Latency and Bandwidth Analysis of LTE for a Smart Grid

XU, YUZHE

Master Thesis
Stockholm, Sweden 2011

XR-EE-RT 2011:018
Latency and Bandwidth Analysis of LTE for a Smart Grid

XU, YUZHE

Master’s Thesis at Electrical Engineering
Supervisor: Fischione, Carlo; Johansson, Karl Henrik
Examiner: Fischione, Carlo
Abstract

Smart grid has been proposed as an alternative to the traditional electricity grid recently thanks to its advantages of real time control on consumption demands. The latest wireless network, 3GPP Long Term Evolution (LTE), is considered to be a promising solution to interconnecting the smart objects in a smart grid because LTE provides both low latency and large bandwidth. However, the theories and standards for deploying a smart grid are still under study. Furthermore, the performance of LTE network depends on the user devices’ conditions as well as the network service operators. Therefore it is important to analyze the performance of LTE network experimentally. In this master thesis report, the specific requirements in terms of latency and bandwidth were first determined for a hypothetical smart microgrid which consists of several key components, such as one substation/distributed generation, Phasor Measurements Units (PMU) and Advanced Meter Infrastructures (AMI). Then the latency and the peak data rates of the LTE networks provided by two service operators TELE2 and TELIA were investigated and compared. The experimental results show that both latency and peak data rate of the LTE network provided by TELE2 fulfil the requirements for the smart microgrid, while the LTE network provided by TELIA gives a little longer latency. In addition, the simulation results based on a proposed scheduler indicate that the latency can be improved by an appropriate scheduler. This study has proven that LTE network is a promising solution for smart grids.
Acknowledgement

I would like to thank my examiner Carlo Fischione for his guidance and patience throughout this thesis. I would also like to express my gratitude to professor Karl Henrik Johansson for all his guidance and valuable suggestions. I would also like to thank Yong Wang for providing useful research materials.

I reserved the most special gratitude for my parents in Shanghai. Without your unconditional support and love, this could have been impossible.

Finally, a special thanks to my wife Yi, for her love, patience and support.
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Contents</td>
<td>iv</td>
</tr>
<tr>
<td></td>
<td>List of Figures</td>
<td>vi</td>
</tr>
<tr>
<td></td>
<td>List of Tables</td>
<td>viii</td>
</tr>
<tr>
<td></td>
<td>List of Abbreviations</td>
<td>ix</td>
</tr>
<tr>
<td>1</td>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>Background</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Smart Grid</td>
<td>1</td>
</tr>
<tr>
<td>1.1.2</td>
<td>LTE</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Motivation</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Outline</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Problem Formulation</td>
<td>6</td>
</tr>
<tr>
<td>2.1</td>
<td>Problem Definition</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>Model for Communication Requirement</td>
<td>7</td>
</tr>
<tr>
<td>2.3</td>
<td>Experiment Configurations for LTE Performance Analysis</td>
<td>7</td>
</tr>
<tr>
<td>2.4</td>
<td>Scheduler Design</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Communication Requirements for a Smart Grid</td>
<td>9</td>
</tr>
<tr>
<td>3.1</td>
<td>Components</td>
<td>9</td>
</tr>
<tr>
<td>3.1.1</td>
<td>PMU</td>
<td>10</td>
</tr>
<tr>
<td>3.1.2</td>
<td>AMI</td>
<td>12</td>
</tr>
<tr>
<td>3.1.3</td>
<td>Distributed Power</td>
<td>13</td>
</tr>
<tr>
<td>3.1.4</td>
<td>Remote Sensing: Monitoring and Control</td>
<td>13</td>
</tr>
<tr>
<td>3.2</td>
<td>Communication Requirement</td>
<td>14</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Communication in A Substation/DG</td>
<td>14</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Collecting and Dissemination of Phasor Data</td>
<td>15</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Collecting and Dissemination of Consumption Data</td>
<td>16</td>
</tr>
<tr>
<td>4</td>
<td>A Hypothetical Smart Microgrid</td>
<td>17</td>
</tr>
<tr>
<td>4.1</td>
<td>Assumption and Structure of Model</td>
<td>17</td>
</tr>
</tbody>
</table>
CONTENTS

4.2 Communication Requirement for LTE Connection . . . . . . . . . . 17
4.3 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 19

5 Analysis of Latency and Bandwidth of LTE 20
5.1 Introduction . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 20
5.1.1 Main Techniques in LTE . . . . . . . . . . . . . . . . . . . . . 20
5.2 Latency Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . 22
  5.2.1 FDD Mode Analysis . . . . . . . . . . . . . . . . . . . . . . . 22
  5.2.2 TDD Mode Analysis . . . . . . . . . . . . . . . . . . . . . . . 22
5.3 Bandwidth Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . 23

6 Experiment Results 26
6.1 Loss Rate via LTE . . . . . . . . . . . . . . . . . . . . . . . . . . . 26
6.2 Latency Analysis via LTE . . . . . . . . . . . . . . . . . . . . . . . 26
  6.2.1 Model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 29
  6.2.2 Maximum Likelihood & Least Squares Estimations . . . . . 30
  6.2.3 Result . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 31
6.3 Throughput via LTE . . . . . . . . . . . . . . . . . . . . . . . . . . 33

7 Scheduling 34
7.1 Scheduler Design . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34
  7.1.1 Problem Formulation . . . . . . . . . . . . . . . . . . . . . . 34
  7.1.2 Solutions . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 36
  7.1.3 Utility Function Design . . . . . . . . . . . . . . . . . . . . . 38
7.2 Simulation . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 39

8 Conclusion & Future Work 42
8.1 Conclusion . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 42
8.2 Future Work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 43

Reference 44

A Ping Introduction 46
## List of Figures

1.1 LTE development Timeline ........................................... 3  
1.2 EUTRAN architecture diagram [2] ................................. 4  
2.1 Experiment Structure ................................................. 7  
3.1 General WAMS Structure ............................................. 16  
4.1 A hypothetical smart microgrid ..................................... 18  
5.1 Construction of a multicarrier OFDM signal ....................... 21  
5.2 Physical layer structure of LTE .................................... 21  
5.3 User plane latency components for FDD ........................... 23  
5.4 User plane latency components for TDD ......................... 24  
5.5 Basic time-frequency resource structure of LTE (normal CP case) ............................................. 25  
6.1 Mean values and Standard variance of RTT for small data packets. ............................................. 27  
6.2 Mean values and Standard variance of RTT for large data packets. ............................................. 28  
6.3 Data Pre-processing. The data set used in this figure is 1000 RTT values collected with 100 bytes data packets via TELE2 LTE network. The left figure shows the point of RTT values. The middle one illustrates the histogram, while the right one shows the probability density function of RTT values. ............................................. 29  
6.4 Probability density function with 100 bytes data packets via TELE2 and TELIA LTE network. ............................................. 30  
6.5 RTT values distribution. The data set is collected via TELE2 LTE network with 100 bytes data packets. ............................................. 32  
6.6 RTT values distribution. The data set is collected via TELIA LTE network with 100 bytes data packets. ............................................. 32  
7.1 Downlink and uplink scheduling process ............................ 35  
7.2 Resource allocation .................................................. 36  
7.3 Allocation example .................................................. 37  
7.4 Latency simulation of PMU data messages .......................... 41
7.5 Simulation allocation result for 1 PMU and 10 other UEs. Different colours represent different UEs, besides red colour illustrates PMU data packet.

A.1 ICMP Packet Example Captured by Microsoft Network Monitor 3.4
List of Tables

2.1 Problem Formulation .............................................. 6
2.2 Experiment hardware List ........................................ 7
3.1 Comparison of a smart grid with the existing traditional grid [5] .... 10
3.2 Data message example ........................................... 11
3.3 Four Type messages for AMI ..................................... 13
3.4 Messages defined by IEC 61850 for a distribution substation ....... 15
4.1 Main parameters in the hypothetical smart microgrid ............... 18
4.2 Communication requirements for worst case ........................ 19
5.1 IMT-A Latency Requirement ...................................... 22
5.2 User plane latency analysis for FDD ................................ 23
5.3 User plane latency analysis for TDD in uplink ........................ 24
6.1 Loss rates of LTE communication network ........................ 26
6.2 RTT time for different data packets lengths ........................ 28
6.3 Summary fits of RTT values for both TELE2 in Figure 6.5 and TELIA in Figure 6.6 .............................................. 33
6.4 Peak data rates of LTE communication network ....................... 33
7.1 Simulation parameters ............................................. 40
8.1 Comparison between communication requirements and experiment results ................................................................. 43
A.1 ICMP Packet Structure ............................................. 46
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP</td>
<td>Third Generation Partnership Project</td>
</tr>
<tr>
<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
</tr>
<tr>
<td>AMI</td>
<td>Advanced Meter Infrastructure</td>
</tr>
<tr>
<td>AMR</td>
<td>Automatic Meter Reading</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>eUTRAN</td>
<td>evolved UMTS Terrestrial Access Network</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Position Satellite</td>
</tr>
<tr>
<td>HARQ</td>
<td>Hybrid Automatic Repeat Request</td>
</tr>
<tr>
<td>ICMP</td>
<td>Internet Control Message Protocol</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fourier Transform</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>LSE</td>
<td>Least Squares Estimation</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input and Multiple Output</td>
</tr>
<tr>
<td>MLE</td>
<td>Maximum Likelihood Estimation</td>
</tr>
<tr>
<td>MTU</td>
<td>Maximum Transmission Unit</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency-Division Multiple</td>
</tr>
</tbody>
</table>

ix
List of Tables

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency-Division Multiple Access</td>
</tr>
<tr>
<td>PAPR</td>
<td>Peak-to-Average Power Ratio</td>
</tr>
<tr>
<td>PDC</td>
<td>Phasor Data Concentrator</td>
</tr>
<tr>
<td>PMU</td>
<td>Phasor Measurement Unit</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RE</td>
<td>Resource Element</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>RTT</td>
<td>Round-Trip Time</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single-Carrier Frequency-Division Multiple Access</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>WAMS</td>
<td>Wide-Area Measurement System</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Background

1.1.1 Smart Grid

The term “Smart Grid” refers to two-way communicational electricity grid. A smart grid is expected to be capable of remotely detecting statuses of electricity generations, transmission lines and substations; of monitoring consumption of user electricity usage; of adjusting the power consumption of household applications in order to conserve energy, reduce energy losses and increase electricity grid reliability. In principle, a smart grid is a upgrade of the 20th century power grid which supplies power from a few central power generations to a large number of users. The current power grid was mainly developed under parts of Nikola Tesla’s design which was published in 1888. Many implementation decisions that are still in use were made for the first time using the limited emerging technology available 120 years ago. Compared with these traditional power grids, the topology of a smart grid is more optimized to meet various electricity need conditions. For instance, decentralized or distributed generations, renewable energy and battery would be widely used in a smart grid in order to supply reliable and clean energy. Through using smart grid, a wider variety of power operations would come into practice, such as recharging the battery in the low power consumption period and providing power from that battery in the consumption peak period.

1.1.2 LTE

The term “LTE” is the abbreviation of 3GPP Long Term Evolution which is the latest standard in use in the mobile communication network [1]. It was developed to fulfil mobile users’ demands for higher data rates and stabler service performance. Its main targets were to provide average users with three to four times the throughput of the Release 6 HSDPA levels in the downlink (100Mbps), and two to three times of the HSUPA levels in the uplink (50Mbps). Furthermore, a simple architecture and backwards compatibility was also required for cost and complexity
reduction. 3GPP summarizes the motivation to develop LTE network.

- Competitiveness of the 3G system
- User demand for higher data rates and service quality
- Packet Switch optimized system
- Continued demand for cost reduction (Capital and Operating Expenditure)
- Low complexity
- Avoid unnecessary fragmentation of technologies for paired and unpaired band operation

In order to meet all these requirements in the near future, in 2004 NTT DoCoMo of Japan proposes LTE as the latest standard. It was first time that LTE appeared as a communication project. After 4 years by December 2008, 3GPP frozen Release 8 code and published it as the basic version standard for developing first wave LTE equipments, such as chipsets, testing devices and base stations. In this specification, several key techniques were determined. For instance, Orthogonal Frequency Division Multiplexing(OFDM) was selected for the downlink and Single Carrier-Frequency Division Multiple Access(SC-FDMA) for the uplink. Data modulation schemes QPSK, 16QAM, and 64QAM were supported by downlink and BPSK, QPSK, 8PSK and 16QAM by uplink. About three-fourth year later, the final version of the LTE Release 8 specifications was frozen in September 2009. In the same year December, Release 9 was functionally frozen with small enhancements. In the same month, the first publicly available LTE service of world was opened by TeliaSonera in Stockholm and Oslo. The LTE development time line is summarized in Figure 1.1.

After being developed for several years, the main advantages with LTE have been proven to provide high throughput, low latency, plug and play, FDD and TDD in the same platform, an improved end-user experience and a simple architecture resulting in low operating costs. Evolved UMTS Terrestrial Radio Access Network (eUTRAN) is chosen as the air interface of LTE. It consists only of eNodeBs on the network side aiming to reduce the latency of all radio interface operation. eNodeBs are connected to each other via the X2 interface, and they connect to the packet switched core network via the S1 interface as shown in Figure 1.2. The data packets are sent from the end terminal, the UEs, to eNodeBs via radio signals. Such an end terminal is connected to a smart grid to make measurements of its electricity status.

To summarize, LTE key features are listed below:

- High spectral efficiency

  - OFDM in downlink, Robust against multipath interference & High affinity to advanced techniques such as Frequency domain channel-dependent scheduling & MIMO (Multiple-Input and Multiple-Output)
- DFTS-OFDM ("Single-Carrier FDMA") in uplink, Low PAPR (Peak-to-Average Power Ratio), User orthogonality in frequency domain
- Multi-antenna application

- **Very low latency**
  - Short setup time & Short transfer delay
  - Short handover latency and interruption time; Short TTI (Transmission Time Interval), RRC (Radio Resource Control) procedure, Simple RRC states

- **Support of variable bandwidth**
  - 1.4, 3, 5, 10, 15 and 20 MHz

- **Simple protocol architecture**
  - Shared channel based
  - PS mode only with VoIP capability

- **Simple Architecture**
  - eNodeB as the only E-UTRAN node
  - Smaller number of Radio Access Network (RAN) interfaces

- **Compatibility and inter-working with earlier 3GPP Releases**

- **Inter-working with other systems, e.g. cdma2000**
• FDD and TDD within a single radio access technology

• Efficient Multicast/Broadcast
  - Single frequency network by OFDM

• Support of Self-Organising Network (SON) operation

The next standard after LTE is LTE Advanced which is currently being standardized in 3GPP Release 10 [3][4]. LTE Advanced is expected to meet the requirements for 4G which is also called IMT Advanced defined by the International Telecommunication Union. For example the peak data rate is up to 1Gbps.
1.2 Motivation

For more efficient use of electricity, a smart grid should monitor and control more status of itself than the traditional grid. To achieve this property, a smart grid needs various sensors, controllers, actuators and the communication infrastructures used for data transmission. So far, many different network types have been promoted for use as those communication infrastructures, including Ethernet, power line carrier (PLC), cellular network, telephone/Internet, and short range radio frequency. However, it is still critical to select a suitable network for a particular application.

On the other hand, wireless communication nowadays is a fast-growing technology. It has the main advantages of dynamic network formation, low cost, easy deployment and reduced cable restriction. As the latest mobile communication network, LTE becomes one promising option for a smart grid.

Therefore, the thesis established a hypothetical smart microgrid in which LTE is the main communication standard. Firstly, the communication requirements in this grid were summarized for both monitoring and control purposes. Secondly, these requirements were compared with the performance of LTE network. Finally, it was verified that LTE can server better for a smart grid with particular scheduling scheme.

1.3 Outline

The rest of the thesis is structured as follows. Chapter 2 provides the definition of problems solved in the thesis report. It discusses the model and experiment configurations. Chapter 3-4 introduce the communication requirement in a smart grid. The former chapter briefly summarizes the requirement focusing on latency and bandwidth in a smart grid. The latter discusses the wireless communication requirement in a hypothetical smart microgrid. Chapter 5 gives theoretical performance analysis in terms of latency and bandwidth for LTE based on the study of the 3GPP Release 8. Chapter 6 presents the experiment results. Chapter 7 introduces a simple scheduler design based on time-domain PF, and the simulation results are given. Finally, Chapter 8 gives the conclusion of this thesis and suggestions of possible future work.
Chapter 2

Problem Formulation

In this chapter, we give the formulation of the problems that we are to addressed in this master thesis project. There are several main tasks in this project, including communication requirements summary for a smart grid, performance analysis of LTE and scheduler design for LTE.

2.1 Problem Definition

For the smart grid communication network, bandwidth and latency are two critical technical requirements. In this thesis the performance of LTE in bandwidth and latency was to be investigated in order to evaluate whether it is a suitable network for a smart grid. We were to establish a simple experiment to collect latency and peak data rates of LTE. After collecting enough data, we would analyse LTE network performance, compare the performance with smart grid requirements and design a suitable scheduler for smart objects in grid via LTE. Figure 2.1, Table 2.1 summarizes the required data and results for all problems defined above.

<table>
<thead>
<tr>
<th>Index</th>
<th>Inputs</th>
<th>Problem (Object)</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Literature</td>
<td>Requirement Summery (Smart Grid)</td>
<td>Latency[ms] and Peak rate[Mbps]</td>
</tr>
<tr>
<td>2</td>
<td>Experiments</td>
<td>Performance Analysis (LTE)</td>
<td>Latency[ms] and Peak rate[Mbps]</td>
</tr>
<tr>
<td>3</td>
<td>1,2 Results</td>
<td>Comparison</td>
<td>Is LTE capable?</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>Scheduler Design (LTE)</td>
<td>Simulation results</td>
</tr>
</tbody>
</table>
2.2 Model for Communication Requirement

There are many literatures describing communication requirements for a smart grid. In this thesis, we would focus on the requirements of latency and bandwidth for various length of message delivered in smart grids. To obtain a more accurate requirement of communication in smart grids, we separated these requirements into three main parts: 

a) communication in substations/distributed generation (DG); 
b) collecting and dissemination of phasor data; and 
c) collecting and dissemination of consumption data. See Chapter 3 for a clear definition of these requirements.

Considering there is relationship between the size of smart grid and specific communication requirements, we were to establish a smart micro-grid as a more specific model which consists of several key components, such as a DG, a controller and different loads.

2.3 Experiment Configurations for LTE Performance Analysis

Three main hardware devices and one key software “ping” would be used to transmit information data packets in the experiment. Table 2.2 summarizes all devices used in this experiments.

<table>
<thead>
<tr>
<th>Type</th>
<th>Connection</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE modem</td>
<td>USB with computer</td>
<td>1. HUAWEI E398</td>
</tr>
<tr>
<td></td>
<td>RF with eNodeB</td>
<td>2. SAMSUNG GT-B3730</td>
</tr>
<tr>
<td>Computer</td>
<td>USB with LTE modem</td>
<td>InterCore <a href="mailto:T5600@1.83GHz">T5600@1.83GHz</a> RAM4G Windows7</td>
</tr>
<tr>
<td>eNodeB</td>
<td>RF with LTE modem</td>
<td>1. Serviced by TELE2 with HUAWEI modem</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Serviced by TELIA with SAMSUNG modem</td>
</tr>
</tbody>
</table>
Here we assume there is an individual cellular network with several users. Each user has the approximately same priority and property. Thus the information transfer between source and destination can be simplified to sending data packets from user equipments to servers of network.

In this experiment, user equipment would send Internet Control Message Protocol (ICMP) echo request packets to the target host using ping command under Windows 7 via LTE modem, and wait for an ICMP response. In the process, it would measure the time from transmission to reception (round-trip time, RTT) and recode any packet loss. The RTT and packet loss data would be used to analyse the performance of LTE network. On the other hand, it would use the official software of LTE modems to monitor the peak data rates when it downloads from or uploads via Internet.

The basic batch files would be used to ping the eNodeBs host in series with messages in different lengths. Considering that the length of message delivered in smart grids are almost smaller than 1024 bytes, the length of message set in the experiment varies from 0 bytes to 1024 bytes. The batch file would ping at least 1000 times for each message, and save the respective latency data into a txt file.

The basic performance of two LTE networks would be investigated and compared using LTE modems from TELE2 and TELIA respectively.

2.4 Scheduler Design

To optimize the LTE performance for communications in a smart grid, we would create a scheduler which gives highest priorities to smart objects. When the scheduler is working, smart objects can use as many as possible resources of LTE to access network, deliver data messages. The simulation result would indicate how many smart objects LTE can handle at most under the given communication requirements.
Chapter 3

Communication Requirements for a Smart Grid

Electrical grid nowadays consists three main subsystem: a) generation subsystem which produces electricity; b) transmission subsystem which transmits electricity to load centre; and c) distribution subsystem which continues to transmit electricity to customers. The existing power grids have severed us with live consumption of electricity for a long time. However, it has been proven that existing grids cannot address the expected requirements including optimal generation control, demand response, energy conservation and reduction of the industry’s overall carbon footprint [5]. Simply stated, the smart grid is created and expected to address these drawbacks of the existing grids. As a result, a smart grid is required to be self-healing, consumer participation, resist attack, high quality power, accommodate generation options, enable electricity market, optimize assets, and enable high penetration of intermittent generation sources. The salient features of smart grid in comparison with the existing grids are shown in Table 3.1.

3.1 Components

To fulfil all the requirements listed in the table, a smart grid needs more components for monitoring, control and communication. In most cases, a smart grid focuses on three main areas: a) household devices for consumption automatic meter reading; b) remote sensing devices for electrical network monitoring and control; and c) distributed power energy source, such as wind and solar, management. Therefore there are several key components in a smart grid. They are, Advanced Meter Infrastructures (AMI) at the houses or buildings, Phasor Measure Units (PMU) for transmission lines, and remote sensing incorporation of distributed.
Table 3.1. Comparison of a smart grid with the existing traditional grid [5]

<table>
<thead>
<tr>
<th>Existing Grid</th>
<th>Smart Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromechanical</td>
<td>Digital</td>
</tr>
<tr>
<td>One-Way Communication</td>
<td>Two-Way Communication</td>
</tr>
<tr>
<td>Centralized Generation</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>Hierarchical</td>
<td>Network</td>
</tr>
<tr>
<td>Few Sensors</td>
<td>Sensors Throughout</td>
</tr>
<tr>
<td>Blind</td>
<td>Self-Monitoring</td>
</tr>
<tr>
<td>Manual Restoration</td>
<td>Self-Healing</td>
</tr>
<tr>
<td>Failures and Blackouts</td>
<td>Adaptive and Islanding</td>
</tr>
<tr>
<td>Manual Check/Test</td>
<td>Remote Check/Test</td>
</tr>
<tr>
<td>Limited Control</td>
<td>Pervasive Control</td>
</tr>
<tr>
<td>Few Customer Choices</td>
<td>Many Customer Choices</td>
</tr>
</tbody>
</table>

3.1.1 PMU

The Phasor Measurement Unit is considered to be one of the most important measuring devices in the next generation power systems. The distinction comes from its unique ability of providing synchronized phasor measurements of voltages and currents in an electrical grid. The ability is achieved by same-time sampling of voltage and current waveform using a common synchronizing sampling signal from the Global Positioning Satellite (GPS). The phasor measurements are calculated via Discrete Fourier Transform (DFT) applied on a moving data window whose width can vary from fraction of a cycle to multiple of a cycle [6]. In an electrical grid, the state of system is defined as the voltage magnitude and angle at each bus of the system. Based on the measurements from PMUs, we can estimate the system state in real time. Besides enhanced state estimation, PMUs are also used in phase angle monitoring and control, Wide-Area power system stabilizer and adaptive protection.

Reporting Rate

Generally speaking, PMU measurements are reported at a rate of 20~60 times a second, namely 20~60 Hz. Based on the GPS timing, each utility has its own Phasor Data Concentrator (PDC) to aggregate and align data from various PMUs. Measurements from each utility’s PDC are sent to the Central Facility (e.g. TVA’s SuperPDC) where the data are synchronized across utilities.
CHAPTER 3. COMMUNICATION REQUIREMENTS FOR A SMART GRID

Message Types

Standard IEEE Std C37.118-2005 defines four message types for PMUs output: data, configuration, header, and command [7]. The configuration, data and command messages are binary message; the header message is a human readable message. There is an example, shown in Table 3.2, of the data message which carries the measurements in its frame. The data frame indicates a balanced 3-phase phase-to-neutral voltage and a constant system frequency. Here the length of the data message is 52 bytes. In most cases, the lengths are about 100∼200 bytes including the IP or TCP header (20 bytes).

Table 3.2. Data message example

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Example</th>
<th>Size (Bytes)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYNC</td>
<td>Synchronization and Frame Format Field.</td>
<td>DataFrame, V1</td>
<td>2</td>
<td>AA 01</td>
</tr>
<tr>
<td>FRAMESIZE</td>
<td>Frame Length</td>
<td>52 bytes</td>
<td>2</td>
<td>00 34</td>
</tr>
<tr>
<td>IDCODE</td>
<td>PMU/ID number, 16-bit integer</td>
<td>7734</td>
<td>2</td>
<td>1E 36</td>
</tr>
<tr>
<td>SOC</td>
<td>Second count</td>
<td>9:00 on 6 June 2006</td>
<td>4</td>
<td>44 85 36 00</td>
</tr>
<tr>
<td>FRACSEC</td>
<td>Time of phasor measurement [ms] with Time Quality.</td>
<td>16817 µs after the second mark</td>
<td>4</td>
<td>00 00 41 B1</td>
</tr>
<tr>
<td>PHASORS</td>
<td>Phasor data, 16-bit integer</td>
<td>VA=14635°, VB=14635°−120°, VC=14635°+120°, I1 =1092°</td>
<td>4</td>
<td>2B 00 00 E3 6A CE 7C E3 6A 31 83</td>
</tr>
<tr>
<td>FREQ</td>
<td>16-bit signed integer. Nominal frequency in millihertz.</td>
<td>+2500 mHz (Nominal 60 Hz with measured 62.5 Hz).</td>
<td>2</td>
<td>09 C4</td>
</tr>
<tr>
<td>DFREQ</td>
<td>Rate of change of frequency</td>
<td></td>
<td>2</td>
<td>00 00</td>
</tr>
<tr>
<td>ANALOG</td>
<td>32 bit floating point</td>
<td>ANALOG1=100, ANALOG2=1000, ANALOG3=10000</td>
<td>4</td>
<td>42 C8 00 00 44 7A 00 00 46 1C 40 00</td>
</tr>
<tr>
<td>DIGITAL</td>
<td>Digital data, 16-bit field</td>
<td>0011 1100 0001 0010</td>
<td>2</td>
<td>3C 12</td>
</tr>
<tr>
<td>CHK</td>
<td>CRC-CCITT</td>
<td></td>
<td>2</td>
<td>D4 3F</td>
</tr>
</tbody>
</table>
3.1.2 AMI

Since nearly 90% of all power outage and disturbances have their roots in the distribution subsystem, automatic meter reading systems (AMR) in the distribution subsystem are indispensable. AMR collects information of consumption records, alarms and status from customers. Although AMR provides information on the customers side, it does not address the major issue: demand-side management due to its one-way communication system. As a result, advanced meter infrastructure (AMI) which contains two-way communication system is developed. AMI is capable of both getting instantaneous information from customers and imposing consumptions of customers. Simply stated, an AMI consists of an AMR, a two-way communication system, and several specific actuators. Based on its two-way communication system, AMI enable a smart grid to manage consumption demands. Its main advantages are listed below:

- **Realtime pricing.** Customers adjust consumption decision based on day-to-day or hour-to-hour price of electricity. These decisions will affect their bills.

- **Peak shaving.** Remove energy consumption from period of high demand, which helps to reduce need for peak-meeting generation. Given the fact that 20% of today electricity grid’s generation capacity exists to meet peak demand only[5], peak-shaving helps to reduce and optimize the energy consumption.

- **Energy conservation.** Reducing usage overall can have substantial environmental and social benefits.

**Reporting Rate**

Generally speaking, AMI needs to report consumption status at a rate of 4~6 times per hour, that is, each consumption measurement is sent every 10~15 minutes.

**Message Types**

Referring to the message types for a PMU, we assume there are four different message types for an AMI outputs: Data, Configuration, Header, and OutCommand; one InCommand message for its input [8][9].

- **Data** message contains the measurements of the consumption from customers including device ID, meter reading, time stamps, and other identification information about the customer and the AMI.

- **Configuration** message contains the configuration information of the AMI.

- **OutCommand** message informs the customers of real-time price and imposes the consumption.

- **Header:** A human readable message.
• **InCommand** message contains commands from supervisor controller.

We use 32 or more bits of floating for representing the meter reading in data information, 8 bits for each device status, and 20 bytes for basic identification information (including AMI ID, time date stamp, checksum and so on) in each type of message. Table 3.3 lists some hypothetical parameters for these message types [10].

**Table 3.3. Four Type messages for AMI**

<table>
<thead>
<tr>
<th>Type</th>
<th>Sink</th>
<th>Destination</th>
<th>Rate (per hour)</th>
<th>Length (Bytes)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>AMI Controller</td>
<td>Controller</td>
<td>4~6</td>
<td>&lt;100</td>
<td>4 bytes per meter reading</td>
</tr>
<tr>
<td>Configuration</td>
<td>AMI Controller</td>
<td>Controller</td>
<td>100~200</td>
<td></td>
<td>Sent to reply a request only.</td>
</tr>
<tr>
<td>OutCommand</td>
<td>AMI Customer Devices</td>
<td>&lt;100</td>
<td></td>
<td>8 bits for on/off switch. Sent when status needs change.</td>
<td></td>
</tr>
<tr>
<td>Header</td>
<td>AMI Controller</td>
<td>Controller</td>
<td>&lt;50</td>
<td></td>
<td>Sent when necessary.</td>
</tr>
<tr>
<td>InCommand</td>
<td>Controller</td>
<td>AMI</td>
<td>100~200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.1.3 Distributed Power

Distributed generations (DG) and substations are two of key power suppliers in a smart grid. Generally, a DG can supply renewable and cheaper electricity such as wind and solar, or provide power in emergency such as fossil fuel (coal, gas powered). A substation transfers power from the transmission subsystem to the distribution subsystem of an area. It transforms high voltage of transmit line to a suitable low level for local distribution. As a result, it can provide relatively more reliable electricity. However, in most cases, it can hardly predict the output of a renewable, clean power generator. Moreover, a fossil fuel generator has heavy air pollution affecting environment. Furthermore, a substation which relies on the centralized generations is difficult to be adjusted. In order to produce clean, reliable electricity power, one promising solution is the hybrid generators which are comprised of two or more generators. Most hybrid configurations are based on a petroleum-fuelled engine-driven generator and one or more solar or wind powered generators.

### 3.1.4 Remote Sensing: Monitoring and Control

Remote sensing of the network has been undertaken for some time in energy distribution grids using Supervisory Control and Data Acquisition (SCADA) solutions.
These systems are deployed to monitor and control other infrastructure utilities in the high voltage network of the electrical grid. These utilities usually include high voltage switches, transformers, and transmission lines. When these systems turn towards a smart grid, the monitoring and control points are fundamentally extended to the medium and low voltage networks. The utilization of PMUs, other remote sensors and actuators makes a smart grid capable of better condition managements.

### 3.2 Communication Requirement

In practice, there are different communication requirements for various functions or applications in a smart grid. These can be categorized into requirements for communication within a substation, communication between substations and control centres, communication between control centres, collection and dissemination of electricity data, wide-area control and monitoring and communication for local protective relaying [11]. As mentioned in Section 2.2, we would focus on communication in a substation/DG, collecting and dissemination of electricity (phasor and consumption) data.

#### 3.2.1 Communication in A Substation/DG

Standard IEC 61850-5 [12] introduces the communication requirements for functions and device models in a substation. Based on IEC 61850-5, there are two independent groups of performance class:

a) for Control and Protection (P1/P2/P3)

- P1 applies typically to the distribution level of the substation or in cases where lower performance requirements can be accepted.
- P2 applies typically to the transmission level or if not otherwise specified by the users.
- P3 applies typically to transmission level applications with high requirements, such as bus protection.

b) for Metering and Power quality applications (M1/M2/M3)

- M1 refers to revenue metering with accuracy class 0.5 (IEC 60687) and 0.2 (IEC 60044) and up to the 5th harmonic
- M2 refers to revenue metering with accuracy class 0.2 (IEC 60687) and 0.1 (IEC 60044) and up to the 13th harmonic
- M3 refers to quality metering up to the 40th harmonic.

IEC 61850-5 also defines seven different types of messages in a substation. Table 3.4 lists all these types with their different communication requirements of latency, rate frequency and resolution.
Table 3.4. Messages defined by IEC 61850 for a distribution substation

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Performance Class</th>
<th>Latency (ms)</th>
<th>Rate (Hz)</th>
<th>Resolution (bit/bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>Fast Message (type A)</td>
<td>P1</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>Fast Message (type B)</td>
<td>P2,3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Medium speed Message</td>
<td></td>
<td>&lt;100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Low speed Message</td>
<td></td>
<td>&lt;500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Raw data Message</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>File transfer function</td>
<td></td>
<td>&gt;1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Time synchronization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Command Message with access control</td>
<td></td>
<td>&lt;500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2.2 Collecting and Dissemination of Phasor Data

In reality, measurements from PMUs are initially delivered to devices called Phasor Data Concentrators (PDCs) where the measurements are time-synchronised, stored for future reference and forwarded to applications and to Super PDCs. This processing is one function of Wide-Area Measurement System (WAMS) [13]. Furthermore, phasor measurement is a technology for the WAMS “backbone”, as shown in Figure 3.1. This phasor network consists of PMUs and PDCs. A complete WAMS will also accommodate measurements of other types, and it will contain many resources that convert acquired data into useful information.

Here is a practical example. The Western Electricity Coordinating Council WAMS has reached the following size by the end of 2004:

- 11 PDC units
- 53 integrated PMUs
- 7 stand-alone PMUs
- ~23 Portable Power System Monitors
- ~10 monitor units of other kinds
WAMS systems are used for both off-line studies and real-time applications. With real-time WAMS, the continuous measurements feed out as a data stream applied to on-line applications such as monitoring and control. They are expected to meet real-time control system requirements with time delay less than 1 second (typically 100-200ms) [13].

### 3.2.3 Collecting and Dissemination of Consumption Data

One key feature expected in a smart grid is demand-side management. Thus the consumption information needs to be collected and analysed by the smart grid controller. Then suitable commands are sent to customers’ devices for controlling electricity demand in the following time period. This processing constructs classical feedback control for demands. The main purpose of this control system is to shift or remove peak electricity consumption for realizing energy conservation.

The AMI is one key component to fulfil this purpose in a smart grid. An AMI network should meet certain communication requirements to achieve real-time feedback control of electricity demand [10].

**Reliability:** The AMI network must guarantee the arrival of each AMI meter reading and command messages.

**Scalability:** The designed network for AMI should be able to provide support to a large number of nodes of AMIs. On the other word, the bandwidth of the connection network should be large enough to support desired AMI service.

**Real time communication:** The time of end-to-end delay is required to be short enough to fulfil the real-time control requirements.

**Order:** The data packets should be stamped with the time of measurements to guarantee the order of the data packets in the receiving base.
Chapter 4

A Hypothetical Smart Microgrid

In order to specify the communication requirements, we establish a hypothetical smart micro-grid which consists of three main subsystem: a) DG, b) WAMS, c) AMI network. We describe the model in details in next subsection.

4.1 Assumption and Structure of Model

As shown in Figure 4.1, we assume that a 50MW DG works as the only electricity supplier. Lines 1 and 2 are part of transmission subsystem. Line 3 and 4 connect the transmission and distribution subsystem. Bus 4 and 6 are distribution bus. Transformer 2 and 3 are mechanical on-load tap change transformers which used to control the output voltages remotely. Breakers CB 1~5 are remote controllable and used to remove the lines. Load 2 transmits the electricity power to factories, while Load 3 gives the electricity power to houses or buildings. There is a control centre outside this DG besides a local controller inside the DG. Engineers can remotely monitor and control those devices installed in the smart microgrid. In addition, there are several PMUs deployed on all power buses, while a few AMI infrastructures are installed in houses, building and factories. Both the phasor measurements and electricity consumptions are sent to the control centre via LTE network, and transmitted to the data store system via Ethernet. PMUs and AMIs receive the commands from control centre via LTE, while DG gets the commands via Ethernet. Table 4.1 shows the main parameters for the key components in this smart microgrid.

4.2 Communication Requirement for LTE Connection

Based on the assumptions above, we conclude the communication requirements for a smart grid.
Figure 4.1. A hypothetical smart microgrid

Table 4.1. Main parameters in the hypothetical smart microgrid

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Packet Length (Bytes)</th>
<th>Rate</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>1</td>
<td></td>
<td></td>
<td>50MW</td>
</tr>
<tr>
<td>PMU</td>
<td>10</td>
<td>200 Uplink</td>
<td>60Hz</td>
<td></td>
</tr>
<tr>
<td>AMI</td>
<td>10,000</td>
<td>100 Uplink</td>
<td>every 15min</td>
<td></td>
</tr>
<tr>
<td>Others</td>
<td>100</td>
<td>100 Uplink</td>
<td>60Hz</td>
<td>IED status</td>
</tr>
<tr>
<td>Control Centre</td>
<td>1</td>
<td>100 Downlink</td>
<td>depends</td>
<td>Control commands</td>
</tr>
</tbody>
</table>
CHAPTER 4. A HYPOTHETICAL SMART MICROGRID

1. Latency

- **PMU, Control Centre & Others**
  Recalling to Chapter 3, [13] announces that transmission latency should be less than 1 second (typically 100~200 microsecond) for WAMS solution. Referring to [11], the latency is required to be less than 10 microsecond. For better performance, we choose 10 microsecond as the deadline for latency in this thesis.

- **AMI**
  Since an AMI reporting rate is less than 1Hz, 1 second latency is short enough for its real-time operation requirement.

2. Bandwidth

In the worst case, all devices upload their measurements simultaneously. In other words, all possible data frames need to be sent before the latency deadline. Considering the parameters shown in Table 4.1 and latency requirements listed above, we can easily determine the required bandwidth in both uplink and downlink for worst case. The results are shown in Table 4.2.

<table>
<thead>
<tr>
<th>Components</th>
<th>Total Length(bits)</th>
<th>Latency(ms)</th>
<th>Bandwidth(Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uplink</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMU</td>
<td>$10 \times 2000$</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>AMI</td>
<td>$10,000 \times 1000$</td>
<td>1000</td>
<td>10</td>
</tr>
<tr>
<td>Others</td>
<td>$100 \times 1000$</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td></td>
<td></td>
<td>22</td>
</tr>
<tr>
<td><strong>Downlink</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Centre</td>
<td>$(10 + 100) \times 1000$</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td><strong>SUM</strong></td>
<td>$10,000 \times 1000$</td>
<td>1000</td>
<td>10</td>
</tr>
</tbody>
</table>

4.3 Conclusion

We specified the communication requirements in term of latency and bandwidth mainly based on IEEE standards and related research. For the hypothetical smart microgrid, the latency less than 10 ms and the peak rate larger than 22 Mbps are required. The performances of LTE are determined both theoretically and experimentally in following chapters to evaluate whether LTE fulfils the requirements obtained above.
Chapter 5

Analysis of Latency and Bandwidth of LTE

We theoretically estimate the performance of LTE in terms of latency and bandwidth based on the standards from 3GPP [14].

5.1 Introduction

5.1.1 Main Techniques in LTE

OFDMA

Orthogonal Frequency-Division Multiple Access (OFDMA) is a multi-user version of the popular Orthogonal frequency-division multiplexing (OFDM) digital modulation scheme. OFDM realizes information transmission on a radio channel through variations of a carrier signal’s frequency, phase and magnitude [15]. Rather than assigning all transmission information to a single carrier, OFDM cuts that information into smaller pieces and places each one to a specific subcarrier. The subcarriers are offset in frequency (δf) which implements orthogonality to prevent interferences.

A serial stream of binary digits $s[n]$ is to be transmitted as shown in Figure 5.1. This stream corresponds the data produced by the measurements of a smart grid. By inverse multiplexing, it is firstly demultiplexed into $N$ parallel streams. Then each stream is mapped to a complex data sequence $(X_0, X_1, ..., X_{N-1})$ using certain modulation, such as QAM, 16QAM. An inverse fast Fourier transform (IFFT) is performed on this sequence, resulting in a set of complex time-domain samples. These samples are used to generate the transmission signal $\nu(t)$.

At the receiver, the signal $\nu(t)$ is demodulated using an FFT process to convert the time-domain samples back to $X_n$ sequence. The original binary digits $s[n]$ are recovered from $X_n$ using their modulations.

The main advantages of OFMDMA are high spectral efficiency and robustness against intersymbol interference and fading caused by multipath propagation.
CHAPTER 5. ANALYSIS OF LATENCY AND BANDWIDTH OF LTE

Figure 5.1. Construction of a multicarrier OFDM signal

SC-FDMA

Single-carrier FDMA (SC-FDMA) is a frequency-division multiple access scheme. In essence, as compared to OFDMA, SC-FDMA scheme has just one more FFT process when creating transmission radio signals as shown in Figure 5.2.

Figure 5.2. Physical layer structure of LTE

Therefore SC-FDMA not only provides the advantages of OFDMA, especially robust resistance to multipath, but also has lower PAR. However, LTE only uses SC-FDMA in the uplink because the increased time-domain processing would be a considerable burden on eNodeBs which have to manage the dynamics of multi-user transmission [16].

MIMO

In radio, multiple-input and multiple-output, or MIMO (commonly pronounced my-moh or me-moh), is a technology that makes use of multiple antennas at both the transmitter and receiver to improve communication performance.
5.2 Latency Analysis

The requirement metric by International Telecommunication Union (ITU) for LTE latency is shown in Table 5.1. Control plane latency is defined as the time required for the User Equipment (UE) to transit from idle state to active state. In idle state, the UE does not have a Radio Resource Control (RRC) connection. Once the RRC is established, the UE turns into the connected state and then into the active state when it enters the dedicated mode. User plane latency is defined as one-way transmit time between a packet being available at the IP layer in the UE/E-UTRAN edge node and the availability of this packet at the IP layer in the E-UTRAN/UE node. The User plane latency would be focused on in this thesis.

Table 5.1. IMT-A Latency Requirement

<table>
<thead>
<tr>
<th>Plane</th>
<th>Max Latency (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Plan</td>
<td>100</td>
</tr>
<tr>
<td>User Plan</td>
<td>10</td>
</tr>
</tbody>
</table>

User plane latency is calculated for both TDD (Time Division Duplex) and FDD (Frequency Division Duplex) cases. The components involved in the latency calculation are:

1. UE processing time
2. Transmission Time Interval (TTI) duration
3. Hybrid Automatic Repeat Request (HARQ) retransmission
4. eNodeB processing time

5.2.1 FDD Mode Analysis

Figure 5.3 shows the FDD components for User plane. In FDD mode HARQ process is fixed to 8 ms. So HARQ retransmission delay is $n \times 8$ ms, where $n$ is number of retransmission. Table 5.2 shows the User plane latency calculations for FDD.

5.2.2 TDD Mode Analysis

Figure 5.4 shows the TDD components for User plane. In TDD, HARQ retransmission time equals the RTT via LTE. Table 5.3 shows the latency calculation for TDD with 0% and 10% HARQ respectively. Different TDD UL/DL frame allocations lead to different alignment time. Due to different alignment time, the latency for TDD varies from 4.1 ms to 5.2 ms even for downlink without HARQ retransmissions.
5.3 Bandwidth Analysis

The LTE downlink transmissions from the eNodeB consist of user-plane and control-plane data from the higher layers in the protocol stack multiplexed together with physical layer signalling to support the data transmission [17]. The multiplexing of all these downlink signals is facilitated by the OFDMA described in Section 5.1, which enables the downlink signal to be subdivided into small units of time and frequency. The LTE uplink transmissions are similar to the downlink, and it selects SC-FDMA, as introduced in Section 5.1, as its multiple-access scheme to fulfil some unique principle characteristics.

Both downlink and uplink transmission resources in LTE possess dimensions of time, frequency and space. The time-frequency resources are subdivided according to the following strategies: the largest unit of time is the 10-ms radio frame, which is further subdivided into ten 1ms subframes, each of which is split into two 0.5-ms slots. Each slot contains seven OFDM symbols in case of the normal cyclic prefix (CP) length, or six if the extended CP is configured in the cell. In frequency domain,
resources are grouped in unite of 12 subcarriers, such that one unit of 12 subcarriers for a duration of one slots is termed a Resource Block (RB) as shown in Figure 5.5.

The smallest unit of resource is the Resource Element (RE) which consists of one subcarrier for a duration of one OFDM symbol. So a RB is comprised of 84 (with normal CP) or 74 (with extended CP) RE respectively. Within certain RBs, some REs are reserved for special purpose: a) synchronization signals, b) reference signals, c) control signalling, and d) critical broadcast system information. The remaining REs are used for data transmission, and are usually allocated in pairs of RBs.

In order to evaluate the peak rates in both downlink and uplink, we consider the best case in both sides of UE and eNodeB. In the downlink, the most efficient modulation is 64QAM (6 bits) for one OFDMA symbol (RE). If we assume that there are 100 RB for 20-MHz RF bandwidth in each 0.5 ms with single antenna
and normal CP, the downlink peak rate could be easily calculated by $100 \times 6 \times 84 \text{ bits}/0.5 \text{ ms} = 100 \text{ Mbps}$. However, the most efficient modulation used in uplink is 16QAM (4 bits) for one RE. Similarly, the uplink peak rate is obtained by $100 \times 4 \times 84 \text{ bits}/0.5 \text{ ms} = 67.2 \text{ Mbps}$.
Chapter 6

Experiment Results

In this chapter, we estimated the performances of LTE in terms of loss rate, latency and peak rates in both uplink and downlink experimentally. The experiments are carried on using two brands of LTE modems from operators TELE2 and TELIA respectively.

6.1 Loss Rate via LTE

We pinged two IP addresses for more than ten thousand times at different time interval. Table 6.1 shows the numbers of both the data packets sent by computers and the data packets lost by communication networks. The results show that the loss rate of LTE is much lower than 0.01%, which proves LTE is a reliable network.

<table>
<thead>
<tr>
<th>LTE Service Operators</th>
<th>Packets Sent</th>
<th>Packets Lost</th>
<th>Loss Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TELE2</td>
<td>202,000</td>
<td>5</td>
<td>0.0025</td>
</tr>
<tr>
<td>TELIA</td>
<td>80,000</td>
<td>20</td>
<td>0.025</td>
</tr>
</tbody>
</table>

6.2 Latency Analysis via LTE

Because we used ping command to send and receive data packets, the lengths of data packets only represent the sizes of data packets which are attached after ICMP headers. Ping command not only sends and receives these ICMP data packets, but also measures and reports the round-trip time (RTT) for each packet. Figure 6.1 shows the mean values and standard variances of RTT time measured by ping com-
mand for respective small data packets ($\leq 100$ bytes), while Figure 6.2 shows those for larger data packets ($\geq 100$ bytes). And Table 6.2 shows several parameters of RTT values corresponding to the lengths of data packets, including mean, standard variance, maximum and minimum values.

![Figure 6.1. Mean values and Standard variance of RTT for small data packets.](image)

These table and figures illustrate that when the length of data packets is smaller than 100 bytes, the RTT is shorter than 20 ms under the service provided by TELE2, while it is around 20 ms for TELIA. The RTT values increase with the length of data packets when the length is larger than 100 bytes. But the standard variances of RTT are approximately the same whatever sizes for the packets for each service operator. The mean values of RTT under TELE2 are lower than those under TELIA. However, the standard variances of RTT under TELE2 is around 4~5 times larger than those under TELIA. This is probably because the measurement equipment is closer to eNodeB of TELE2 than that of TELIA. The equipment could use more efficient data modulation schemes and turbo coding to send message via TELE2 LTE network. As a result, the messages sent by TELE2 modem have shorter RTT, while there is little probability of being re-transmitted by HARQ in TELIA LTE network.

If we calculate the latency by dividing RTT by half. The minimum values for small size packet verifies the theoretical latency which described in Chapter 5. Considering the sizes of data messages used in PMUs, it is 100 bytes packets that we try to find the distribution of RTT for. Since the ping command uses sort
Figure 6.2. Mean values and Standard variance of RTT for large data packets.

Table 6.2. RTT time for different data packets lengths

<table>
<thead>
<tr>
<th>Length (byte)</th>
<th>TELE2 (ms)</th>
<th>TELIA (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std</td>
</tr>
<tr>
<td>50</td>
<td>16.4740</td>
<td>13.1485</td>
</tr>
<tr>
<td>100</td>
<td>18.5450</td>
<td>17.8746</td>
</tr>
<tr>
<td>200</td>
<td>22.3390</td>
<td>14.5283</td>
</tr>
<tr>
<td>300</td>
<td>23.8780</td>
<td>14.6845</td>
</tr>
<tr>
<td>400</td>
<td>25.3300</td>
<td>13.0220</td>
</tr>
<tr>
<td>500</td>
<td>26.2300</td>
<td>14.6324</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>1000</td>
<td>29.6577</td>
<td>19.2486</td>
</tr>
</tbody>
</table>
of quantization filter when calculating the RTT time, we can not use probability density function directly (pdf) to fit distributions. In this thesis, we integrated pdf functions for each 1-ms interval, \([i - 0.5, i + 0.5](ms)\) as following:

\[
F_{\text{RTT}}(i) = \int_{i-0.5}^{i+0.5} f_{\text{pdf}}(x) \, dx \quad \text{for all } i = 0, 1, 2, \ldots \tag{6.1}
\]

Where \(F_{\text{RTT}}(i)\) is the possibility of measured RTT which equals \(i\), \(f_{\text{pdf}}\) is the probability density function of certain distribution, for instance, normal and Poisson distributions. Before fitting probability distribution, we transfer the data set to histogram, and then to probability function \(Pr(X \in [i - 0.5, i + 0.5])\) as shown in Figure 6.3. The probability function \(Pr(X \in [i - 0.5, i + 0.5])\) was calculated using Equation 6.2, where \(n\) is number of times \(i\) occurs inside \(N\) samples.

\[
Pr_i = Pr(X \in [i - 0.5, i + 0.5]) = \frac{n}{N} \quad \text{for all } i = 0, 1, 2, \ldots \tag{6.2}
\]

Figure 6.3. Data Pre-processing. The data set used in this figure is 1000 RTT values collected with 100 bytes data packets via TELE2 LTE network. The left figure shows the point of RTT values. The middle one illustrates the histogram, while the right one shows the probability density function of RTT values.

### 6.2.1 Model

After the above data preprocessing, both histograms and pdf figures illustrate that the RTT values seems to fit the mixture distribution because of several obvious peaks in Figure 6.3 and Figure 6.4. Furthermore, these figures indicate that the data might appropriately fit a mixture of two or more normal distribution. If we assume that the possibility of HARQ occurs is \(p\) and HARQ happens for \(j\) times for a data packet, the probability for successful sendings can be calculated using Equation 6.3. We assume the mean values and variances of the each normal distribution are the same. Then we propose to model this mixture of normal distributions as:

\[
P_{\text{Success}} = p^{j-1}(1 - p) \tag{6.3}
\]

\[
f_{\text{pdf}}(x) = \sum_{j=0}^{H} (1 - p)^j p^{j-1} \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x - \mu - i\sigma_{HARQ})^2}{2\sigma^2}} \tag{6.4}
\]
6.2.2 Maximum Likelihood & Least Squares Estimations

The methods to estimate the appropriate fitting are the maximum likelihood(MLE) and least squares estimations(LSE).

\[ F_{\text{RTT}}(i) = \int_{i-0.5}^{i+0.5} f_{pdf}(x) dx \]
\[ = \int_{i-0.5}^{i+0.5} \sum_{j=0}^{H} (1 - p) p^{j-1} \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x - \mu - jT_{\text{HARQ}})^2}{2\sigma^2}} \]
1. Maximum Likelihood Estimation:
Suppose there is a sample $x_1, x_2, ..., x_n$ of observations coming from RTT dataset with $F_{RTT}(i)$. Rewrite $F_{RTT}(i)$ as $Pr(i|\Theta)$ which means the probability of RTT which equals $i$ given parameter set $\Theta$. Here,

$$\Theta = [\mu, \sigma, p, T_{HARQ}]^T$$ (6.6)

Then the joint density function for all observations is obtained as:

$$Pr(x_1, x_2, ..., x_n|\Theta) = Pr(x_1|\Theta) \cdot Pr(x_2|\Theta) \cdots Pr(x_n|\Theta)$$ (6.7)

Now we can get the likelihood function as:

$$L(\Theta|x_1, x_2, ..., x_n) = Pr(x_1, x_2, ..., x_n|\Theta) = \prod_{k=1}^{n} Pr(x_k|\Theta)$$ (6.8)

In this thesis, we used the logarithm of the likelihood function called log-likelihood:

$$\ln L(\Theta|x_1, x_2, ..., x_n) = \sum_{k=1}^{n} \ln Pr(x_k|\Theta)$$ (6.9)

The method of MLE estimates the appropriate parameter set $\theta$ by finding a value of $\Theta$ which maximizes its likelihood function $\ln L(\Theta|x)$:

$$\theta_{MLE} = \arg\max_{\theta \in \Theta} \ln L(\Theta|x_1, x_2, ..., x_n)$$ (6.10)

2. Least Squares Estimation:
We supposed the data set for RTT consists of $n$ points(data pairs)$(i, P_{ri})$ obtained by Equation 6.2 as illustrated in Figure 6.4, where $i$ and $P_{ri}$ are obtained from observations. The model function $F_{RTT}(i)$ is given by Equation 6.5. The goal is to find the parameter set $\Theta$ for this model. The least squares estimation finds its optimum by minimizing the sum of squared residuals:

$$\Theta_{LSE} = \arg\min_{\theta \in \Theta} \sum_{i=1}^{N} r_i^2 \quad \text{where} \quad r_i = P_{ri} - F_{RTT}(i)$$ (6.11)

6.2.3 Result
Based on the model given by Equation 6.4, we get the “best” fitting distribution functions by applying MLE and LSE. Figure 6.5, 6.6 and Table 6.3 show those parameters and curves estimated by MLE and LSE.

These result shows that it is appropriate to use the mixture normal distribution model for analysis.
Figure 6.5. RTT values distribution. The data set is collected via TELE2 LTE network with 100 bytes data packets.

Figure 6.6. RTT values distribution. The data set is collected via TELIA LTE network with 100 bytes data packets.
Table 6.3. Summary fits of RTT values for both TELE2 in Figure 6.5 and TELIA in Figure 6.6

<table>
<thead>
<tr>
<th></th>
<th>TELE2 MLE</th>
<th>TELE2 LSE</th>
<th>TELIA MLE</th>
<th>TELIA LSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSE ( r^2 )</td>
<td>0.8075</td>
<td>0.8075</td>
<td>0.9872</td>
<td>0.9872</td>
</tr>
<tr>
<td>Mean Value[ms] ( \mu )</td>
<td>13.9111</td>
<td>14.1847</td>
<td>26.3201</td>
<td>26.4449</td>
</tr>
<tr>
<td>Standard Variance ( \sigma )</td>
<td>1.7333</td>
<td>1.7894</td>
<td>2.0160</td>
<td>1.8635</td>
</tr>
<tr>
<td>Time for HARQ[ms] ( T_{HARQ} )</td>
<td>7.8892</td>
<td>7.5175</td>
<td>8.7179</td>
<td>9.2640</td>
</tr>
<tr>
<td>Probability of HARQ ( p )</td>
<td>0.1875</td>
<td>0.2241</td>
<td>0.0175</td>
<td>0.0160</td>
</tr>
<tr>
<td>Maximum Repeat times ( H )</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

6.3 Throughput via LTE

We use different softwares and protocols to achieve the peak downlink and uplink data rate. Table 6.4 shows the peak data rates via both TELE2 and TELIA LTE networks. It can be seen that these two service operators provides the same peak rate for both uplink and downlink.

Table 6.4. Peak data rates of LTE communication network

<table>
<thead>
<tr>
<th>LTE Service Operators</th>
<th>Peak Downlink Rate (Mbits/s)</th>
<th>Peak Uplink Rate (Mbits/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TELE2</td>
<td>Approaching 30</td>
<td>Approaching 30</td>
</tr>
<tr>
<td>TELIA</td>
<td>Approaching 30</td>
<td>Approaching 30</td>
</tr>
</tbody>
</table>
Chapter 7

Scheduling

Unlike 3GPP, the scheduling decisions are not made at centralized base station but at distributed eNodeBs for both downlink and uplink radio transmissions. The process of LTE scheduling is shown in Figure 7.1.

The main purpose of a scheduler is to allocate suitable physical resources for the set of users for communication. Because OFDMA and SC-FDMA are used in downlink and uplink respectively, LTE can schedule resources for users in time domain, frequency domain and modulation/coding scheme (MCS) domain. In order to make good scheduling decisions for high performance, a scheduler requires knowledge of both channel conditions and users’ device conditions. Based on these knowledges, Adaptive Modulation and Coding (AMC) is used to choose optimal MCS for UEs to transmit, for example, using QPSK, 16-QAM, or 64-QAM following turbo coding for certain subcarriers. Ideally, the scheduler needs to know the channel condition for each subcarrier, each UE in every scheduling time and TTI in LTE. However, due to limited signalling channel resources, a UE seldom reports all subcarrires channel conditions, but average condition and several conditions in best subcarriers. The smallest resource unit allocated by a scheduler to a user is an SB, which consists two consecutive RBs, spanning TTI of 1 ms and a bandwidth of 180 kHz.

7.1 Scheduler Design

7.1.1 Problem Formulation

As mentioned above, the main purpose of a scheduler is to determine the allocation of SBs to a subset of UEs in order to maximize some objective function, for instance, overall system throughput and fairness. Here, due to more specific communication requirements for PMUs to update data measurements, we created a suitable scheduling scheme in uplink with the following requirements.

- Fulfil communication requirements for PMUs in the smart grid of short latency and high bandwidth.
- Trade off overall system throughput and fairness for each UE.
Now we can design the scheduler as solving an optimal problem which describes the allocation performance of the physical resources. In this case, the uplink scheduler allocates resources for $N$ users. So the optimal problem can be simplified to allocate $(i, j)$ resources block in time- and frequency-domain as shown in Figure 7.2, which maximizes the sum of utility $\log R_{i,j}^{(c)}$. The problem is:

$$
\max_{c=1}^{N} \sum_{i=1}^{N_{TTI}} \sum_{j=1}^{N_{RB}} \log R_{i,j}^{(c)}
$$

(7.1)

where:

$$
R_{i,j}^{(c)} = \lambda_{(c)} x_{i,j}^{(c)}
$$

(7.2)

subject to:

$$
\sum_{c} x_{i,j}^{(c)} \leq 1 \quad \forall i, j
$$

(7.3)

$$
\sum_{i} x_{i,j}^{(c)} \leq N_{TTI} \quad \forall j, c
$$

(7.4)

$$
\sum_{j} x_{i,j}^{(c)} \leq N_{RB} \quad \forall i, c
$$

(7.5)

$$
\sum_{i} \sum_{j} x_{i,j}^{(c)} \leq L_{(c)} \quad \forall c
$$

(7.6)

$$
x_{i,j}^{(c)} \in \{0, 1\}
$$

(7.7)

where $\lambda_{(c)}$ is the utility weight function for the $c$-th user, $x_{i,j}^{(c)}$ is the occupant status:

$$
x_{i,j}^{(c)} = \begin{cases} 
1 & \text{if } (i, j) \text{ resource block is occupied by } c\text{-th user} \\
0 & \text{otherwise}
\end{cases}
$$

(7.8)
There are several constraints on this problem. Equation 7.3 indicates that each resource block can be allocated to one user at most, and Equation 7.4 and 7.4 limit the greatest value in time and frequency domain. Equation 7.6 formulates that resource blocks allocated to UE are limited by each UE transmission demand.

### 7.1.2 Solutions

We assume that the weight function $\lambda$ depends on users’ information only. Thus user devices only report the average channel condition for all available channels in every TTI. Then, Equation (7.1) becomes:

$$\max \sum_{c=1}^{N} \lambda(c) l(c)$$

(7.9)

where:

$$l(c) = \sum_{i=1}^{N_{TTI}} \sum_{j=1}^{N_{RB}} x_{i,j}(c)$$

(7.10)

subjects to:

$$\sum_{c} l(c) \leq \min(N_{TTI} N_{RB}, \sum_{c} L(c))$$

(7.11)

$$0 \leq l(c) \leq \min(N_{TTI} N_{RB}, L(c)) \quad \forall c$$

(7.12)

Figure 7.3 shows an example of the scheduling allocation, where the value inside each resource block represents the utility value for each user. The resource blocks
selected by the scheduler are labelled by red boxes. Obviously the solution for this optimal problem has to fulfil:

\[
\sum_c l(c) = \min(N_{TTI}N_{RB}, \sum_c L(c)) \tag{7.13}
\]

**Optimal Solution:**

Before solving this problem, we sorted data set \(\lambda(c)\) from largest to smallest to a value sequence \(\{\lambda_i\}\), where \(\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_N\). According to this order, the allocation solution is also transferred to sequence \(\{l_i\}\) with up-limit \(\{L_i\}\). Using discrete dynamic programming, we obtained the solution for each \(i\). The following expressions show the steps to find the first two optimal solutions.

- To find the optimal solution for \(l_1\):

  \[
  \sum_c \lambda(c)l(c) = \sum_i \lambda_il_i = \lambda_1l_1 + \lambda_2l_2 + \ldots + \lambda_Nl_N
  \]

  \[
  \implies s_1 = \arg\max_{l_1} (\lambda_1l_1 + \lambda_2l_2 + \ldots + \lambda_Nl_N) = \min(N_{TTI}N_{RB}, L_1) \tag{7.14}
  \]

**Proof:**

Assume there exist:

\[
\{\hat{l}_i\} = \arg\max_{\{l_i\}} \sum_i \lambda_il_i \quad \text{and} \quad \hat{l}_1 < s_1
\]

Denote \(\delta = s_1 - \hat{l}_1 > 0\) and assume arbitrary \(\Delta l_i \geq 0\) fulfils:

\[
\sum_{i=2}^N \Delta l_i = \delta \quad \text{and} \quad \hat{l}_i - \Delta l_i \geq 0 \quad \forall i = 2, 3, \ldots, N
\]
Then, from:

\[ \lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_N \]

\[ \Rightarrow \lambda_1 \delta - \lambda_N \delta \geq \lambda_1 \delta - \sum_{i=2}^{N} \lambda_i \Delta l_i \geq \lambda_1 \delta - \lambda_2 \delta \geq 0 \]

\[
\left\{ \begin{array}{l}
\text{IF } \delta < \sum_{i=2}^{N} \hat{l}_i :\\
\sum_{i} \lambda_i \hat{l}_i = \lambda_1 \hat{l}_1 + \lambda_2 \hat{l}_2 + \ldots + \lambda_N \hat{l}_N \\
\leq \lambda_1 \hat{l}_1 + \lambda_2 \hat{l}_2 + \ldots + \lambda_N \hat{l}_N + \lambda_1 \delta - \sum_{i=2}^{N} \lambda_i \Delta l_i \\
= \lambda_1 s_1 + \lambda_2 (\hat{l}_2 - \Delta l_2) + \ldots + \lambda_N (\hat{l}_N - \Delta l_N) \\
\text{ELSE : }\\
\lambda_1 s_1 = \lambda_1 \hat{l}_1 + \lambda_1 \delta \geq \lambda_1 \hat{l}_1 + \lambda_1 \sum_{i=2}^{N} \hat{l}_2 \geq \lambda_1 \hat{l}_1 + \sum_{i=2}^{N} \lambda_i \hat{l}_2 = \sum_i \lambda_i l_i
\end{array} \right.
\]

\[ \Rightarrow \text{Conflict with assumption.} \]

- To find the optimal solution for \( l_2 \):

\[ s_2 = \text{argmax}_{l_2} (\lambda_1 s_1 + \lambda_2 l_2 + \ldots + \lambda_N l_N) \]

\[ = \left\{ \begin{array}{l}
\min(N_{\text{TTI}} N_{\text{RB}} - s_1, L_2) \quad \text{if } N_{\text{TTI}} N_{\text{RB}} - s_1 > 0 \\
0 \quad \text{otherwise}
\end{array} \right. \]  

(7.15)

Similarly, we can find the solutions set \( \{s_i\} \) for other \( l_i \) step by step.

### 7.1.3 Utility Function Design

Since LTE transmits data flows not only for use in a smart grid but also for public use in a wide area, we would like to determine what data comes from smart grid. Due to short delay dead-line for PMUs, the scheduler needs to give the highest priorities to ensure message from PMUs would be transmitted first. As a result, we created a scheduler which consists of an estimator and a priority calculator. The estimator determines the possibility for UEs of being in a smart grid based on the buffer status reports from UEs. The features of a UE used in a smart grid can be summarized as follows: a) constant data updating rates \( \hat{r} = 0 \), b) equivalent data packets lengths \( \hat{l} = 0 \) and c) approximately invariant channel qualities \( \hat{q} = 0 \).

Then priority calculator gives the priority value to each UE. With combining all the components in the scheduler, the whole utility function can be obtained as Equation 7.16 for \( c \)-th UE.

\[ \lambda_{(c)} = W_{P,c} + P_{PF,c} \]  

(7.16)
Here $W_{P,c}$ indicates the weight for the UE in a smart grid and can be obtained by

$$W_{P,c} = \frac{P}{0.3r + 0.5l + 0.2q} \quad (7.17)$$

Where $P_{PF,c}$ is traditional scheduling algorithm as given by Equation (7.18) which is used in variant wireless communication networks. Here $(C/I)$ represents the channel conditions and $R(t)$ is the throughput within the time interval $t$.

$$P_{PF,c} = \frac{(C/I)_c}{R_c(t)} \quad (7.18)$$

The whole algorithm is concluded as the following Algorithm 1:

**Algorithm 1 Scheduling**

1: Let $M$ be the set of available RBs at time interval $t$
2: Let $N$ be the set of schedulable UEs
3: for $i = 0$ to $n$ do
4: calculate $\lambda_i$ based on buffer status reports and channel conditions
5: map data packets of $i$th UE to required RBs quantity $c_i$ using AMC
6: end for
7: $Index \leftarrow 1$
8: while $M \neq \emptyset$ do
9: pick the user $k \in N$ with largest value $\lambda_k$
10: if $M \leq c_k$ then
11: assign $Index : Index + c_k$ RBs to $k$th user
12: $M \leftarrow M - c_k$
13: $Index \leftarrow Index + c_k$
14: else
15: Assign $Index : m$ RBs to $k$th user
16: $M \leftarrow \emptyset$
17: end if
18: end while

### 7.2 Simulation

In order to evaluate the performance of our scheduler, uplink system level simulations have been conducted based on 3GPP LTE system model. Table 7.1 summarizes a list of the simulation parameters and assumptions.

We analyzed the performance of the scheduler in terms of latency of PMUs as well as total throughput. As illustrated in Figure 7.4, it can be seen that the short latency requirements are fulfilled by using this scheduler which always gives the highest priority on smart objects. However, in the first TTI, the latency is much more inconstant than the others. This is because the scheduler is not able to
allocate smart objects for communication with the highest priority due to limited information in the first place. Figure 7.5 shows the RBs allocations with 1 PMU and 10 other UEs.

Based on this simulation, we can easily obtain how many PMUs can be mounted in a cell fulfilling the 10 microsecond latency requirement. Here we assume that a PMU data message is 200 bytes and sent at a rate of 60 Hz. Since the scheduler always gives the highest priorities to PMUs, PMU data messages are always allocated to physical resource first. In a 10-ms interval, LTE can transmit 67 Mbps×10 microsecond= 670 Kbits≈ 67 KB in uplink. Therefore LTE can handle 335 PMUs in one cell on uplink. For AMIs whose latency deadline is 1 second, data message length is 100 bytes and sent every 15 minutes, this result is calculated to be 67 Mbps×1 second= 67 Mbits≈ 6.7 MB, which means LTE can accommodate up to 67,000 AMIs communication in uplink even in the worst case.

Table 7.1. Simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>System bandwidth</td>
<td>5MHz</td>
</tr>
<tr>
<td>Subcarriers per RB</td>
<td>12</td>
</tr>
<tr>
<td>OFDM symbols per RB</td>
<td>7</td>
</tr>
<tr>
<td>RB bandwidth</td>
<td>180Hz</td>
</tr>
<tr>
<td>Number of RBs</td>
<td>25</td>
</tr>
<tr>
<td>Cell-level user distribution</td>
<td>Uniform</td>
</tr>
<tr>
<td>Number of PMUs in cell</td>
<td>1,2,3,4,5</td>
</tr>
<tr>
<td>Rate for PMUs</td>
<td>60Hz</td>
</tr>
<tr>
<td>Data Packet size for PMUs</td>
<td>53bytes</td>
</tr>
<tr>
<td>Number of other active users in cell</td>
<td>10</td>
</tr>
<tr>
<td>Traffic model</td>
<td>Uniform</td>
</tr>
<tr>
<td>Transmission time interval (TTI)</td>
<td>1 ms</td>
</tr>
<tr>
<td>User move speed</td>
<td>Slow</td>
</tr>
<tr>
<td>Modulation and coding setting</td>
<td>QPSK,16QAM,64QAM</td>
</tr>
<tr>
<td>HARQ model</td>
<td>None</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>50 TTI</td>
</tr>
</tbody>
</table>
Figure 7.4. Latency simulation of PMU data messages

Figure 7.5. Simulation allocation result for 1 PMU and 10 other UEs. Different colours represent different UEs, besides red colour illustrates PMU data packet.
Chapter 8

Conclusion & Future Work

8.1 Conclusion

This master thesis investigated the performance of LTE network utilized in a smart grid. The study has proven that LTE network is a promising solution due to its low latency and large bandwidth.

Firstly, the communication requirements in a smart objects are categorized into three parts: a) communication in substations/distributed generation (DG); b) collecting and dissemination of phasor data; and c) collecting and dissemination of consumption data. In each part, we specified the communication requirements in term of latency and bandwidth mainly based on IEEE standards and related research. The latency less than 10 ms and the peak rate larger than 22 Mbps are required for a proposed hypothetical smart microgrid in this thesis. Secondly, we estimated the single antenna LTE performance both theoretically and experimentally. The theoretical analysis indicates that the latency is less than 9.5 ms, the peak rate is more than 100 Mbps in downlink and 67 Mbps in uplink. The experimental measurements show that the latency and peak rates of the LTE network provided by TELE2 fulfil the requirements for the communication in the hypothetical smart microgrid as summarized in Table 8.1, while the latency of the LTE network provided by TELIA is a little longer than the required. The latency can be improved using an appropriate scheduler.

Last, a scheduler was designed to optimize the latency. The simulation results show the latency is reduced to around 5 ms for smart objects communication via LTE. In addition, the results show that LTE can handle more than 300 PMUs in a single cell.

It must be noted that we assume all the physical resources are allocated to data transmission without considering any resources needed for control signalling in this thesis.
Table 8.1. Comparison between communication requirements and experiment results.

<table>
<thead>
<tr>
<th>Type</th>
<th>Requirements</th>
<th>Experiment TELE2</th>
<th>Experiment TELIA</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latency</td>
<td>10 ms</td>
<td>9.2725 ms</td>
<td>13.2375 ms</td>
<td>83.27%</td>
</tr>
<tr>
<td>Peak rate</td>
<td>22 Mbps</td>
<td>$\geq$ 30 Mbps</td>
<td>$\geq$ 30 Mbps</td>
<td></td>
</tr>
</tbody>
</table>

Here latency results from experiment is obtained by halving mean RTT value of 100 bytes from Chapter 6. Based on the “best” fitting model, the probability that the latency of each LTE network will be less than 10 ms is evaluated and filled in Comments column.

8.2 Future Work

Although it has been proven that 3GPP LTE is a promising solution to interconnect devices in a smart grid, this smart microgrid only includes the components PMU and AMI. In practice, there are many other potential components which need two-way communicational infrastructures to help a power grid achieve the goals of a smart grid. For instance, the transformers, breakers and other devices mounted on electricity buses need to report their status and receive remote control commands. More investigation needs to be done before PMU and AMI are deployed in a real smart grid. In addition, the real time electricity price is still under development.

Furthermore, we only studied the performance of one single antenna LTE network in this thesis. The performance of MIMO LTE needs to be analysed not only for fulfilling the communication requirements but also for the scheduler design. Therefore a more complete simulation model for LTE is required. Based on the model, a scheduler which can allocate physical resources in both time and frequency domains can be designed.
Reference

[1] 3GPP, "LTE Introduction" http://www.3gpp.org/LTE


[14] 3GPP LTE Encyclopedia, An Introduction to LTE, 2010-12-03


[21] 3GPP, 3GPP TS 36.211 V8.9.0, 2009-12
Appendix A

Ping Introduction

As mentioned in preview section, the experiment uses **ping** command to send and receive data packets. The main advantages of ping are easy implement and understand, relatively accurate latency calculation, Internet Protocol (IP) based application, and arbitrary data packets length. Ping operates by sending and waiting for an ICMP packet, then measures RTT and records the loss rate. Table A.1 shows the general structure of an ICMP packet. Figure A.1 is one example packet without additional data captured by Microsoft Network Monitor 3.4 via Ethernet.

<table>
<thead>
<tr>
<th>Table A.1. ICMP Packet Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IP Header</strong> (20 bytes)</td>
</tr>
<tr>
<td>Bit 0-7</td>
</tr>
<tr>
<td>Version</td>
</tr>
<tr>
<td>Identification</td>
</tr>
<tr>
<td>Time to Live (TTL)</td>
</tr>
<tr>
<td>Source IP address</td>
</tr>
<tr>
<td>Destination IP address</td>
</tr>
<tr>
<td><strong>ICMP Payload</strong> (8+ bytes)</td>
</tr>
<tr>
<td>Message Type</td>
</tr>
<tr>
<td>Quench</td>
</tr>
<tr>
<td>Data (optional)</td>
</tr>
</tbody>
</table>

It is worthy to mention that the data can be arbitrary length as desired. However must be less than the maximum transmission unit (MTU) of the network. Here is an example of ping command which used to collect latency data in this paper.

```
ping 130.237.32.143 -l 32 -n 4 -f
```

It means to ping the target host 130.237.32.143 four times with additional 32 bytes
APPENDIX A. PING INTRODUCTION

Figure A.1. ICMP Packet Example Captured by Microsoft Network Monitor 3.4

data attached and structure the data frame without fragments. The result of ping looks like following:

Pinging 130.237.32.143 with 32 bytes of data:
Reply from 130.237.32.143: bytes=32 time=19ms TTL=53
Reply from 130.237.32.143: bytes=32 time=18ms TTL=53
Reply from 130.237.32.143: bytes=32 time=17ms TTL=53
Reply from 130.237.32.143: bytes=32 time=18ms TTL=53

Ping statistics for 130.237.32.143:
Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
Approximate round trip times in milli-seconds:
Minimum = 17ms, Maximum = 19ms, Average = 18ms

The output shows the result of 4 pings to the target, 130.237.32.143, with the results summarized at the end.