allocated these subcarriers for a predetermined amount of time by the eNodeB, so that multiple users can be scheduled for data transmission simultaneously. The OFDMA solution leads to high Peak-to-Average Power Ratio (PAPR) requiring increased power amplifier linearity requirements and reduced power efficiency on the transmit side [23]. Therefore, in order to avoid excessive cost for the mobile terminals, the SC-FDMA approach is selected for the uplink, which generates a signal with single carrier characteristics, hence with a low PAPR.

Figure 3.6 illustrates the physical layer frame structure with FDD. Each frame has a duration of 10 ms and is divided into 10 subframes. Each subframe is further divided into two slots of 0.5 ms length. Assuming a normal short Cyclic Prefix (CP), each slot consists of 7 OFDM symbols.

In the time domain, radio resources are distributed every Transmission Time Interval (TTI). TTI is considered the minimum scheduling unit in LTE and corresponds to a subframe with a duration of 1 ms. In the frequency domain, the available bandwidth (1.4, 3, 5, 10, 15 or 20 MHz) is divided into a number of sub-channels each including 12 subcarriers with spacing of 15 KHz. Each sub-channel has a bandwidth of 180 KHz and along with the 7 symbols in the time domain constitutes a Resource Block (RB).
Depending on the available bandwidth, the number of RBs ranges from 6 to 110. Two consecutive RBs form a scheduling block, which is the smallest resource unit that a scheduler can allocate to a user. Figure 3.7 illustrates the resource grid of LTE downlink. Each box in the grid represents a single subcarrier for one symbol period and is called a Resource Element (RE). Therefore, each RB is composed of 84 REs in total. Some of them are reserved for synchronization and channel estimation purposes and they follow a certain pattern within the grid [24].
Chapter 4

Distribution Automation
Applications in Smart Grid

Distribution automation is considered an integral component within the Smart Grid paradigm. It facilitates the employment of computer technology and communication infrastructure to advance management, control and operation of the distribution network. This chapter provides an overview of the control system applications in the distribution electricity grid.

4.1 Introduction to Smart Grid

Smart Grid generally refers to the modernization of the existing aging power grid, turning it into a modern, interoperable network that integrates information and communication technologies in the energy distribution infrastructure. Bidirectional flow of both energy and information is its main feature. Smart Grid deploys a large-scale dedicated communication infrastructure to enable a two-way flow of information between consumers, providers, and grid devices. The intelligent characteristics, evident at all stages - from generation, transmission and distribution to consumption as well as pricing of energy - render the network more efficient, robust, environmental-friendly and manageable, while facilitating the monitoring and control of all the components of the grid.

During the recent years, a rapid transformation of the current electric power systems is witnessed in order to meet the increasing demand for higher resilience, adaptability, and sustainability. Utility companies recognize that the conventional unidirectional and centralized model for electricity production, distribution and control becomes inadequate for achieving these goals. Moreover, the numerous challenges posed by the undergoing technology advancements lead to the evolution of the next-generation electricity grid towards a Smart Grid [1].

In particular, important factors that constitute the driving force behind the need for the modernized electric power network are:

- The widespread deployment of renewable DERs (e.g. micro-generators at residential customers’ premises or small-scale wind and solar farms) which appear as important supplements and replacements for fossil fuels, due to sustainability and environmental friendliness.
• The need of a more active role for consumers, who should better control their electricity usage in response to variable energy supply conditions and/or prices.

• The large-scale integration of electric vehicles without overloading the electricity grid.

• The integration of widely dispersed battery storage systems.

A Smart Grid network enhances the capacity and efficiency of the existing power grids, optimizing the utilization of the facilities. Moreover, in order to ensure optimal awareness of the network conditions, operators need a lot of information regarding the state of the grid. This insight is achieved using fast and real-time system information in the substations with the use of PMUs. PMUs provide synchronized phasor measurements of voltages and currents in the electricity grid with a sample frequency of 60 Hz. Information is then used by Energy Management Systems (EMS) in the control centers to provide improved assessment, monitoring, control and protection mode [14].

Therefore, it becomes evident that communication plays a critical role in the real-time operation of the power system. The Smart Grid communication network constitutes an important factor in the overall deployment of the grid and the communication infrastructure must support the expected functionality and meet the performance requirements.

The following section provides an overview of the communication network architecture in a Smart Grid.

### 4.2 Smart Grid Communication Network Architecture

The key for achieving the potential advantages of the Smart Grid is the successful design and implementation of a reliable, secure, yet cost-effective communication infrastructure. This constitutes a challenging task since it requires the integration of various network segments that are responsible for maintaining the communications among a vast number of heterogeneous industrial devices. These smart devices are characterized by diverse QoS constraints and are distributed over large geographical regions.

The communication infrastructure in a Smart Grid connects a huge number of electrical devices and manages their complex communication. It is organized in a hierarchical structure with interconnected individual subnets, each of which is responsible for a specific geographical region. The communication network topology is illustrated in Figure 4.1.

In a Smart Grid context, communication networks can be classified into four main categories, each one having particular features [12]. More specifically:

• The Home Area Network (HAN): It gathers sensor information from a variety of smart devices within the home and delivers control information to them for better energy consumption management. In an AMI system, which constitutes a two-way communication system, HAN acts as data acquisition network and provides low-cost, scalable, and reliable solutions to monitor and control smart electric appliances deployed at residential and business premises.

• The Neighbor Area Network (NAN): The NAN (also referred as Field Area Network, FAN) constitutes the communication unit for the power distribution systems.
This network domain is responsible both for collecting data from smart meters and transferring them to the Data Aggregation Points (DAPs). NAN is considered a critical communication domain since it is responsible for transporting a huge volume of different types of data and distributing control signals. There is a variety of wireless and wired technologies available to be applied in this domain, which should however provide broadband speed and security.

- **The Wide Area Network (WAN):** The WAN aggregates the data from multiple NANs and transfers them to the utility companies’ private networks. It is responsible for providing the two-way network needed for substation communications, distribution automation and power quality monitoring. It also enables the interconnection between the control centers with the highly dispersed DAPs deployed at different locations of the power system. To be effective, the WAN, should cover the entire transmission and distribution grids, including all substations and integrate a massive number of distributed power generation and storage facilities. In addition, it should also support data management services for the large amounts of information generated by AMI systems and other data collection networks deployed in the distribution grid. Therefore, not only broadband connectivity is required but also the network installation needs to be cost efficient and as simple as possible. In addition, the routes and connections through which the data flows, should be flexible and seamless.

- **The wired backhaul network:** It is usually built in optic fibers. Its primary objective is to support the interconnection between the numerous substations and the utilities. Therefore, the corresponding communication technology requires high capacity and bandwidth availability in order to manage and accommodate the large amount of data transferred from the other domains.

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**Figure 4.1** The overall architecture of a Smart Grid Network: (a) power system layer (b) communication layers. [12]
4.2.1 Communication Technologies

Various communication technologies have been proposed for the implementation of the different segments in the Smart Grid communication network. Optical communications appear as a reliable option but of high cost, and thus only suitable for high-speed back-haul links. On the other hand, PLC technologies are cost effective; however, the lack of globally recognized standards resulting in coexistence and interoperability issues (noise/interference, attenuation, etc.), has hindered the mass market penetration of PLC-based technology [12].

Zigbee (IEEE 802.15.4, ZigBee Alliance) can be used to embed wireless communications into HAN devices without the prohibitive installation cost of wiring. In addition, for implementing HAN communications, WiFi (IEEE 802.11a/b/g/n) appears as a mature technology with established worldwide adoption.

In the context of the thesis, the focus is given on the cellular technologies for WAN and NAN. In particular, LTE communication technology emerges as a promising candidate for satisfying the requirements of many advanced Smart Grid applications including distribution automation, demand response, outage management, fault detection and restoration. Using the existing cellular communication infrastructure, utility companies do not need to invest time and money building a dedicated communication infrastructure. Furthermore, remote control applications in the distribution grid must be supported and deployments are allowed to be spread over a wide geographical region. In addition to the low latency that it provides, LTE is applicable to achieve high data rates especially when data exchanges in the distribution grid are frequent to support emerging applications [11].

The thesis focuses on the real-time remote control communications in the distribution grid and how LTE can support distribution substation applications. As the international standard for power substation automation systems, IEC 61850 defines the communication between devices in the substation and related system requirements [10]. The following section provides a technical description of the IEC 61850 standard and its role for supporting communication in substation automation systems.

4.3 Overview of IEC 61850 Standard

IEC 61850 standard has been defined in cooperation with manufacturers and users to create a uniform and future-proof basis for the protection, communication and control of substations. The standard is part of the International Electrotechnical Commission’s (IEC) Technical Committee 57 (TC57) architecture for electric power systems. It introduces a model-driven approach about substation automation resulting in significant improvements in both costs and performance of electric power systems. IEC 61850 has contributed immensely to the way communication and information exchange are implemented within an electrical substation [10].

While the IEC 61850 standard was originally addressing applications and communications within the substation, recent work is undergone for extending it beyond the substation fence. With its object oriented structure, IEC 61850 can provide comprehensive and accurate information models for various components of distribution automation systems, while providing an efficient solution for this naturally multi-vendor environment. It aims to ensure, amongst other things, interoperability among devices from different vendors.
The various aspects of the substation communication network are defined in ten specific sections as shown in Table 4.1.

<table>
<thead>
<tr>
<th>Part</th>
<th>Title</th>
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<tbody>
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<td>2</td>
<td>Glossary of terms</td>
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<td>3</td>
<td>General Requirements</td>
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<td>4</td>
<td>System and Project Management</td>
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<tr>
<td>5</td>
<td>Communication Requirements for Functions and Device Models</td>
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<tr>
<td>6</td>
<td>Configuration Description Language for Communication in Electrical Substations Related to IEDs</td>
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<td>7</td>
<td>Basic Communication Structure for Substation and Feeder Equipment</td>
</tr>
<tr>
<td>7.1</td>
<td>Principles and Models</td>
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<tr>
<td>7.2</td>
<td>Abstract Communication Service Interface (ACSI)</td>
</tr>
<tr>
<td>7.3</td>
<td>Common Data Classes (CDC)</td>
</tr>
<tr>
<td>7.4</td>
<td>Compatible logical node classes and data classes</td>
</tr>
<tr>
<td>8</td>
<td>Specific Communication Service Mapping (SCSM)</td>
</tr>
<tr>
<td>8.1</td>
<td>Mappings to MMS (ISO/IEC 9506 - Part 1 and Part 2) and to ISO/IEC 8802-3</td>
</tr>
<tr>
<td>9</td>
<td>Specific Communication Service Mapping (SCSM)</td>
</tr>
<tr>
<td>9.1</td>
<td>Sampled Values over Serial Unidirectional Multidrop Point-to-Point Link</td>
</tr>
<tr>
<td>9.2</td>
<td>Sampled Values over ISO/IEC 8802-3</td>
</tr>
<tr>
<td>10</td>
<td>Conformance Testing</td>
</tr>
</tbody>
</table>

Table 4.1 Structure of the IEC 61850 standard [4]

4.3.1 Key Features and Benefits

IEC 61850 standard provides a real object-oriented approach for substation automation. Its key features can be summarized as follows [10]:

- IEC 61850 defines an object-oriented and application-specific data model focused on substation automation. This model, as explained in the following section, includes object types representing nearly all existing equipment and functions in a substation (circuit breakers, protection functions, current and voltage transformers, etc.).

- New communication services are introduced for providing multiple information exchange methods. These services cover reporting and logging of events, control of switches and functions, polling of data-model information, real-time peer-to-peer communication, sampled value exchange, and file transfer for disturbance recordings.

- The above-mentioned data model and communication services are decoupled from specific communication technologies. This technology independence guarantees
long-term stability for the data model and opens up the possibility of switching over to successor communication technologies.

- IEC 61850 proposes a common formal description code, the Substation Configuration Language (SCL), which allows a standardized representation of a system’s data model and its mappings to communication services. SCL covers all communication aspects according to the standard and provides an ideal electronic interchange format for configuration data.

### 4.3.2 Data Modeling Approach

IEC 61850 standard introduces an innovative abstract approach concerning the definition of data objects and services, making them independent of the underlying protocols [27]. Furthermore, it enables an appropriate suitable mapping with the protocols that meet the requirements set by the upper layers.

According to the modeling approach that is proposed, the power system devices organize their data in a manner that is consistent across all types and brands of devices. Consequently, the abstract data and object models of IEC 61850 introduce standardized naming conventions for power system devices that enables all IEDs to operate with common structures directly related to their power system context. This seamless naming of data objects simplifies the handling of communication.

More specifically, the base of the modeling architecture is the physical device. A physical device is the device that is connected to the network and is typically defined by its network address. Within each physical device, there may be one or multiple logical devices. The IEC 61850 logical device model allows a single physical device to act as a proxy or gateway for multiple devices thus providing a standard representation of a data concentrator [10].

Each logical device contains one or more logical nodes. A logical node is a named grouping of data and is associated with services that are logically related to some power system function. Each logical node contains one or more elements of data. Each element of data has a unique name and conforms to the specification of a Common Data Class (CDC). Each CDC describes the type and structure of the data within the logical node. For instance, there are CDCs for status settings, measured information, controllable status information, etc. A CDC is addressed with a specific name and possesses a set of attributes each with a defined name, type and specific purpose.

The definition of the abstract services is described in part 7.2 [27] of the standard and the abstraction of the data objects (referred to as Logical Nodes) is analysed in part 7.4 [28]. Part 8.1 [29] defines the mapping of the abstract data objects and services with the Manufacturing Messaging Specification (MMS) whereas parts 9.1 [30] and 9.2 [31] define the mapping of the measured sampled values into an Ethernet data frame.

### 4.3.3 Communication Model and Services Mapping

The Abstract Communication Service Interface (ACSI) models of IEC 61850 define a set of services that enable all the components of a power automation system to behave in an identical manner from the network behaviour perspective [27]. While the abstract model is critical to achieving this level of interoperability, these models need to be operated...
Important services include:

- Reliable system-wide distribution of substation events.
- Fast and cyclic transfer of sampled values.
- Grouping of data and data attributes.
- Retrieve or write particular data attribute values.
- Time synchronization.
- File transfer.

The communication between the different types of devices is achieved by establishing either a Two Party Application Association (TPAA) or a MultiCast Application Association (MCAA) [27]. In particular, in a TPAA a bidirectional connection-oriented information exchange is performed with a reliable and end-to-end flow control, as shown in Figure 4.2. On the other hand, in a MCAA a unidirectional information exchange is performed between one source (publisher) and one or many destinations (subscriber), as illustrated in Figure 4.3. The subscriber shall be able to detect loss and duplication of information received whereas the receiver shall notify the loss of information to its user and discard the duplicated one.
Chapter 4. Distribution Automation Applications in Smart Grid

The abstract services defined by the standard are mapped to specific protocol profiles according to their requirements. Figure 4.4 illustrates the different communication profiles associated with IEC 61850.

Sampled Values (SV) represents a protocol for carrying measured voltage and current values. The Generic Object Oriented Substation Event (GOOSE) is a controlled model mechanism in which any format of data (status, value) is grouped into a data set and transmitted to more than one physical devices through the use of multicast services. GOOSE messages are used for fast transmission of substation events, such as commands, alarms, etc. SV and GOOSE applications are directly mapped into the Ethernet data frame thereby eliminating processing of any middle layers. The Simple Network Time Protocol (SNTP) is used to provide the synchronized time to devices and system.

MMS is an international standard (International Organization for Standardization (ISO) 9506) dealing with messaging system for transferring real time process data and supervisory control information between networked devices and/or computer applications. The core ASCI services are mapped to the MMS standard which can operate over TCP/IP or ISO. In specific, MMS defines a communication mechanism which includes:

- A set of standard objects which must exist in every device, on which operations can be executed.
- A set of standard messages exchanged between a client and a server stations for the purpose of monitoring and/or controlling these objects.
- A set of encoding rules for mapping these messages to bits and bytes when transmitted.
The Generic Substation Status Event (GSSE) is an identical implementation as the GOOSE and operates over connectionless ISO services.

For all the profiles, high speed switched Ethernet is used to obtain the necessary response times within the substation Local Area Networks (LAN). The data frame uses either the ISO/IEC 8802-3 Ethertype in the case of SV, GOOSE, TimeSync, and TCP/IP or ISO/IEC 8802-3 data type for the ISO and GSSE messages. However, in order to support remote control communications Ethernet introduces some disadvantages whereas wireless cellular LTE can provide significant benefits [4].

4.4 Communication Requirements

In this section, the various communication requirements in transfer time for substation automation systems are presented. The requirements are described in IEC 61850-5 [4] where the transfer time is defined as the complete transmission time of a message including the handling at both ends. As illustrated in Figure 4.5, the time requirement is applicable for the complete transmission chain. The overall transfer time consists of the individual times of the communication processors and the network transfer time, including waiting time and time used by each intermediate forwarding node that adds extra delay to process and relay the message.

The acceptable transfer time varies depending on the control applications and is categorized in performance classes as illustrated in Table 4.2. IEC 61850 classifies the message exchange events in power systems into several categories and requires the transfer times experienced in the communication networks to be less than the default guideline values. These types of messages with their description are summarized in Table 4.3.

The communication networks that are used in the Smart Grid are equipped with the delivery mission of a diversity of messages used in substation automations with some of them having critical delay requirements. The most time urgent messages are related to the important system protection functions and require a delivery delay in the order of tens of milliseconds, which is measured as an end-to-end time from the IED to the control center for problem alarming and back to the IED for emergency responding. It is of paramount importance to guarantee the timely and reliable delivery of these messages within the specified delay windows.
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### Table 4.2 Performance classes for control data [4]

<table>
<thead>
<tr>
<th>Performance class</th>
<th>Requirement description</th>
<th>Transfer time Class</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>The total transmission time shall be below the order of a quarter of a cycle (5 ms for 50 Hz, 4 ms for 60 Hz)</td>
<td>TT6</td>
<td>≤3</td>
</tr>
<tr>
<td>P2</td>
<td>The total transmission time shall be in the order of half a cycle (10 ms for 50 Hz, 8 ms for 60 Hz)</td>
<td>TT5</td>
<td>≤10</td>
</tr>
<tr>
<td>P3</td>
<td>The total transmission time shall be of the order of one cycle (20 ms for 50 Hz, 17 ms for 60 Hz)</td>
<td>TT4</td>
<td>≤20</td>
</tr>
<tr>
<td>P4</td>
<td>The transfer time for automation functions is less demanding than protection type messages (trip, block, release, critical status change) but more demanding than operator actions</td>
<td>TT3</td>
<td>≤100</td>
</tr>
<tr>
<td>P5</td>
<td>The total transmission time shall be half the operator response time of ≤1 s regarding event and response (bidirectional)</td>
<td>TT2</td>
<td>≤500</td>
</tr>
<tr>
<td>P6</td>
<td>The total transmission time shall be in line with the operator response time of ≤1 s regarding unidirectional events</td>
<td>TT1</td>
<td>≤1000</td>
</tr>
</tbody>
</table>

### Table 4.3 Message types defined by IEC 61850 standard [4]

<table>
<thead>
<tr>
<th>Message types</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Messages requiring immediate actions at receiving IEDs</td>
</tr>
<tr>
<td>Type 2</td>
<td>Messages requiring medium transmission speed</td>
</tr>
<tr>
<td>Type 3</td>
<td>Messages for low speed auto-control functions</td>
</tr>
<tr>
<td>Type 4</td>
<td>Continuous data streams from IEDs</td>
</tr>
<tr>
<td>Type 5</td>
<td>Large file transfer functions</td>
</tr>
<tr>
<td>Type 6</td>
<td>Time synchronization messages</td>
</tr>
<tr>
<td>Type 7</td>
<td>Command messages with access control</td>
</tr>
</tbody>
</table>
Chapter 5

Methodology

The present chapter describes the proposed approach for the integration of IEC 61850 communication services with the LTE communication technology. The approach consists of four particular stages:

- Mapping over LTE protocol stack layers: The set of services defined by the IEC 61850 standard should be compatible with the LTE radio protocol architecture, as described in section 3.4. Since LTE was not initially designed to support energy automation tasks, adaptation protocols are introduced above the transport layer in the OSI model.

- Quality of Service provisioning: Since the remote control communication is considered time-critical, it should be treated with a particular prioritization policy in order to guarantee the performance requirements. This task requires a differentiation of the control traffic with respect to the conventional human-to-human LTE background traffic.

- Analytical modeling: An analytical mechanism is proposed for the description of the queuing and LTE scheduling model. In particular, the queuing model is used to provide a quantitative analysis for the LTE scheduling time and its association with the scheduling resources.

- Scheduler design: The scheduling algorithm implemented in the LTE MAC scheduler should be designed in a way that the performance of remote control communication is guaranteed. Therefore, the scheduling policy takes into consideration the highest priority assigned to the remote control communication flows and allocates the resource blocks accordingly.

In the following sections, the above mentioned implementation stages are presented in detail.

5.1 Mapping over LTE protocol stack layers

In the context of the thesis, emphasis is given on the integration of two specific IEC 61850 application profiles, as described in section 4.3.3, with the TCP/IP protocol stack:
• Client/server (core ACSI) services.
• GOOSE management services.

As illustrated in Figure 4.4, the MMS standard provides the information modeling methods required by the ACSI, since IEC 61850 message types 2, 3 and 5 entail information exchange services. Furthermore, the MMS protocol suite can be mapped over the TCP/IP protocol stack (TCP/IP T-Profile) and thus fulfils the functional requirement [29]. The MMS environment involves an establishment of a single application-to-application association that is created and maintained via a connection-oriented communication profile.

Provided that MMS is not by itself a communication protocol, a set of protocols is introduced in order to satisfy the specifications related to the upper three layers of the ISO OSI reference model (e.g. the layers of application, presentation and session) and conform to the underlying communication principles (TCP/IP communication stack). In particular, as shown in Figure 5.1,

• In the application layer, the Association Control Service Element (ACSE, ISO 8649/8650) application protocol is added for the establishment of the association between the MMS client and server.
• In the presentation layer, the Abstract Syntax Notation (ASN, ISO 8822/8823) presentation protocol is included for the proper deliver and formatting of information.
• In the session layer, the session protocols ISO 8326/8327 and RFC 1006 are implemented for managing the remote procedure calls.

For the GOOSE services, IEC 61850-90-5 technical report [32] describes a standardized mechanism to route IEC 61850-8-1 GOOSE packets by forwarding them as inter-substation traffic, exchanged among different geographic locations (endpoints). The report specifies a communication profile that allows GOOSE to be transferred over an IP
based network in a secure and routable manner with the use of User Datagram Protocol (UDP) as the transport protocol. The property of being routable over wide area IP networks is necessary and suited for a protocol to support wide area applications. UDP is a TCP/IP standard defined in RFC 768 and provides a connectionless datagram service that offers best-effort delivery. In addition, application-specific adaptation protocols are added in the session layer in order to accomplish the operability. As illustrated in Figure 5.2,

- In the application and presentation layers, IEC 61850-8-1 GOOSE is implemented.
- In the session layer, the session protocol consists of three parts:
  - A session protocol that is used to convey key parameters required in order to satisfy the use cases identified for the particular application.
  - The ITU X.234 information technology protocol for providing the OSI connectionless transport services.
  - The RFC 1240 protocol for supporting OSI connectionless transport services on top of UDP.

5.2 Quality of Service Provisioning

As described in section 3.5, the class-based QoS mechanism for LTE relies on the concepts of data flows and bearers. Data flows are mapped to bearers, with three individual bearers (Radio, S1 and S5/S8) combining to provide the end-to-end QoS support via the EPS Bearer. In LTE architecture, bearers are enabled to be mapped to a limited number of discrete classes. Network nodes can be preconfigured for these classes, limiting the amount of QoS information needed to be dynamically signaled.

A set of nine QoS classes has been prescribed in 3GPP specifications, corresponding to an equal number of standardized QCI profiles, as illustrated in Table 5.1. Common
services (conversational voice and video, streaming video, gaming, IMS signaling) are classified based on the resource type (GBR/non-GBR), priority order, packet delay budget and packet loss rate characteristics.

<table>
<thead>
<tr>
<th>QCI</th>
<th>Resource type</th>
<th>Priority</th>
<th>Packet delay budget (ms)</th>
<th>Packet loss rate</th>
<th>Example services</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>100</td>
<td>$10^{-2}$</td>
<td>Conversational Voice</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4</td>
<td>150</td>
<td>$10^{-3}$</td>
<td>Conversational Video (Live Streaming)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3</td>
<td>50</td>
<td>$10^{-3}$</td>
<td>Real Time Gaming</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>5</td>
<td>300</td>
<td>$10^{-6}$</td>
<td>Non-Conversational Video (Buffered Streaming)</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>1</td>
<td>100</td>
<td>$10^{-6}$</td>
<td>IMS Signaling</td>
</tr>
<tr>
<td>6</td>
<td>Non-GBR</td>
<td>6</td>
<td>300</td>
<td>$10^{-6}$</td>
<td>Video (Buffered Streaming), TCP-based (e.g. www, e-mail, ftp, p2p file sharing, etc.)</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>7</td>
<td>100</td>
<td>$10^{-3}$</td>
<td>Voice, Video (Live Streaming), Interactive Gaming</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td>300</td>
<td>$10^{-6}$</td>
<td>Video (Buffered Streaming), TCP-based (e.g. www, e-mail, ftp, p2p file sharing, etc.)</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1 Standardized QCI characteristics [25]

The QCI values presented in Table 5.1 are primarily defined to support human-to-human communications. However, since QCI corresponds to an 8-bit field in the LTE frame, new QCI values can be introduced in order to support remote control communication for Smart Grid [24]. These new values correspond to the IEC 61850 performance classes defined for the various message types in Table 4.2. QoS provisioning is achieved through the establishment of dedicated EPS bearers which are exclusively used by the control traffic. In addition, the control flows are assigned a particular QCI value, associated with a higher priority with respect to the conventional LTE traffic. A GBR resource type and a packet loss rate of $10^{-6}$ are also considered [7]. This QoS differentiation mechanism allows for different packet-forwarding treatment (i.e. scheduling and queue management policy, resource allocation, link layer configuration) for the Smart Grid traffic.

Based on the QCI values, the MAC scheduler makes the scheduling allocation subject to the associated QoS parameters. The following section provides the analytical model of a queuing system and the design principles of a QoS-aware scheduler, where the described priority handling is used to differentiate between remote control and human-to-human communication.

### 5.3 Analytical Model

In order to study theoretically the queuing system and the proposed LTE uplink scheduling framework, a communication scenario is considered where $C$ performance traffic classes arrive with different priorities in the scheduler. Designing an effective scheduling...
algorithm requires the consideration of an accurate traffic model. The traffic flows are characterized by different QCI values and it is assumed that they are all competing simultaneously for resource allocation. A smaller class number $c$ corresponds to a higher priority and a particular class-$c$ traffic flow ($\forall c = 1, 2, \ldots, C$) is characterized by four parameters:

1. The arrivals of the class-$c$ requests, which are modeled as a Poisson process (realistic event-driven traffic) with average arrival intensity $\lambda_c$ requests per time unit.

2. The average request size $F_c$ bytes/request, which is specified by the size of every request.

3. The upper bound of the overall transfer time $\tau_c$, as specified in section 4.4 for the energy automation traffic.

4. The possibility $p_c$ that an arriving request belongs to class-$c$.

For sake of simplicity, it is assumed that the queuing model consists of $C$ queues connected to a scheduler, and each queue is used to hold the traffic of the corresponding class. In accordance with the composition property of the Poisson process [33], the arrivals of class-$c$ requests follow a Poisson process with intensity $\lambda_c = p_c\lambda$ and the total arrivals of all requests follow a Poisson process with average arrival intensity

$$\lambda = \sum_{c=1}^{C} \lambda_c. \quad (5.1)$$

The service time for class-$c$ traffic flow is assumed to follow the Poisson distribution with a mean value of

$$S_c = \frac{F_c}{R_c}, \quad (5.2)$$

where $R_c$ indicates the service rate for class-$c$. The offered traffic load for class-$c$ is denoted as

$$A_c = \lambda_c S_c, \quad (5.3)$$

and in order to ensure the stability of each queue, $A_c < 1$ should be satisfied.

As discussed in section 3.6, the scheduler in LTE has a critical role, which is to determine which RBs will be occupied by each data flow every TTI. At each TTI, multiple RBs can be assigned to a number of flows with different classes; each resource block, however, can be assigned to at most one flow [24].

The scheduling policy is determined according to specific rules that take into consideration the QoS requirements and exploit the time and frequency channel variations at the RBs. In current LTE systems, schedulers are mostly designed for maximizing the overall throughput, while taking into account some fairness and QoS rules. However, while enabling LTE for control system applications, IEC 61850 communication requirements create a totally different landscape, where QoS constraints are increasingly becoming important for the scheduling algorithms.
It is assumed that the LTE scheduler has $B$ MHz available bandwidth, divided into $N$ RBs. Let $n = \{1, 2, \ldots, N\}$ denote the RB index set. The scheduler is capable of assigning RBs arbitrarily to all users, and each RB $n$ has a bandwidth of $B/N$. Moreover, assuming that the throughput usage achieves the Shannon rate limit, the service rate for class-$c$, $R_c$, according to Shannon-Hartley theory, can be expressed as

$$R_c = x_c \frac{B}{N} \log_2 (1 + \text{SINR}_{c,n}),$$

(5.4)

where the variable $x_c$ is introduced for each performance class and indicates the number of resource blocks assigned to class-$c$ traffic flows. \text{SINR}_{c,n} is the average Signal to Interference and Noise Ratio for the RB $n$ at the transmitter. The LTE standard provides reporting mechanisms (Channel Quality and Traffic Load Information) which offer valuable information to the packet scheduler about the cellular environment, assisting the scheduling operation in the uplink [24].

Following the Kendall notation from the queuing theory [33], the particular problem can be modeled as an M/M/1 queuing system. Due to the real-time traffic characteristics of the smart energy system, a preemptive-resume queuing discipline is employed where an ongoing service is interrupted by the arrival of a class with a higher priority [34, 35]. Later the service continues from where it was interrupted.

The mean waiting time $W_c$ for a traffic flow in class-$c$ consists of two discrete components:

1. The waiting time due to the traffic flows with higher or same priority which already exist in the queuing system. This is the waiting time experienced by a flow in a system without priority where only the first $c$ classes exist [34] and is given by

$$W_{c,1} = \frac{V_c}{1 - A'_c},$$

(5.5)

where

$$V_c = \frac{1}{2} \sum_{i=1}^{c} \lambda_i m_{2,i},$$

(5.6)

is the expected remaining service time due to flows with a higher or the same priority and $m_{2,i}$ the second moment of the service time distribution of the $i$-th class [36]. $A'_c$ is defined as the cumulative traffic load given by

$$A'_c = \sum_{i=1}^{c} A_i.$$

(5.7)

2. The waiting time due to the flows with higher priority, which arrive during the waiting or service time and overtake the flow, is considered. This part of the waiting time is equal to

$$W_{c,2} = (W_c + S_c) \cdot \sum_{i=1}^{c-1} \lambda_i S_i = (W_c + S_c) \cdot A'_{c-1}.$$

(5.8)
Therefore, in overall,
\[ W_c = W_{c,1} + W_{c,2} = \frac{V_c}{1 - A'_c} + (W_c + S_c) \cdot A'_{c-1}, \]  
(5.9)
which can be rewritten as follows
\[ W_c (1 - A'_{c-1}) = \frac{V_c}{1 - A'_c} + S_c A'_{c-1}, \]  
(5.10)
and finally gives
\[ W_c = \frac{V_c}{(1 - A'_{c-1}) (1 - A'_c)} + \frac{A'_{c-1}}{1 - A'_{c-1}} S_c. \]  
(5.11)
Combining the previous analytical expressions, the total response time \( T_c \) \((\forall c = 1, 2, ..., C)\) becomes
\[ T_c = W_c + S_c = \frac{\sum_{i=1}^{C} p_i \lambda m_{2,i}}{2 (1 - A'_{c-1}) (1 - A'_c)} + \frac{S_c}{1 - A'_{c-1}}. \]  
(5.12)
Figure 5.3 illustrates the proposed scheduling framework based on the above analysis.

### 5.4 Scheduler Design

Based on the queuing model that was discussed in the previous section, the resource allocation minimization problem for the LTE scheduling model is provided. Moreover, a heuristic scheme is proposed for the resource allocation algorithm.

The resource blocks minimization problem is formulated by taking into consideration the transfer time and throughput constraints for each performance class while ensuring the stability of each queue. Defining \( x \triangleq [x_1, \ldots, x_C]^T \) as the vector of resource blocks assigned to the \( C \) performance classes, the problem can be written as in the form of Equation (5.13):

\[
\begin{align*}
\text{maximize} & \quad x \\
\text{subject to} & \quad \sum_{c=1}^{C} x_c \leq N, \\
& \quad \lambda_c F_c < R_c, \quad \forall c = 1, 2, ..., C, \\
& \quad \sum_{i=1}^{C} \frac{p_i \lambda F_i}{R_i} < 1, \\
& \quad T_{c,\text{total}} \leq \tau_c, \quad \forall c = 1, 2, ..., C, \\
& \quad R_c \geq R_{c,\text{min}}, \quad \forall c = 1, 2, ..., C.
\end{align*}
\]  
Equation (5.13b) indicates that the number of allocated resource blocks cannot be more than the total number of resource blocks. Equation (5.13c) indicates that the arrival rate for class-c should be less than the corresponding service rate to avoid queue overflowing.
Queue State Information

Data queue for class 1

Data queue for class 2

Data queue for class C

Scheduler Function

Channel Quality Information

Traffic Load Information for UL transmission

Different Modulation and Coding Schemes may be used in the different allocated RBs

Figure 5.3 A generic view of the scheduler
Equation (5.13d) is related to the requirement of system stability for a preemptive-resume discipline [37]. Equation (5.13e) represents the upper bound of the overall transfer time for class-\(c\),

\[ T_{c,\text{total}} = T_{\text{core}} + T_c, \quad (5.14) \]

where the delay of the EPC network domain, \(T_{\text{core}}\), is taken into consideration. \(T_c\) is given by Equation (5.12) and the \(\tau_c\) values are specified according to the QoS requirements for the different performance classes [4]. Finally, Equation (5.13f) indicates the lower bound of the throughput for class-\(c\), \(R_{c,\text{min}}\), where its value depends on the specific application that is performed [8, 12].

A dynamic, optimized on a per-TTI basis, QoS-, queue- and channel-aware heuristic scheduling scheme is then proposed, for multiplexing IEC 61850 control traffic over LTE frames. The proposed heuristic scheme constitutes an enhanced implementation of the proportional-fair scheduling algorithm and dynamically decides the number of resource blocks allocated to each class. Every TTI, the scheduler calculates the SINR values according to the Buffer Status Report (BSR) and Channel Quality Information (CQI) that receives from the user equipments. The priority handling is performed by assigning RBs in sequential order from the higher-priority classes to lower-priority classes.

In particular, the initial number of resource blocks to be allocated for class-\(c\), \(RB\), is set to 1. The scheduler then calculates the response time \(T_c\) and the achieved throughput \(R_c\) using Equations (5.12) and (5.4) respectively. Then, the overall transfer time \(T_{c,\text{total}}\) and \(R_c\) are compared with the constraints \(\tau_c\) and \(R_{c,\text{min}}\) respectively, in addition to the stability requirement. Based on the outcomes, in case that at least one of the conditions is violated, RB is increased by 1. The scheduler keeps increasing the resource blocks, which results in a decrease of \(T_c\) and a corresponding increase of \(R_c\), until the requirements of the total transfer time and throughput are both met. It is assumed that \(T_{\text{core}}\) has a fixed value during the scheduling process.

When the overall time \(T_{c,\text{total}}\) becomes less than or equal to \(\tau_c\) and \(R_c\) meets its lower bound, \(x_c\) is determined and the scheduler allocates \(x_c\) resource blocks to the class-\(c\) traffic flow. Iteratively, the scheduler proceeds by processing the following traffic flows that are characterized with lower priority. Finally, once the allocation is performed, the system updates all the relevant parameters. It is noted that, every TTI, the described scheduling algorithm dynamically assigns resources in order to meet the QoS requirements while aiming to allocate the minimum possible for each traffic class-\(c\).
Algorithm 1 LTE scheduling and resource allocation scheme

1: \( N \leftarrow \text{set of available resource blocks} \)
2: \( I \leftarrow \text{set of assigned resource blocks} \)
3: \( U \leftarrow \text{set of unassigned resource blocks} \)
4: \( x_c \leftarrow \text{number of resource blocks assigned to class-c data flow} \)
5: \( T_{c,\text{total}} \leftarrow \text{overall transfer time} \)

6: \( \triangleright \) Initialization
7: \( I \leftarrow \emptyset ; U \leftarrow N ; \text{RB} \leftarrow 0 ; x_c \leftarrow 0 \quad \forall c \)
8: \textbf{for} \( n \leftarrow 1 \) to \(|N|\) \textbf{do}
9: \textbf{for} \( c \leftarrow 1 \) to \(C\) \textbf{do}
10: \hspace{0.5cm} Calculate SINR value for each class and resource block
11: \textbf{end for}
12: \textbf{end for}

\hspace{0.5cm} \triangleright \) Main iteration
13: \textbf{for} \( c \leftarrow 1 \) to \(C\) \textbf{do}
14: \hspace{0.5cm} \text{RB} \leftarrow 1
15: \hspace{0.5cm} \textbf{while} \( |I| < |N| \) \textbf{do}
16: \hspace{1.0cm} \text{Calculate} \( T_c, \text{R}_c \)
17: \hspace{1.0cm} \textbf{if} \( T_{c,\text{total}} \leq \tau_c \& \& \text{R}_c \geq \text{R}_{c,\text{min}} \& \& \sum_{c=1}^{C} \frac{R_i \cdot \lambda_i F_i}{R_i} < 1 \) \textbf{then}
18: \hspace{1.5cm} \textbf{if} \( |I \cup \{x_c\}| < |N| \) \textbf{then}
19: \hspace{2.0cm} \text{x}_c \leftarrow \text{RB} \quad \text{(Assign RB blocks to class-c)}
20: \hspace{2.0cm} I \leftarrow I \cup \{x_c\}
21: \hspace{2.0cm} U \leftarrow U \setminus \{x_c\}
22: \hspace{1.5cm} \textbf{else}
23: \hspace{2.0cm} \text{x}_c \leftarrow |U|
24: \hspace{2.0cm} \text{Resume allocation in next TTI}
25: \hspace{1.5cm} \textbf{end if}
26: \hspace{1.0cm} \textbf{end if}
27: \hspace{1.0cm} \textbf{else}
28: \hspace{1.5cm} \text{RB} \leftarrow \text{RB} + 1
29: \hspace{1.5cm} \textbf{end if}
30: \hspace{1.0cm} \textbf{end while}
31: \textbf{end for}
Chapter 6

Simulation

The following part of the thesis aims to integrate the analysis performed in the previous chapters through extensive simulations with the use of Ericsson’s radio system simulator platform. The primal objective is to verify the performance of the proposed scheduling framework, as presented in chapter 5, while integrating IEC 61850 services within LTE networks. The simulator provides various options regarding the implementation of realistic communication scenarios which are specifically designed to emulate real network operations. It also offers flexibility in all the simulation stages with replaceable modules and well defined interfaces and, therefore, a high level of external credibility is achieved. In the present chapter, the features of the simulation framework are presented and a performance evaluation of the simulation results is carried out with the use of relevant network performance metrics.

6.1 Simulation Scenarios

As discussed in Chapter 4, the IEC 61850 standard supports client-server and peer-to-peer type of communications. In the simulation scenarios implemented, both cases are considered. In particular, the first scenario proposes a centralized architecture where MMS traffic is exchanged between the IEDs and the control center. In the second scenario, a distributed approach is presented where GOOSE messages are exchanged between IEDs. In both scenarios, LTE background traffic is present and competes for resource allocation. Thus, remote control traffic needs to be prioritized in order to support the power automation tasks which, in certain cases, require time-sensitive and data-intensive information exchange.

6.1.1 Scenario 1: Centralized Architecture

In the first application scenario, state estimation data is sent from two (or more) IEDs to a controller that detects out-of-step conditions (e.g. excessive and increasing phase angle) between substations or system areas. In other cases, the data may refer to online pre-fault information exchange to avoid unstable conditions on the power system network. In turn, the controller uses the information to perform various processing, alarming and visualization functions while initiating control actions in order to rectify the problem (e.g.
reduce the angle) and/or isolate the system. The information is periodically exchanged and provides situational awareness for the power system performance.

Figure 6.1 illustrates the simulation topology. A regular cellular deployment with a hexagonal grid is considered where the eNodeB serves both the Smart Grid control traffic and the background traffic generated by normal LTE subscribers (via smartphones, tablets, etc.). The IEDs are equipped with LTE radio interfaces and belong to the same substation LAN which can accommodate in total up to 20 smart devices.

For the control traffic, a client/server communication architecture is considered where the configuration services use the conventional IEC 61850 methods with MMS over TCP/IP as described in section 5.1. MMS specifies a set of messages which allow an MMS client (control center) to control an MMS server (IED). As shown in Figure 6.2, MMS is in principle independent from the communication stack and assumes that an MMS client establishes first an association (connection) with an MMS server. A server may sustain several simultaneous associations with different clients in the grid. In the simulation process, emphasis is given on the event reporting phase of the client/server communication, where the MMS server sends message requests to the MMS client that is associated with.

Table 6.1 summarizes the minimum throughput requirement and the maximum allowable delay, in terms of transfer time, that can be tolerated in the uplink direction per connection, for this application scenario.

<table>
<thead>
<tr>
<th>Minimum throughput</th>
<th>Maximum allowable delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 kbit/s</td>
<td>100 ms</td>
</tr>
</tbody>
</table>

Table 6.1 Performance requirements for control traffic in scenario 1

1The performance requirements are specified by Siemens in the context of the EIT research activity 'LTE for Smart Energy'.
6.1.2 Scenario 2: Distributed Architecture

The second scenario proposes a fully distributed architecture for remote control communications within the grid. It is the peer-to-peer communications ability that is used to exchange time-critical GOOSE messages between IEDs which belong to the same or different substation LANs. The scenario corresponds to use cases where there is a need for event-driven communications (e.g. for certain critical control applications) and GOOSE services are employed. Upon detecting an event, the IEDs are triggered for sending protection relevant GOOSE messages to neighbouring IEDs for notification and localized decision-making purposes.

Figure 6.3 illustrates the simulation topology for the second scenario. A single-site area accommodating two substation LANs with up to 20 IEDs each is considered. The LANs are located in adjacent geographical regions and served by the same eNodeB. Similar to the first scenario, both IEDs and conventional LTE user equipment devices compete simultaneously for resource allocation.

The mapping methods for GOOSE over UDP/IP described in section 5.1 are applied in order to enable inter-substation traffic. The GOOSE service model offers the capability for a fast and reliable system-wide distribution of input and output data values. It uses a specific retransmission scheme in order to achieve the appropriate level of reliability. The data set values are encoded in a GOOSE message which is triggered by a local application issue. As illustrated in Figure 6.4, the additional reliability is achieved by retransmitting the same data. Since the use of UDP transport protocol does not guarantee message/data delivery, the GOOSE send service and message, as specified in [32], addresses this issue through a repeat mechanism where the transmitted dataset is repeated multiple times at increasing time intervals once an event occurs. As such, there is a high probability, given
that the network is intact, that a lost GOOSE message will eventually be received by the intended IED.

Table 6.2 summarizes the minimum throughput requirement and the maximum allowable delay, in terms of transfer time, measured in the receiving IED, that can be tolerated in this application scenario².

<table>
<thead>
<tr>
<th>Minimum throughput</th>
<th>Maximum allowable delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 kbit/s</td>
<td>50 ms</td>
</tr>
</tbody>
</table>

Table 6.2 Performance requirements for control traffic in scenario 2

²The performance requirements are specified by Siemens in the context of the EIT research activity "LTE for Smart Energy".
Chapter 6. Simulation

6.2 Simulation Parameters

This section provides the basic network parameters that are configured for the implementation of the two communication scenarios described before.

6.2.1 General Settings

In the simulation procedure, a channel bandwidth of 5 MHz is used which corresponds to 25 available RBs. In addition, a number of three sector antennas is established on the same base station site, each having a different direction. The propagation environment is considered to be a suburban area where the background LTE users and the substation LANs are located in. Both LTE subscribers and IEDs are considered to be uniformly distributed within the cell area and generate a mixed traffic landscape over the LTE network. The transmission power of the eNodeB has a value of 43 dBm, which is recommended for a 5 MHz carrier, whereas the user transmission power is 24 dBm [39]. Moreover, a multi-user MIMO 2x2 antenna configuration is used in order to:

- Achieve additional diversity against fading compared to the use of only multiple receive or multiple transmit antennas.
- Allow for more efficient utilization of high SINR and significantly higher data rates over the radio interface.

Table 6.3 summarizes the basic deployment and propagation parameters used in the simulation sets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>System bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Number of subcarriers per RB</td>
<td>12</td>
</tr>
<tr>
<td>RB bandwidth</td>
<td>180 kHz</td>
</tr>
<tr>
<td>Transmission Time Interval</td>
<td>1 ms</td>
</tr>
<tr>
<td>Transmission mode</td>
<td>MIMO 2x2</td>
</tr>
<tr>
<td>User transmission power</td>
<td>24 dBm</td>
</tr>
<tr>
<td>eNodeB transmission power</td>
<td>43 dBm</td>
</tr>
<tr>
<td>User noise figure</td>
<td>9 dB</td>
</tr>
<tr>
<td>eNodeB noise figure</td>
<td>5 dB</td>
</tr>
<tr>
<td>Channel Model</td>
<td>Suburban</td>
</tr>
<tr>
<td>User distribution</td>
<td>Uniform</td>
</tr>
<tr>
<td>EPC delay</td>
<td>10 ms</td>
</tr>
<tr>
<td>Internet delay</td>
<td>10 ms</td>
</tr>
</tbody>
</table>

Table 6.3 General settings overview
6.2.2 Traffic Models

In the simulation scenarios, a number of LTE subscribers is assumed to coexist with the IEDs, representing the background traffic within the eNodeB coverage area. Typical human-to-human applications, such as web browsing (HTTP), Voice-over-IP (VoIP), video streaming and file transfer (FTP) are considered to be present in the system, each of them characterized with a specific average arrival intensity. The following sections provide additional information regarding the traffic models that are used for modeling both conventional LTE and energy automation traffic types.

6.2.2.1 Background Traffic

The traffic model characteristics for the LTE background users, as considered in the simulations, are summarized as follows.

- The HTTP traffic model corresponds to a typical web browsing session. Each session is divided into ON/OFF periods representing web-page downloads and intermediate reading times. During an ON period (packet call), users are sending HTTP requests to the corresponding web server and the initial index page (referred to as the main object) is first downloaded. However, within the initial page, there can be embedded object files such as graphics and buttons, which are also loaded. The detailed parameters of the model are specified according to [40].

- VoIP refers to the real-time delivery of packet voice across networks using the Internet protocols. A VoIP session is characterized by periods of active talking interleaved by silence/listening periods. A two-state Markov process (active - inactive) is used to model the VoIP source. During the active state, packets of fixed sizes are generated at a regular time interval. The packet size and the rate at which the packets are sent depend on the corresponding voice codecs and compression schemes. In the simulations, a simplified Adaptive Multi-Rate (AMR) audio data compression is used to model the VoIP service. Every call length has a fixed value of 30 seconds and a 50% voice activity factor is considered.

- A video streaming session is defined as the entire video streaming call time. Each frame of video data arrives at a regular time interval and can be treated as a packet call. Within each frame (packet call), packets arrive randomly and the packet sizes are also random. In the simulations, a typical video-telephony is considered with a duration of 30 seconds. Using the H.264 video compression format, a frame rate of 30 frames per second is supported, resulting in an overall bit rate of 220 kbit/s.

- A typical FTP session consists of a sequence of file transfers separated by the reading time. In the simulations, the size of the file to be transferred has a value of 100 kbytes and the basic set of parameters defined in the technical proposal [40] is used. Each file transfer can be treated as an individual packet call and the reading time can be treated as the OFF period within a session.
6.2.2.2 Smart Grid Control Traffic

In the case of the Smart Grid control traffic, the traffic patterns considered in the simulations follow the principles of the IEC 61850 specifications for MMS and GOOSE traffic. In specific, as illustrated in Table 6.4, the remote control traffic sent between the MMS servers (IEDs) and the MMS client (control center) is assumed to follow a periodic traffic pattern with constant inter-arrival times. A size of 150 bytes is used for the MMS traffic which constitutes a typical value for control application demands, e.g. status indications, interlocks [22]. Since it is desirable to evaluate the system performance under situations of high traffic load, the periodicity is chosen to have a relatively small value of 6 ms. Furthermore, in the overload case, it is assumed that the total number of IEDs, which belong to the same substation LAN, are sending data to the control center.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inter-arrival time</td>
<td>Constant</td>
</tr>
<tr>
<td>Payload</td>
<td>150 bytes</td>
</tr>
<tr>
<td>Periodicity</td>
<td>6 ms</td>
</tr>
<tr>
<td>Maximum number of active IEDs</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 6.4 MMS traffic characteristics

In the second scenario, the GOOSE traffic pattern is characterized by a twofold structure. Under stable conditions, when no event occurs, the IED sends periodical GOOSE messages to the other IEDs in the same or different substation LANs. When a random event is captured by the IED, the periodic retransmissions are shortened by a GOOSE burst. Each GOOSE traffic burst can be modeled as a Poisson process with the sequence of inter-arrival times following the exponential distribution\(^3\). A size of 250 bytes is considered for the GOOSE traffic [7] and the values for the retransmission times in both stable and burst conditions, as defined in Figure 6.4, are summarized in Table 6.5. In the simulations, it is assumed that in the overload case the total number of IEDs belonging to the two substation LANs identify an event and change from steady to burst mode nearly at the same time. Moreover, the value of the first inter-arrival time in the burst mode, \(T_1\), is assumed to have a relatively low value of 1 ms, resulting in an intense sending of high priority GOOSE messages [7].

6.2.3 Performance Metrics

For each scenario, independent sets of simulations are conducted while considering two different approaches for the handling of the Smart Grid control traffic. In particular:

- In the first set of simulations, both background LTE and Smart Grid flows are mapped to the same default EPS bearer and the proportional-fair scheduling algorithm is applied for the resource allocation. In this case, the default network

\(^3\)The superposition of the bursts generated by different IEDs is also a Poisson process provided that the individual bursts are considered to be independent with each other [41].
configuration is considered where there is no special handling of the Smart Grid control flow with respect to the other LTE traffic types.

- In the second set of simulations, a dedicated EPS bearer is established for the Smart Grid traffic flow, with QoS requirements as specified in Tables 6.1 and 6.2 respectively for each scenario. The Smart Grid control traffic is prioritized with respect to the conventional LTE traffic types which are mapped to the default EPS bearer. In addition, an enhanced implementation of the proportional-fair scheduling algorithm is applied for the Smart Grid flow, where the resource allocation is performed according to the delay, throughput and stability constraints proposed in section 5.4.

In the simulations, a comparative study of the two approaches is performed. The main objective is to verify whether the performance requirements for each scenario are satisfied with the use of the proposed scheduling and traffic differentiation scheme. The following performance metrics are used for the evaluation of the simulation results:

- Network latency, which is defined as the maximum transfer time in which a particular message should reach its destination through the communication network. In situations of network congestion, when the queuing waiting time significantly increases, the overall delay calculation constitutes a critical task for the evaluation of the system availability.

- Throughput, which represents the rate of successful message delivery over the communication channel. It is calculated as the total data received from the corresponding network entity over the total transmission time. The throughput estimation is also a reliable measure of the link quality characterization, especially in overload cases.

The following section provides the simulation results for each scenario. Given the arrival intensities of the different traffic types, a performance evaluation is performed as the system gradually reaches the overload case.
6.3 Results

This section presents the results of the performed simulations in Ericsson’s radio simulation platform for each particular scenario. In the following figures:

- The red curves correspond to the first set of simulations (Simulation 1) where all traffic flows are assigned to the default EPS bearer with the default proportional-fair scheduling settings. The Smart Grid control traffic is treated equally with respect to the background LTE traffic types.

- The blue curves correspond to the second set of simulations (Simulation 2) where Smart Grid control traffic is prioritized over the background LTE traffic and mapped to a dedicated EPS bearer where the proposed scheduling algorithm is applied.

6.3.1 Scenario 1

For the first scenario, Table 6.6 provides numerical information regarding the system capacity, captured in the start and end of the simulation time. It is noted that in the overload case, all IEDs that belong to the same substation LAN send simultaneously periodic messages to the control center. Under these network conditions of high traffic load, the maximum number of active background LTE users are presented for each traffic type, with the specific characteristics defined in section 6.2.2.1.

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>Web</th>
<th>VoIP</th>
<th>Video</th>
<th>FTP</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial number of active users/IEDs</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Arrival intensity</td>
<td>2.0</td>
<td>3.0</td>
<td>0.75</td>
<td>4.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Number of active users/IEDs in overload case</td>
<td>27</td>
<td>34</td>
<td>15</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 6.6 Capacity calculations for scenario 1

Figure 6.5 presents the CDF of the delay experienced by the MMS-type messages for both simulation sets, measured in the MMS client (control center). It is observed that the proposed network approach outperforms the default one. In addition, 99.5% of the message delays are below the maximum allowed threshold of 100 ms whereas the corresponding percentage for the default case reaches the 79.8%. The superiority of the proposed prioritized scheduling scheme is further illustrated in Figure 6.6, where the traffic load increases with the simulation time. When the network overload phase starts (∼12 seconds), the delay remains in relatively lower levels compared with the case where no special handling of control traffic is applied, which in turn results in rapidly increasing delays.

Figure 6.7 demonstrates the CDF of the throughput for MMS control traffic for both simulation sets. It can be seen that, when applying the proposed priority-scheduling approach, the throughput measured in the MMS client (control center) satisfies the requirement of 2 kbit/s per connection. However, when the default network configuration is applied, 4% of the MMS traffic throughput is below the threshold. In addition, Figure 6.8 depicts the throughput performance with respect to the simulation time. The
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Figure 6.5 CDF of delay for MMS traffic

Figure 6.6 Time plot of delay for MMS traffic
results reflect the delay improvement that is previously observed, where the prioritized control messages experience lower delays than in the default case. In specific, it can be observed that when the network overload phase starts (∼ 12 seconds), the throughput of the priority-scheduled MMS-type messages remains always over the threshold and in higher levels than in the case when no prioritization is concerned.

Figures 6.9 and 6.10 illustrate the impact of the priority-handling of MMS traffic on the performance of background real-time voice and video services respectively. In particular, a slight increase in the delay of the voice frames can be observed, which can reach up to 20 ms with respect to the default case. However, this level of delay can be considered negligible as it does not affect significantly the voice users’ satisfaction. VoIP typically tolerates delays up to 150 ms before the quality of the call is unacceptable [42]. For the video users, the respective delay increase can reach up to 0.5 seconds with respect to the default case. The performance degradation is higher compared with the voice traffic since real-time video-telephony sessions are now considered. However, since 95% of video frames are transmitted with less than 0.6 seconds delay, the performance can be considered acceptable.

### 6.3.2 Scenario 2

For the second scenario, Table 6.7 provides the numerical results regarding the system capacity, captured in the start and end of the simulation time. The arrival intensities for the different traffic types are given lower values than in the first scenario, resulting in an increased simulation time. Since a distributed communication architecture is now
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Figure 6.8 Time plot of throughput for MMS traffic

Figure 6.9 CDF of voice delay for scenario 1
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Figure 6.10 CDF of video delay for scenario 1

considered, the low intensities are used in order to smoothly reach the overload system phase, where all IEDs from both substation LANs are assumed to be active and exchange GOOSE messages. Moreover, it is noted that the system is able to accommodate the traffic of a lower number of background LTE users than in the first scenario.

<table>
<thead>
<tr>
<th>Traffic Type</th>
<th>Web</th>
<th>VoIP</th>
<th>Video</th>
<th>FTP</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial number of active users/IEDs</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Arrival intensity</td>
<td>0.75</td>
<td>1.0</td>
<td>0.75</td>
<td>2.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Number of active users/IEDs in overload case</td>
<td>25</td>
<td>18</td>
<td>29</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 6.7 Capacity calculations for scenario 2

Figure 6.11 illustrates the CDF of the delay experienced by the GOOSE messages for both simulation sets, measured in the receiving IED. It can be seen that the proposed priority-scheduling scheme outperforms the default one. In specific, despite the intense traffic conditions imposed by the GOOSE bursts, 77.6% of the message delays are below the maximum allowed delay threshold of 50 ms. The corresponding percentage in the default case reaches the 66.4%. The delay improvement is further depicted in Figure 6.12, where the system traffic load increases with the simulation time. In both approaches, the delay peaks corresponding to simultaneous GOOSE bursts triggered from several IEDs are visible. However, when the network overload phase starts (∼ 26 seconds), the delay
remains in relatively lower levels than in the case where the default scheduling settings are applied.

Figure 6.13 shows the CDF of the throughput for GOOSE control traffic for both simulation sets, measured in the receiving IED. As observed, by applying the proposed priority-scheduling approach, the achieved throughput improves with respect to the default case. In specific, only 4.8% of the throughput is below the threshold of 70 kbit/s whereas the corresponding percentage in the default case reaches the 18%. The superiority of the proposed approach is further illustrated in Figure 6.14, where the throughput performance is plotted with respect to the simulation time. For both approaches, the throughput nadirs are observed in the same time instants when the delay peaks in Figure 6.12 occur. Moreover, as soon as the network overload phase starts (∼ 26 seconds), the number of throughput nadirs rapidly increases for the default case, whereas for the proposed scheme, the throughput remains in relatively higher levels.

Figures 6.15 and 6.16 illustrate the impact of the priority-handling of GOOSE traffic on the performance of background real-time voice and video services respectively. Comparing with the first scenario, the delay levels are now higher due to the stringent QoS requirements of the GOOSE traffic. For the voice users, the delay increase can reach up to 30 ms with respect to the default case. However, this delay level is considered acceptable since it is lower than the threshold of 150 ms and does not lead voice users to drop their ongoing calls [42]. For the video users, the respective delay increase can reach up to 0.85 seconds with respect to the default case. The overall delay levels are now higher with respect to Figure 6.10, reaching up to 2.6 seconds. Moreover, 77% of video frames are now transmitted with less than 0.6 seconds delay. Thus, the video quality can
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Time plot of delay for GOOSE traffic
Each serie corresponds to a separate simulation.

Simulation 1
Simulation 2

0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0 22.5 25.0 27.5 30.0 32.5

Time [sec]

0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13 0.14 0.15

delay [s]

Figure 6.12 Time plot of delay for GOOSE traffic

C.D.F. of throughput for GOOSE traffic
Each serie corresponds to a separate simulation.

Simulation 1
Simulation 2

0 25,000 50,000 75,000 100,000 125,000 150,000 175,000 200,000 225,000

throughput [bps]

0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90 0.95 1.00

C.D.F.

Figure 6.13 CDF of throughput for GOOSE traffic
Figure 6.14 Time plot of throughput for GOOSE traffic

still be considered acceptable; however, the performance deterioration may lead to some unsatisfied video users.
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Figure 6.15 CDF of voice delay for scenario 2

Figure 6.16 CDF of video delay for scenario 2
Chapter 7

Conclusion and Future Work

The present Master thesis investigates whether remote control communications between entities within the Smart Grid communication network can be supported by making use of the existing public LTE network infrastructure. In particular, the thesis presents the technical and performance requirements introduced by IEC 61850 standard for substation automation systems and discusses the ability of LTE to meet these requirements in terms of latency and throughput. This technical integration can be achieved through the design and implementation of a scheduling framework where Smart Grid traffic is prioritized and allocated a dedicated radio bearer with respect to the background LTE traffic. Moreover, the resource allocation process is performed according to specific delay, throughput and queue stability requirements imposed by IEC 61850 message types.

The performance evaluation is conducted under the consideration of realistic communication scenarios that correspond to basic automation functionalities within the Smart Grid. Furthermore, the network congestion case when the traffic load gradually increases, is considered. More specifically, in the first scenario,IEDs belonging to a substation LAN, communicate with the control center exchanging MMS-type messages through the public LTE connectivity provided by the eNodeB. It is shown that the performance requirements of the grid-state messages are fulfilled with no significant effect on the background LTE traffic.

The second scenario corresponds to a distributed network architecture, where IEDs belonging to different substation LANs, exchange protection messages in case that an event occurs. The simulation results also prove that performance requirements of these event-driven messages are satisfied. Due to the intense traffic characteristics of GOOSE messages, the effect on the performance of the background users is now higher comparing with the first scenario but, in overall, considered acceptable.

The thesis presents a technical-feasibility analysis of LTE for smart energy solutions. The use of QoS functionality in LTE communications for supporting control applications within the Smart Grid provides significant outcomes for the energy sector and demonstrates the advanced capabilities of LTE. At this transitional phase of shifting to the next-generation electric power systems, the communication architectures for automated and intelligent system management constitute a vibrant research field. A variety of technical challenges are therefore awaiting solutions.

Future work would include the consideration of a quantitative measure of fairness in the proposed scheduling framework for IEC 61850 traffic. The development of a fairness
index would provide information about the treatment of the competing nodes and the user satisfaction. It would be also interesting to investigate the signaling limitations that occur when the number of energy nodes increases and how this signaling overhead affects the resource allocation mechanism. The study case of multiple eNodeB, covering a large geographical region with many substation LANs, presents high research interest, since factors such as handover and inter-cell interference are affecting the system availability.

This research focuses on control system applications in the Smart Grid. Nevertheless, other typical communication scenarios in power systems which involve various performance requirements for energy traffic can be examined. Energy usage scheduling used to configure the consumption of electrical appliances and video surveillance for protecting the utility assets and monitor the grid operation, constitute representative cases. The study of multiple characteristic scenarios would provide a comprehensive and integrated overview regarding the application of LTE features in smart energy systems. Considering the global LTE ecosystem, such an evolution would constitute an attractive path for future wireless communication.
Bibliography


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