NOVEL PERFORMANCE EVALUATION OF INFORMATION AND COMMUNICATION TECHNOLOGIES TO ENABLE WIDE AREA MONITORING SYSTEMS FOR ENHANCED TRANSMISSION NETWORK OPERATION

A thesis submitted for the degree of Doctor of Philosophy

by

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ABSTRACT

The penetration of renewable energy sources has increased significantly in recent years due to the ongoing depletion of conventional resources and the transition to a low carbon energy system. Renewable energy sources such as wind energy are highly intermittent and unpredictable in nature, which makes the operation of the power grid more dynamic and therefore more complex. In order to operate the power system reliably under such conditions, Phasor Measurement Units (PMUs) through the use of satellite technology can offer a state-of-the-art Wide Area Monitoring System (WAMS) for improving power system monitoring, control and protection. They can improve the operation by providing highly precise and synchronised measurements near to real-time with higher frequency and accuracy. In order to achieve such objectives, a high-speed and reliable communications infrastructure is required to transfer time-critical PMU data from remote locations to the control centre. The signals measured by PMUs are transmitted across Local and Wide Area Networks, where they may encounter excessive delays. Signal delays can have a disruptive effect and make applications at best inefficient and at worse ineffective.

The main research contribution of this thesis is the performance evaluation of communication infrastructures for WAMS. The evaluation begins from inside substations and continues over wide areas from substations to control centre. Through laboratory-based investigations and simulations, the performance of communications infrastructure in a typical power system substation has been analysed. In addition, the performance evaluation of WAMS communications infrastructure has been presented. In the modelling and analysis, an existing WAMS as installed on the GB transmission system has been considered. The actual PMU packets as received at the Phasor Data Concentrator (PDC) were captured for latency analysis. A novel algorithmic procedure has been developed and implemented to automate the large-scale latency calculations. Furthermore, the internal delays of PMUs have been investigated, determined and analysed. Subsequently, the WAMS has been simulated and detailed comparisons have been performed between the simulated model results and WAMS performance data captured from the actual WAMS. The validated WAMS model has been used for analysing possible future developments as well as to test newly proposed mechanisms, protocols, etc. in order to improve the communications infrastructure performance.

ACKNOWLEDGEMENTS

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AUTHOR'S DECLARATION

The work described in this thesis has not been previously submitted for a degree in this or any other university and unless otherwise referenced it is the author's own work.

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TABLES

ABBREVIATIONS

ACSI	Abstract Communication Service Interface
APCI	Application Protocol Control Information
APDU	Application Protocol Data Unit
ASDU	Application Service Data Unit
CDC	Common Data Class
CDF	Cumulative Distribution Function
CRC	Cyclic Redundancy Code
CSV	Comma Separated Values
CT	Current Transformer
DECC	Department of Energy and Climate Change
DES	Discrete Event Simulation
DFT	Discrete Fourier Transform
DFR	Digital Fault Recorder
DNP3	Distributed Network Protocol Version 3
ENCC	Electricity National Control Centre
EPA	Enhanced Performance Architecture
EtE	End to End
EWMA	Exponentially Weighted Moving Average
FDR	Frequency Disturbance Recorder
FEC	Forwarding Equivalence Class
FES	Future Energy Scenarios
FIFO	First In First Out
FTP	File Transfer Protocol
GB	Great Britain
GEV	Generalized Extreme Value
GOOSE	Generic Object Oriented Substation Event
GPS	Global Positioning System
GSSE	Generic Substation State Event
GUI	Graphical User Interface
HDFS	Hadoop Distributed File System
HMI	Human Machine Interface

HVDC	High Voltage Direct Current
ICT	Information and Communications Technology
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IP	Internet Protocol
ISO	International Standards Organization
LAN	Local Area Network
LDP	Label Distribution Protocol
LER	Label Edge Router
LN	Logical Node
LSP	Label Switched Path
LSR	Label Switch Router
MMS	Manufacturing Messaging Specification
MPLS	Multi-Protocol Label Switching
MU	Merging Unit
NETS	National Electricity Transmission System
NETSO	National Electricity Transmission System Operator
NG	National Grid
NI	National Instruments
NTP	Network Time Protocol
OO	Object Oriented
OSI	Open Systems Interconnection
OSPF	Open Shortest Path First
PDC	Phasor Data Concentrator
PDU	Protocol Data Unit
PICOM	Piece of Information for Communication
PMU	Phasor Measurement Unit
PV	Photovoltaic
QoS	Quality of Service
RDBMS	Relational DataBase Management System
ROCOF	Rate Of Change Of Frequency
RTU	Remote Terminal Unit

SAN	Storage Area Network
SAS	Substation Automation System
SCADA	Supervisory Control And Data Acquisition
SCSM	Specific Communication Service Mapping
SEL	Schweitzer Engineering Laboratories
SO	System Operator
SOC	Second Of Century
SV	Sampled Value
TC	Traffic Class
TCP	Transmission Control Protocol
TE	Traffic Engineering
TO	Transmission Owner
ToS	Type of Service
TPDU	Transport Protocol Data Unit
TSDU	Transport Service Data Unit
TVA	Tennessee Valley Authority
TVE	Total Vector Error
UDP	User Datagram Protocol
UK	United Kingdom
UTC	Coordinated Universal Time
VT	Voltage Transformer
WAMS	Wide Area Monitoring System
WAN	Wide Area Network
WFQ	Weighted Fair Queuing

Chapter 1

Introduction

1.1 Environmental Legislation

The emission of greenhouse gases like carbon dioxide in an uncontrolled manner can cause average global temperature to rise by up to 6°C by the end of this century [1]. In this condition, extreme weather events like floods and drought, and issues such as public health-related deaths, migration of people, conflict, and global instability are anticipated to become more prevalent. Correspondingly, the UK is also likely to be affected by an increase in floods, heat waves, and droughts. In order to prevent the critical impacts of climate change, the average global temperatures must rise no more than 2 degrees Celsius. To achieve this aim, the global emissions must start falling before 2020 and then fall to at least 50% below 1990 levels by 2050 [1]. To restrain global warming to this level requires reducing global emissions. However, decarbonising the energy systems will be a gradual process over the coming decades. Britain needs to become a low carbon country to play its part in reducing emissions. The 2008 Climate Change Act [2] made Britain the first country in the world to set legally binding 'carbon budgets', aiming to cut emissions by 34% by 2020 and at least 80% by 2050 [3].

Based on this plan, by 2050 the UK is allowed to produce very few greenhouse gas emissions overall. Considering the costs and potential of all the options in different sectors, the emissions from the power sector should be reduced to almost zero [1]. Renewables play a key part of the decarbonisation of the energy sector, alongside other clean energy technologies including nuclear, carbon capture and storage. According to the determined goals, 15% of energy demand should be provided from renewable sources by 2020 in a cost effective way. The Committee on Climate Change also proposed that the penetration of 30-45% renewable energy to the total energy consumption in the UK is achievable by 2030 [4]. The UK leads the world in offshore wind farms and more than 700 turbines were installed by 2011 [4]. The deployment of onshore wind farms is accelerating with the biggest projects in Europe which already operating and under construction in Scotland and Wales. Currently, the UK wind energy installed capacity is 12 GW, which 4.05 GW of it is from offshore wind farms [5]. In addition to meeting the carbon reduction objectives, increasing the renewable energy deployment will secure the UK's future energy requirements, protect consumers from fossil fuel price fluctuations, and will drive investment in new jobs and businesses in the renewable energy sector [4].

Apart from deploying clean energy technologies, the efficiency of energy usage needs to improve. Demand for energy should be reduced dramatically through 2030 to 2050 and in some projections the level of this reduction has been set at 40% of 2005 levels. However, it should be noted that even when the demand for energy is reduced, the need for electricity is likely to increase [1]. This is because as well as meeting traditional demand, electricity creates opportunity in the future for heat, transport, and industrial processes to be electrified in a sustainable way [3]. Recent DECC (Department of Energy and Climate Change) analysis shows that electricity demand is likely to increase by between 30% and 100% by 2050 [6].

1.2 The GB Future Transmission System

National Grid (NG) owns the high-voltage electricity transmission network in England and Wales and is the System Operator (SO) of the high-voltage electricity transmission network for the whole of Great Britain. The transmission network in Scotland is owned by two separate transmission companies and the offshore transmission systems are also separately owned [7]. In fact, NG is responsible for managing the flows of electricity from generators to consumers on a real time basis [8]. NG does not generate the power neither does it sell power to consumers. It is paid by energy suppliers who buy electricity from the power stations and other electricity producers [9].

The National Electricity Transmission System (NETS) mainly consists of 400 kV, 275 kV and 132 kV assets connecting separately owned generation and distribution systems. The ‘transmission’ classification applies in Scotland or offshore to assets at 132 kV or above, and in England and Wales to assets at 275 kV or above. Assets that are at the lower voltage levels of grid are part of the six regional distribution companies supplying customers down to domestic level. There are also a number of separately owned interconnections to the European countries. Interconnectivity between European member states improves the security of the system, facilitates competition, and helps to integrate the renewable generation effectively [7].

Currently, the NETS peak demand is approximately 60 GW. 10 GW of renewable generation capacity is connected to the NETS, with a peak recorded output of 7.2 GW [7]. There are ongoing developments and radical changes in the energy landscape of the UK. Higher growth in nuclear and wind power is expected. Wind power is mainly being installed to the north and east of the system, particularly within Scotland. Accordingly, the power transfer from north to south has been increased, which intensifies the reinforcement requirements. The widespread location and intermittent nature of these generations need progressive development of transmission networks and advanced system operations [7]. Therefore, a larger and smarter electricity grid is required to manage a more complex system of electricity supply and demand [1].

National Grid has developed energy scenarios to visualise and plan how energy should be delivered in the future. In this regard, four scenarios have been determined which consider a range of potential drivers that might have an impact on the future of energy in the UK. These scenarios are distinctive based on the energy trilemma of security of supply, affordability and sustainability as shown in Figure 1 [3]. In order to develop the future transmission system based on the challenges ahead, a flexible approach has been adopted. The National Electricity Transmission System Operator (NETSO) and the Transmission Owners (TOs) deal with this uncertainty about the timing and location of future generation by considering these scenarios. The Future Energy Scenarios (FES) provide a detailed analysis of a range of credible futures. Based on the provided details in FES, the Gone Green will be generally the worst-case scenario for system strength in

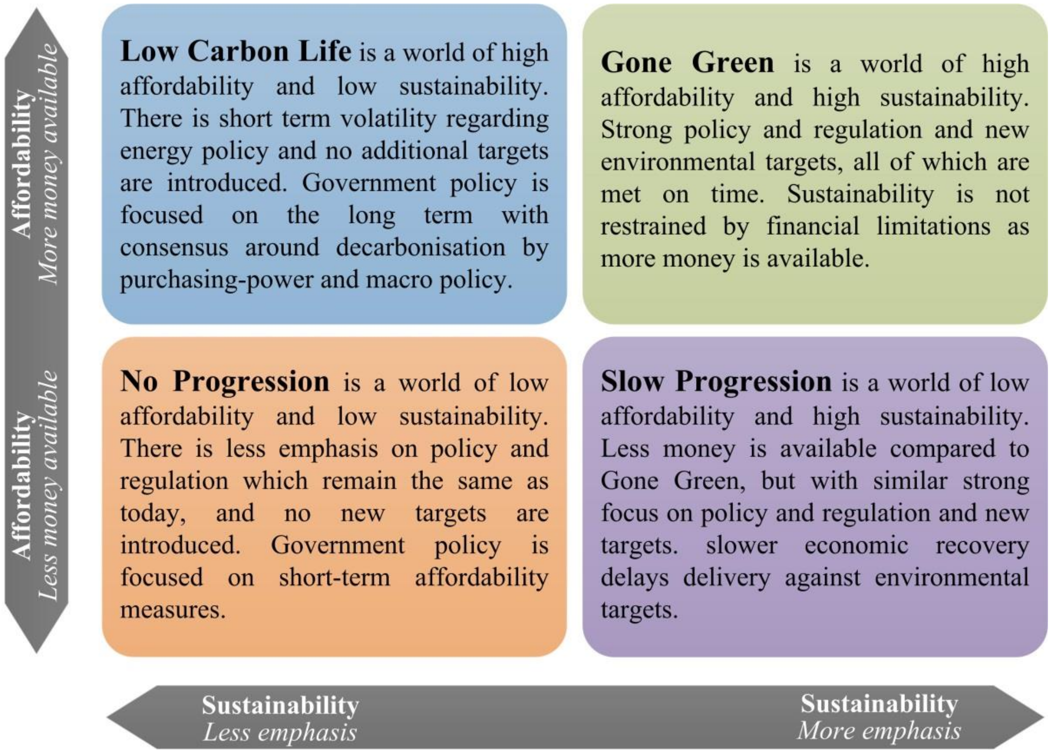


Figure 1 UK future energy scenarios [3]

terms of system inertia reduction, stability constraints and short circuit level, while No Progression is the closest to current situation [7].

Figure 2 [7] shows the impact of Gone Green scenario on the generation mix, up to 2035/2036. As can be seen, wind reaches approximately 20 GW of capacity by 2020 (just under 12 GW of this being offshore) and 47 GW by 2035 (35.5 GW of this being offshore). Furthermore, other renewables increase by 1.4 GW to 2020 and by 3.6 GW over the full period to 2035 [7]. It should be noted that these capacity values do not include any small and medium embedded generations. Embedded generations are small generation units that are connected to the distribution network, such as solar photovoltaic (PV) and wind [8].

In such a condition, the transmission network needs to be designed in a way to ensure required capacity for sending generated powers to consumers. In providing transfer capacity, the new infrastructure construction is not necessarily the first choice. NG's priority for network reinforcement is to optimise the existing assets to fully utilise the available capability of the system. The higher boundary transfer can be achieved by

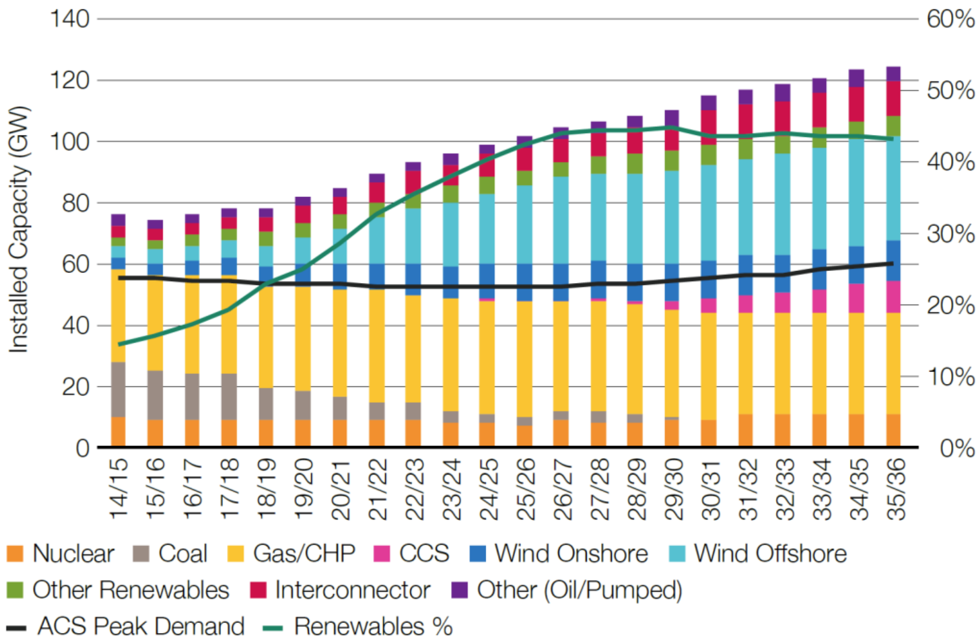


Figure 2 Generation mix in Gone Green scenario [7]

improving system operation using advanced monitoring, control, and protection tools [7]. In order to address the issues arising from integrating renewable energy sources number of projects have been defined. For example, VISOR project demonstrates the potential for new technologies to improve monitoring and understanding of the electrical transmission system in GB. The project will create a nationwide WAMS that can be used to improve the efficiency of network operation by reducing security margins [10]. Smart Frequency Control (SFC) project proposes a sustainable and cost-effective way for a greater volume and speed of frequency response to keep the system stable [11].

1.3 Wide Area Monitoring Systems

The environmental constraints described in Section 1.1 has led to the more complicated operation of power systems, and therefore they encounter more challenges. From the generation viewpoint, power industries have been deregulated and more independent power generators contribute as suppliers. In addition, there is a wider penetration of renewable and variable sources of generation. Furthermore, by the presence of less predictable load patterns and more power electronics driven sensitive loads, there is a higher requirement for providing reliability and power quality. Difficulties also exist in upgrading the transmission system proportional to the growing generations and loads, such as high cost and siting new transmission facilities.

Reliability is one of the prominent factors in operation of power systems that has notable economic impact and influence on society. Historically, power systems have been remarkably reliable. Although minor outages have been common, large-scale and wide-spread outages rarely happened and such interruptions have occurred over relatively limited areas. However, changes in the wholesale electricity market alongside the difficulties in upgrading the transmission systems have caused power systems to face more challenging network-wide issues. In this condition, a minor disturbance can be intensified by a series of events leading to network-wide effect. Subsequently, system may completely collapse if timely actions are not adopted [12]. To avoid this, advanced and smart monitoring tools are required to quickly and reliably observe the changing state of the key electrical parameters in real time, take appropriate corrective measures, and isolate faults.

Traditionally, Supervisory Control And Data Acquisition (SCADA) systems were designed for monitoring of the power systems by polling the Remote Terminal Units (RTUs) at all substations. These have been the essential component for monitoring in power system for years. However, the current SCADA systems collect data and observe grid conditions every few seconds. Thus they are incapable of providing information about the dynamic state of the power system and the monitoring is relatively static and infrequent. In addition, SCADA data are not consistently time-synchronised and shared widely across the network. Therefore, SCADA does not provide operators with real-time and wide-area visibility. Consequently, it is not effective for the real-time wide-area monitoring applications.

The emergence of the new generation of measurement technology, known as Phasor Measurement Units (PMUs), provides a significant improvement in reliability [13]. PMUs offer unprecedented time-synchronised and high resolution information over a wide-area, in real-time. By using PMUs data can be provided in higher rates, commonly once every cycle, and at higher levels of accuracy. Many advanced smart grid applications can take advantage of the measurement capabilities of PMUs. These applications enable utilities to react promptly to the contingencies and prevent large-scale blackouts [13].

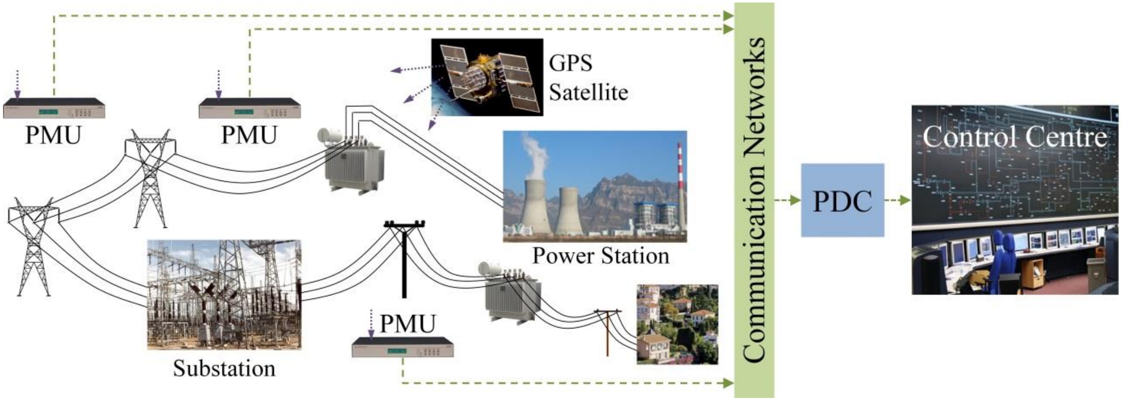


Figure 3 Deployment of PMUs in Wide Area Monitoring Systems

A PMU-based WAMS is a system in which PMUs measure power system parameters including frequency, voltage and current phasors with a high degree of accuracy, as shown in Figure 3 [14]. Meanwhile, the phasors are time-stamped using signals from Global Positioning System (GPS) so that the microsecond when the measurement taken is permanently attached to it. This feature enables simultaneous measurement of system parameters from different locations in the power system, making the comparison of measured parameters simple. Afterwards, the time-critical phasor data are collected from various locations in the electrical grid and will be transmitted to a central location known as Phasor Data Concentrator (PDC). A PDC receives and time-synchronises phasor data from geographically distributed PMUs and produces a real-time, synchronised output data stream. This information can be exploited by many smart grid applications, ranging from visualisation and alarms for situational awareness, to applications that provide sophisticated analytical, control, or protection functionality. The collected data can be also stored for future offline analysis [15].

Even though PMUs found their use mainly in transmission systems, the interest in highly accurate measurements has driven to their deployment at lower voltage levels. Current investigations are taking place in order to exploit PMUs benefits in distribution networks. PMUs have a significant role to play in the successful transition of today’s huge amount of power delivery into a “Smart Transmission Grid” since the number of PMUs is growing in Europe and around the world [14, 15].

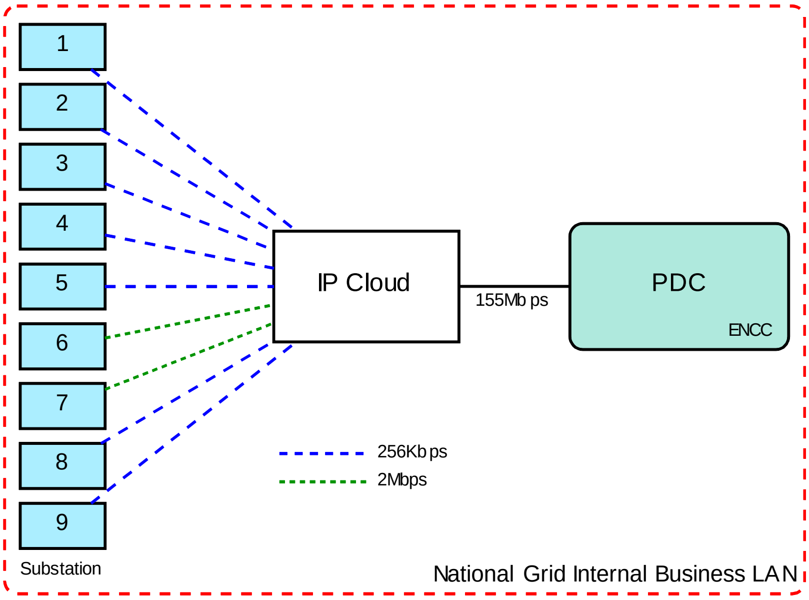


Figure 4 WAN infrastructure schematic of the GB WAMS

In this thesis, a WAMS as installed on the GB transmission system is considered in order to evaluate the performance of Information and Communications Technologies (ICT) for communicating PMUs' time-critical data. The WAMS consists of 9 substations, which are geographically distributed and they are equipped with PMUs. Figure 4 shows the Wide Area Network (WAN) schematic of the real system and will be further discussed in Chapter 5.

1.4 Research Objectives

In order to achieve real-time monitoring, a high-speed and reliable communications infrastructure is required to transfer time-critical PMU data from remote locations to the PDC. Therefore, communications infrastructure represents potential bottlenecks in the architecture of such systems. In order to fulfil the communication requirements a number of factors should be considered, including:

- Data volume

PMUs provide higher sampling rates when compared to conventional Remote Terminal Units (RTU) in SCADA systems, which gives rise to a significant increase in the rate of packet generation.

- Load profile

Different types of data may also be carried by the communications network including data from other substation based devices and applications. Such devices and applications may use the same shared communication infrastructure as PMUs.

- Latency

Communication delays play a crucial role in WAMS that support mission-critical applications, such as power system protection. It is obvious that excess delays in the communication network are a challenging factor that affects the PMUs data transmission and could make the applications at best inefficient and at worse ineffective. Therefore, the performance evaluation of latency exhibited in a WAMS is a very important aspect that should be fully investigated [16, 17].

A WAN is more than just end user devices. It comprises of links, routers, protocols, mechanisms, etc., which means that when all these components are considered, setting up a WAN can be a complex and costly process. The extent of WAN makes the direct experiment of new designs almost impossible. Apart from the economic issues, it can lead to a serious damage and loss of data. Hence there is a need to have simulation models and testbeds which can accurately imitate the network behaviour. By simulating the intended network, it is possible to test the newly proposed mechanisms, protocols, topologies, etc. or modify some network parameters and observe the effect before actual deployment.

In this regard, reference [18] analyses the communication requirements from the viewpoint of the anticipated smart grid applications. The authors used the open source network simulator NS2 [19] for simulating the possible communication scenarios on a Western Electricity Coordinating Council 225 bus and a Polish 2383 bus transmission system model.

Reference [20] examines the performance aspects of Internet Protocol (IP) network infrastructures when utilised by continuous PMU data streams. A set of simulation models characterizing a network of a Nordic Transmission System Operator were built to perform the analysis. OMNeT++, an open source communication simulation environment [21], was used to simulate and study the impact of QoS mechanisms on PMU communications.

In reference [22] a simulation model of communication infrastructure was built based on requirements from transmission system operators with regard to wide area monitoring and control applications. This model, which is based on possible locations of PMUs in Sweden, was implemented in OPNET Modeler [23] to simulate the effect of different architectures. The authors considered different architectures with regards to dedicated or shared communication links and different data-sorting algorithms. In this paper the impact of PDC on the overall delay is also taken into consideration.

The discussed references did not consider the impact of PMUs' internal delay in WAMS operation. Furthermore, the obtained simulation results were not validated by the actual latency measurements of networks. The actual latency measurement enables monitoring of the communication infrastructures and can also be actively used to provide latency values as inputs to the power system controllers. Employing different communication protocols in accordance with WAMS applications and investigating the latency characteristics on this basis need to be also considered.

The choice of the proper transmission media, network architecture, and protocols will play an important role in fulfilling the idea of wide area monitoring, protection and control. Early communication media, such as power line carrier and microwave, had constraints with regard to channel capacity, data transfer rate, reliability, scalability, robustness and so on. As a consequence of the emergence of optical fibre, these constraints have been improved significantly and it has now become the most suitable candidate for WAMS applications [17]. Furthermore, early communication networks carried continuous bit streams over physical links using a technique called circuit switching. Although this method was well suited for transmitting real-time data, a single physical link failure had dramatic consequences. In fact, this would cause interruption of all communications that were using the failed link. It is important to note that the Internet is a datagram packet switched network that solves this problem by dividing data into small chunks called packets [24]. These packets are individually routed through the network and during a link failure they can be rerouted to avoid the failed link. Compared to circuit switching networks, packet switching networks are more robust, flexible and efficient. However, it is more difficult to guarantee or manage flows of data in a packet switching network than in a circuit switching network since each packet is handled separately [24].

Nowadays the Internet is playing a vital role due to the wide variety of applications and services provided. Meanwhile, the wide range of different Internet applications can cause problems with the communications. Some applications like WAMS need real-time communication and therefore low end-to-end delay. While for other applications like File Transfer Protocol (FTP), delay may not be an important issue. Therefore, a high performance communications network should consider the different applications when routing a packet. Fulfilment of such a requirement on the Internet is a challenging task for the conventional IP networks [25]. The Internet architecture has evolved over time to integrate new technologies and meet the new requirements of the users [26]. Multi-Protocol Label Switching (MPLS) as a Traffic Engineering (TE) tool has emerged to provide service requirements and managements for the next generation IP based backbone networks [24]. It should be noted that MPLS is not a replacement for IP. In fact, MPLS adds a set of rules to IP so that the traffic can be classified and policed [25].

1.5 Principal Research Contributions

The principle contributions to knowledge, as presented in this thesis, can be summarised as follows:

- The performance of a WAMS communications infrastructure as installed on the GB transmission system has been evaluated. The thesis can be considered as the first reference that provides performance evaluation of the British transmission system WAMS communications infrastructure in detail. Therefore, it can be a reference to be used for comparison of WAMS in other transmission systems. The evaluation steps are as follows:

    - The actual PMU packets at PDC server were captured using Wireshark [27], an open source network analyser. Furthermore, a novel algorithmic procedure was implemented in MATLAB to automate the large-scale latency calculations. Automating the calculation process can save time, reduce error and enables more detailed and larger scale analyses, especially for the high-resolution PMU data. This represents an original research contribution and to the best of researcher’s knowledge this is the first time that it has been applied to an actual WAMS on a real transmission system. This novel procedure:

- Uses the Wireshark exported files and is able to find the required information for latency calculation in that file automatically.
- As each PMU type may have different formats when defining time stamps, such as number of digits, the algorithmic procedure calculates the latency value according to the PMU type.
- Then a new Excel file is created and details of each packet along with its latency are written in a separate row.
- This file also includes the Exponentially Weighted Moving Average (EWMA) of the PMUs latency value as well as other characteristics, such as maximum and minimum latency values for better statistical comparison. The user can also specify the desired EWMA smoothing constant to be used in the calculations.
- Provides the time stamp of the packet that has maximum or minimum latency.
- In the case of capturing traffic discretely in specified time intervals, the algorithmic procedure is able to open each exported file from Wireshark automatically one by one and then calculate the latency. At the end, calculated latency values for all packets are written continuously in a single Excel file, which is saved in a predefined location. It also records the maximum and minimum latency in each individual file with their relevant time stamps.
- The novel algorithmic procedure as implemented can be used in future for the monitoring of WAMS communication networks. It can indicate the latency characteristics at specified time intervals. For example, the maximum latency can be monitored and when calculated values exceed the setting values, they trigger the events. The maximum delay for a PMU is an important factor that has an impact on the PDC time-out parameter and, in turn, on the whole WAMS performance. The time-out is the amount of time

the PDC is actively waiting for the remaining PMU packets with the same time stamp.

- Simulations were performed through the models developed in Discrete Event Simulation (DES) tools, OPNET and OMNeT++, to determine the characteristics of communication delays and bottlenecks that can occur in WAMS. The effect of communication links data rates, deploying more than one PMU in substations, and background traffic have been fully investigated.

- The internal delays of PMUs have been investigated, analysed and calculated in detail. It has been shown that the internal delays of PMUs can introduce considerable delay and, in turn, have significant impact on the performance of WAMS applications. Furthermore, the internal delays of PMUs have been modelled in the designed node models of PMUs in DES and their impact were taken into consideration for simulation.

- Detailed comparisons have been performed between the simulation results and data captured from the existing WAMS. Through this comparison, the implemented modelling and simulation approach has been validated. Therefore, the novel WAMS model can be confidently used for analysing possible future developments as well as test the newly proposed mechanisms, protocols, etc. in order to improve the performance.

▪ The performance of a typical power system substation communications infrastructure based on IEC 61850 standard has been evaluated through the following:

- A laboratory-based IEC 61850 standard analysis has been provided.

- Simulations were performed in a DES tool, OMNeT++, to investigate the performance of communications infrastructure in a typical power system substation.

- The deployment of IEC 61850 for PMU communications has been investigated.

- A comprehensive overview of the common open standards within the scope of power system ICT has been provided.

1.6 List of Publications

1.6.1 Conference Publications

M. Golshani, G. A. Taylor, I. Pisica, P. M. Ashton, "Investigation of Open Standards to Enable Interoperable Wide Area Monitoring for Transmission Systems", in Proc. UPEC 2012, 4-7 September 2012, London, UK.

M. Golshani, G. A. Taylor, I. Pisica, P. M. Ashton, "Laboratory-Based Deployment and Investigation of PMU and OpenPDC Capabilities", in Proc. The IET ACDC, 4-6 December 2012, Birmingham, UK.

M. Golshani, G. A. Taylor, I. Pisica, P. M. Ashton, "Implementation of Wide Area Monitoring Systems and Laboratory-Based Deployment of PMUs", in Proc. UPEC 2013, 2-5 September 2013, Dublin, Ireland.

M. Golshani, G. A. Taylor, I. Pisica, "Simulation of Power System Substation Communications Architecture Based on IEC 61850 Standard", in Proc. UPEC 2014, 2-5 September 2014, Cluj-Napoca, Romania.

M. Golshani, G. A. Taylor, I. Pisica, P. M. Ashton, C. Chen, J. Liu, J. Lin, "Performance Analysis of Wide Area Network Communications using Discrete Event Simulation Tools", in Proc. POWERCON 2014, 20-22 October 2014, Chengdu, China.

M. Golshani, G. A. Taylor, I. Pisica, P. M. Ashton, "Performance Evaluation of MPLS-Enabled Communications Infrastructure for Wide Area Monitoring Systems", in Proc. The IET ACDC, 10-12 February 2015, Birmingham, UK.

1.6.2 Journal Publication

M. Golshani, P. M. Ashton, I. Pisica, G. A. Taylor and A. M. Carter, "Novel Performance Evaluation of Communications Infrastructure to Enable Wide Area Monitoring System Deployment" (submitted to CSEE Journal of Power and Energy Systems, September 2015).

1.7 Organisation of the Thesis

This thesis has been divided into 6 chapters as follows:

Chapter 1 - Introduction

This chapter provides an outline of the context and research motivations behind the thesis followed by contributions. It describes the targets set for emissions of greenhouse gases as well as renewable energy and highlights the relevant challenges. Using advanced monitoring systems to manage increasing transmission system issues are discussed and a brief background regarding WAMS is presented. Furthermore, the research rationale for evaluating the performance of communications infrastructure and the relevant research contributions are addressed.

Chapter 2 - Open Standards for ICT in Power Systems

In this chapter, the most common open standards for smart grid and in the area of Information and Communications Technology (ICT) are investigated. As there are various manufacturers in the market, open standards are necessary in providing interoperability between equipment from these manufacturers. The chapter starts with synchrophasor standards for PMUs and describes the course of evolution for the standards, in detail. Then, the existent communication protocols for transferring data in a typical power system are discussed. Each of these communication protocols covers certain domains and specific groups of data.

Chapter 3 - Wide Area Monitoring Systems

This chapter provides a comprehensive overview of WAMS. It divides WAMS into the four main parts of PMUs, PDCs, applications, and communication infrastructures. Then each part and its requirements will be fully discussed. Furthermore, the description of work carried out for deployment of WAMS on the GB system is provided. This includes both the high voltage transmission level and low voltage laboratory-based WAMS. Samples of events happened on the GB system that have been captured using WAMS will be also presented.

Chapter 4 - Performance Evaluation of Substation Communications Infrastructure

At the beginning of this chapter, a laboratory-based IEC 61850 standard analysis is provided. Afterwards, a brief introduction to the key concepts of network simulation and network simulators are presented. The three most commonly used network simulators: OPNET, OMNeT++, and NS3 are considered and their main features are investigated. Furthermore, the simulation and modelling of a typical power system substation communications infrastructure is also presented. The considered substation is based on IEC 61850 communication protocol and its communication performance is evaluated with regard to delays. The deployment of IEC 61850 for WAN applications, such as PMUs, will be also investigated.

Chapter 5 - Performance Evaluation of WAMS Communications Infrastructure

This chapter presents the main contribution of the thesis. It provides a novel performance evaluation of the communications infrastructure with regard to latency from PMUs to PDC. In the novel modelling and analysis, an existing WAMS as installed on the GB transmission system is considered. Firstly, the actual PMU packets as received at the PDC server are captured using Wireshark for latency analysis. A novel algorithmic procedure will be implemented in MATLAB to automate the large-scale latency calculations. This algorithmic procedure can save time, reduce error and enables more detailed and larger scale analyses, especially for the high-resolution PMU data. Furthermore, the internal delays of PMUs will be investigated, determined and analysed in detail. Subsequently, the WAMS will be simulated using both open source and commercial DES tools, and detailed comparisons will be performed between the simulated model results and WAMS performance data captured from the actual WAMS using Wireshark. In the WAMS simulated model, the internal delays of PMUs are modelled and their impacts will be taken into consideration. As a number of substations in this model have been equipped with two PMUs, the effect of deploying multiple PMUs will be analysed. Moreover, different communication protocols, mechanisms, and topologies will be investigated for the GB WAMS future developments.

Chapter 6 - Conclusions and Further Research

Finally, this chapter concludes the thesis and presents an overview of the aims and objectives fulfilled in this research. It summarises the results obtained and discusses the key findings. The thesis is ended with the proposal for further steps that can be taken as well as recommendations for possible future research directions.

Chapter 2

Open Standards for ICT in Power Systems

2.1 Introduction

Smart grids have an essential role in transforming the functionality of the electricity supply system to provide a user-oriented service, high security, quality, and economic efficiency in an open market environment [28]. In this regard, having a wide area monitoring system is vital in order to detect problems and react to them as quickly as possible. The high number of different manufacturers active in the power system and WAMS markets, each implementing proprietary protocols and applications, could result in systems that cannot be interconnected. Therefore, standardization is key for the advancement of connectivity and interoperability within systems. In the past, utilities used to employ proprietary protocols, which were specified by the product vendors. Gradually, it was decided to move towards open standards to provide an interoperable environment and improve modelling capabilities. Apart from PMU standards, in a typical power system, several communication protocols exist and are required for transferring data, and each of them cover certain domains and specific groups of data. The objective of this chapter is to investigate the adoption, development and performance of the most common open standards to enable interoperable wide area monitoring systems.

2.2 Synchrophasor Standards

2.2.1 Background

The primary purpose of the synchrophasor standard is to ensure PMU interoperability. The first standard for synchrophasors, IEEE 1344, was introduced in 1995 and reaffirmed in 2001. It defined the basic concepts for the measurement and method of data handling. However, technology is constantly evolving and standards should be updated in order to accommodate new requirements. Thus, the new standard, IEEE C37.118, was published in 2005. This significantly improved the previous standard, while still maintaining basic compatibility [29]. The IEEE C37.118-2005 open standard specified a set of fundamental characteristics, including Time Reference (UTC - Coordinated Universal Time), Rate of Measurement, Phase Reference (cosine), Accuracy Metrics (Total Vector Error), and Communication Model (format of messages). By defining these specifications, the real-time and off-line processing of synchrophasor data from different measuring systems can be performed more easily [30]. Although the publication of IEEE C37.118-2005 was an important step in the standardisation of phasor measurements, this standard does not cover all aspects. For example, it does not specify PMU performance requirements under dynamic conditions, which could lead to PMUs using the same standard to show different results under transient situations. Moreover, it does not address frequency measurement requirements, and does not specify a communication protocol; it only defines the data format with basic methods for data transfer [29].

Due to the above issues, further work was done to revise the standard in 2008. In addition, IEC 61850 was proposed to be employed as a communication standard for transferring measured synchrophasors [31]. However, there were some problems in merging C37.118 into IEC 61850. As a solution to these issues, it was proposed to split the C37.118 standard into two parts. In fact, the revision separates the measurement and communication sub-clauses into individual standards. This facilitates widespread adoption and deployment of this standard by allowing freer use of other standards for synchrophasor communication. The two new revised standards were completed and published in December 2011. The first part, C37.118.1-2011, includes the synchrophasor measurement definitions and requirements, and the second part, C37.118.2-2011, includes a new standard for synchrophasor data transfer, which is designed to be compatible with IEC 61850. Both standards have maintained features from the previous version, but with updates and additional provisions [32, 33].

2.2.2 IEEE C37.118.1-2011

This standard, entitled ‘IEEE Standard for Synchrophasor Measurements for Power Systems’, defines synchronised phasor and frequency measurements across power systems using PMUs. In addition, it specifies a set of performance requirements for evaluating these measurements and compliance of devices from different manufacturers. When the measurements taken from various substations in power grids are compliant with the standard, they are comparable and can be accurately combined for power system operation analysis. This standard has five clauses along with six informative annexes [32]. The details regarding measurement accuracy and evaluation criteria, as well as PMU reporting times, are provided in Clause 5.

2.2.2.1 Measurement Evaluation

The values obtained from a PMU and the actual values of parameters may show differences. In order to assess the accuracy of measurements, this standard defines the uncertainty requirements for PMUs in terms of Total Vector Error (TVE). It defines TVE as the vectorial difference between the measured and theoretical values of the phasor, expressed as a fraction of the magnitude of the theoretical phasor. Considering the synchrophasor representation of a signal $X(n)$ is a complex value as in Equation (1) , the TVE value is given by Equation (2) [34].

$$X(n) = X_r(n) + jX_i(n) \tag{1}$$

$$TVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 + (\hat{X}_i(n) - X_i(n))^2}{(X_r(n))^2 + (X_i(n))^2}} \tag{2}$$

where, at the instant of time n of measurement, $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the measured values, given by the PMU, and $X_r(n)$ and $X_i(n)$ are the theoretical values of the input signal.

A PMU is deemed to be compliant with the standard, if TVE is maintained below the limit value of 1%. In fact, the magnitude and phase angle differences are considered together in the TVE quantity. However, as the phase angle is measured with respect to a time synchronised reference, signal timing errors cause errors in the phase angle measurement. Thus, timing errors will result in a different TVE depending on the system frequency. In this regard, for the 1% TVE criterion, the maximum magnitude error is ±0.01 when the error in phase angle is zero, and the maximum error in phase angle is 10 mrad (±0.5730°). The corresponding timing error at 50 Hz is ±31.8 μs (26.5 μs at 60 Hz). The relationship between the actual phasor, the measured phasor and the TVE for an arbitrary limit of ε is shown in Figure 5. The 1% criterion for TVE can be presented as a circle with the radius of $\varepsilon = 0.01$ drawn at the end of the phasor. If the end point of the measured phasor lies inside the circle, the measurements fulfil the required accuracy and the PMU is compliant. It should be noted that Figure 5 is not to scale and has been greatly exaggerated for clarity [35, 36].

Apart from the TVE, the standard defines criteria for evaluating errors in frequency and rate of change of frequency (ROCOF) measurements. In addition, measurement response time and delay time, as well as measurement reporting latency, are also considered for the exact analysis of PMU operations.

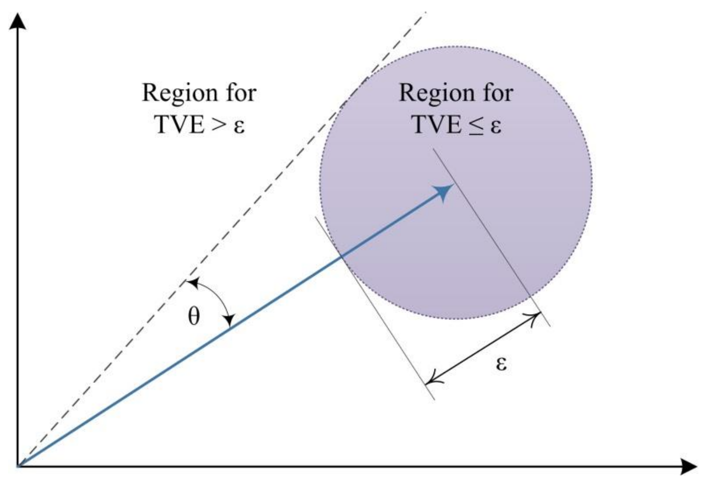


Figure 5 TVE criterion for an arbitary limit of ε

2.2.2.2 Measurement Reporting

PMUs are required to be configured in a way to provide measurement reporting at multiples of the power system frequency. Reporting rate (F_s) is an integer number of times per second when the rate of measurement is greater than one per second, or is an integer number of seconds between measurements when the measurement rate is equal to or slower than one per second. As lower reporting rates are not suitable for dynamic analysis of power systems, Fs is considered as the frequency of measurement in frames per second in this thesis. The measurements are reported at a constant rate and the intervals between them are all the same. As the UK power system is based on 50 Hz, the acceptable reporting rates (F_s) for the deployed PMUs are 10, 25, 50, 100, etc. frames per second.

A data frame consists of a set of information that may include multiple channels of phasor estimates, analog words, and digital words with a measurement status word and a time tag, as described in the IEEE C37.118.2-2011 standard.

2.2.2.3 Measurement Compliance

The C37.118.1 standard defines two classes of performance: P class and M class. P class is used for applications requiring fast response. The letter P is adopted since protection applications require a fast response. M class is used for applications that do not require a high reporting speed. The letter M is adopted since analytical measurements often require greater precision rather than minimal reporting delays. Therefore, the standard evaluates the compliance with requirements in accordance with the PMU's class of performance. Clause 5 of the standard describes details regarding measurement conditions and requirements for PMUs in steady and dynamic states in order to be compliant with the standard.

The concept of reporting latency, which is the maximum time interval between the data report time as indicated by the data time tag and the time when the data becomes available at PMU output, is fully described in Chapter 5, where the internal delays for the NG PMUs are investigated. Clause 5 also provides the minimum accuracy for the reporting latency values and the PMU internal delay results obtained in Chapter 5 will be checked and compared with the standard performance requirements.

2.2.3 IEEE C37.118.2-2011

This standard, entitled ‘IEEE Standard for Synchrophasor Data Transfer for Power Systems’, defines a method for real-time exchange of synchronised phasor measurement data in power systems. It specifies data transmission formats that can be used with any suitable communication protocol for real-time data transfer between PMUs, PDCs, and relevant smart grid applications. It does not impose any constraints on the communication system or media itself. In fact, any communication system that is able to support the provided message structure in the standard and has sufficient bandwidth can be deployed for PMU data transmission. The required bandwidth depends on the reporting rate and message size. The message size in turn corresponds to the parameters included in the frame and is discussed in detail in the following subsections. This standard has six clauses along with six informative annexes. Clause 6 is the main one defining the real-time communication protocol and message formats. Informative annexes are provided to clarify the standard and give supporting information about communication options and requirements.

2.2.3.1 Message Framework

Four message types are defined in this standard, namely data, configuration, header, and command. The first three message types are transmitted from the data source, PMU or PDC, and the last one is received by the data source. It should be noted that PDC itself can be considered as a data source when it sends data to another PDC. The data, configuration and command messages are binary messages, and the header message is in a human-readable format. Data messages contain the actual measurements from PMUs. Configuration messages contain information required to decode the data messages. Headers contain descriptive information sent from the PMU/PDC but provided by the user. Command messages control the operation of the synchrophasor measurement device.

All four types of message frames start with a 2-byte SYNC word followed by a 2-byte FRAMESIZE word, a 2-byte IDCODE, a time stamp consisting of a 4-byte second-of-century (SOC) and 4-byte FRACSEC. Finally, after DATA relevant to the messages, the frames end with a 2-byte check word (CHK).

- The SYNC word provides synchronization and frame identification. Bits 6-4 in the SYNC word determine which of the four message types the frame is, and bits 3–0 show the version number. All previously defined messages in IEEE C37.118-2005 are version 1 and the messages added in IEEE C37.118.2-2011 are version 2.

- The FRAMESIZE shows the total number of bytes in the frame, including CHK
- The IDCODE indicates the source of a data, header, or configuration message, or the destination of a command message. In fact, the message IDCODE is related with a data stream and links data frames with the provided configuration and header information.
- The SOC (Second of Century) time with FRACSEC shows the time stamp recorded on the PMU during measurement. In fact, the time stamp is an 8-byte message comprised of a 4-byte SOC and a 4-byte FRACSEC, which includes 3-byte for fraction of second and 1-byte time quality indicator. The SOC is the representation of the UTC time in seconds calculated from midnight of January 1, 1970.
- CHK, which is a CRC-CCITT, is finally used for providing error detection.

All frames are transmitted with the same order and format described with their relevant DATA and without any delimiters as shown in Figure 6. In normal operation, the PMU only sends data frames. Since the plan in this thesis is to analyse the WAMS latency over the data transmission period, the format for data messages is specifically investigated here.

2.2.3.2 Data Frame

The PMU data frame consists of binary data ordered as shown in Figure 7. Each row of the table contains a field of the message. The data frame contains measured data and is identified by having bits 4–6 in the SYNC word set to zero. The STAT provides status information for the data in its data block. The data can be one block from a single PMU or multiple blocks from different PMUs. Each PMU data block is headed by a STAT,

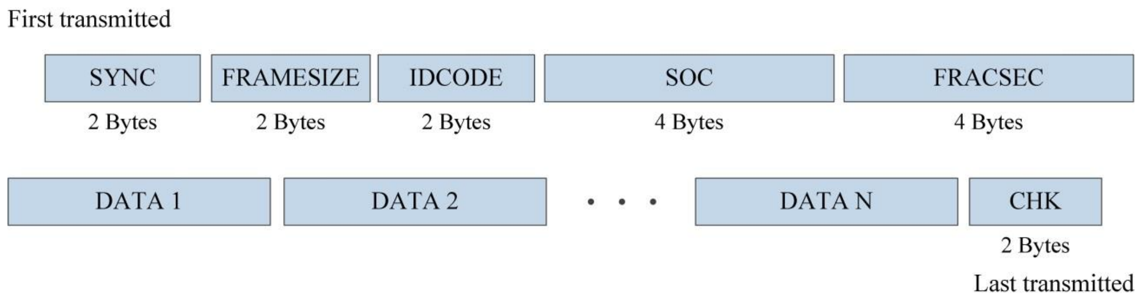


Figure 6 Frame transmission order in the IEEE C37.118.2-2011 standard

No.	Field	Size (Bytes)	Comments
1	SYNC	2	First byte: AA hex Second byte: 01 hex (frame is version 1, IEEE Std C37.118-2005)
2	FRAMESIZE	2	Number of bytes in frame
3	IDCODE	2	Stream source ID number, 16-bit integer
4	SOC	4	SOC time stamp, for all measurements in frame
5	FRACSEC	4	Fraction of Second and Time Quality
6	STAT	2	Bit-mapped flags
7	PHASORS	4 × PHNMR or 8 × PHNMR	Phasor estimates. May be single phase or 3-phase positive, negative, or zero sequence. 4 or 8 bytes each depending on the fixed 16-bit or floating-point format.
8	FREQ	2 / 4	Frequency (fixed or floating point)
9	DFREQ	2 / 4	ROCOF (fixed or floating point)
10	ANALOG	2 × ANNMR or 4 × ANNMR	Analog data, 2 or 4 bytes per value depending on fixed or floating-point format
11	DIGITAL	2 × DGNMR	Digital data, usually representing 16 digital status points (channels)
	Repeat 6–11		Fields 6–11 are repeated for as many PMUs as in NUM_PMU field in configuration frame
12	CHK	2	CRC-CCITT

Figure 7 Data frame in the IEEE C37.118.2-2011 standard

which applies to that block only. Bits are set in this STAT flag first by the PMU that generates the data, and then can be also changed by other devices in the data chain, such as a PDC. As can be seen, the frame size is precisely described in the standard and varies depending on the number of phasors and analog and digital parameters included in the frame. Based on the provided information, typical frame sizes vary from 40–70 bytes for a single PMU to over 1000 bytes in a frame from a PDC with data from numerous PMUs across the network.

This standard considers that data are transmitted in real-time and immediately after measurement. Originally, only RS-232 serial communications were employed for PMU communications. Later, as communications evolved into network methods, PMUs moved towards using IP as well.

2.3 Modbus

The Modbus transmission protocol was developed by Gould Modicon (now Schneider) for process control systems. Basically, Modbus is a simple, inexpensive, robust, and easy to use serial communications protocol that has become the de facto standard communication protocol in the industry since 1979 [37, 38]. In fact, Modbus is an Application Layer protocol positioned at level 7 of the Open Systems Interconnection (OSI) model. Appendix A provides background information about network architectures, including the OSI model, as well as protocol layers. Modbus offers client/server communication for one server and up to 247 clients, which are connected to different networks [39]. Transactions are either of query/response type where only a single client is addressed, or of broadcast/no response type where all clients are addressed [37]. In either case, only the server initiates messages, and in other words, report by exception is not supported except for Modbus over Ethernet TCP/IP [39]. Therefore, the server must routinely poll each client to identify changes in the data. Accordingly, this occupies bandwidth and takes a great deal of time, which is significant where bandwidth is limited and expensive, such as over a low-bit-rate radio link. Modbus is currently implemented using the following different transmission protocols [39]:

- TCP/IP over Ethernet
- Asynchronous serial transmission over a variety of media (wire RS-232, 422 or 485, fiber, radio, etc.)
- Modbus Plus, a high speed token passing network (which is currently proprietary to Modicon)

For Asynchronous Modbus and Modbus Plus, the Application Data Unit (ADU) is directly mapped to the Physical Layer, while in Modbus Ethernet TCP/IP it is first passed through the Transport and Network Layers. Figure 8 shows the concept of the Modbus communication stack for these three implementations [31]. By using gateways, these three implementation types can exist in a communication network at the same time and the Modbus protocol enables all types of network architecture to communicate with each other in a simple manner [31].

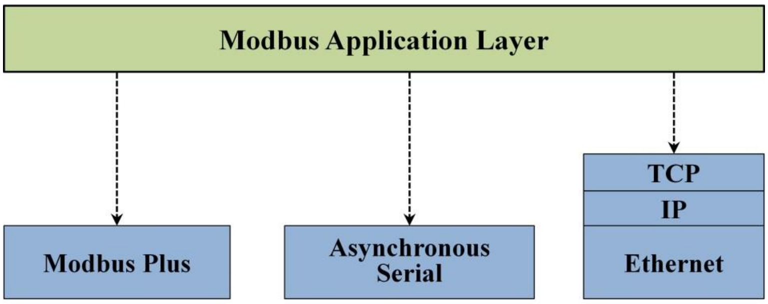


Figure 8 Modbus communication stack

Some characteristics of the Modbus protocol are fixed, such as frame format, frame sequence, dealing with communications errors and exception conditions, and the functions performed. On the other hand, other characteristics can be determined by the user. These include transmission medium, transmission characteristics and transmission modes (RTU or ASCII) [37].

A transaction is comprised of a single request from the host to a particular secondary device and afterwards a single response from that device back to the host. Both of these messages are formatted as Modbus message frames. The Modbus protocol defines a simple Protocol Data Unit (PDU) independent of the underlying communication layers for transmission of messages between server and clients [37]. Figure 9 shows a general Modbus frame (bytes demonstrated here are in Hex format and not in ASCII) [31].

As indicated, such message frames includes a series of bytes classified into four fields. These are described in the following paragraphs:

Address Field, the first field of the Modbus frame is the address field, which is composed of a single byte of information. In the request frame, this byte identifies the controller to which the request is being directed. The response frame begins with the address of the responding device. Theoretically, each client may have an address field between 1 and 247. However, practical limitations will limit the maximum number of clients [37].

Application Data Unit (ADU)			
	Protocol Data Unit (PDU)		
1 Byte	1 Byte	Variable	2 Bytes
Address Field	Function Field	Data Field	Error-Check Field

Figure 9 Modbus frame format

Function Field, the second field in each frame is the function field, which is also composed of a single byte of information. When a request message is sent from a host to a target, the function code field tells the target device what kind of action to perform. If the target device is able to perform the requested function, the response frame will have the same function field as the original request. Otherwise, the function field of the response frame will be echoed with its most-significant bit set to one. Thus, signalling an exception response including an appropriate exception code that the host application can use to determine the next action to be taken. Valid function codes are in the range of 1 to 255 decimal, where the range 128-255 is reserved and applied for exception responses (function code “0” is not valid) [39].

Data Field, the third field in a message frame is the data field. The length of this byte is variable according to the function that is applied in the function field of the frame. In a host request, this field contains additional information that target devices use to take the action defined by the function code and in a target device response this field is comprised of any data requested by the host. The data field may have zero length where the server does not require any additional information and the function code alone specifies the action [39].

Error-Check Field, the last field of a message frame is the 2-byte error-check field, which is used to verify that a set of data has not been corrupted. The numerical value of this field is calculated by performing a 16-bit Cyclic Redundancy Check (CRC-16) on the message frame. CRC is a technique for error detection and is based on the remainder of a polynomial division. During the receipt of a message, the receiving device also calculates a CRC and compares the calculated value to the one which was calculated by the transmitting device. If the two values differ, this will result in error.

In order to provide reliable communication, the message’s reception must be synchronised with its transmission. In other words, the start of the new message frame must be recognizable by the receiving device. Under the Modbus RTU protocol, frame synchronization is established by limiting the elapsed time between the receipt of characters. If three character times (approximately three milliseconds) elapse without a new character or completion of a frame, then the pending message will be discarded, and the next received byte will be treated as the address field of a new message frame. Character time is the time it takes to transmit one character at the chosen baud rate [40].

2.4 IEC 60870

In 1988, the International Electrotechnical commission (IEC) started publishing a standard entitled 'IEC 870 Telecontrol Equipment and System'. The standard was developed and published progressively and was later renamed IEC 60870 by adding the prefix 60. There are six main parts in the standard of which part five is for transmission protocols. IEC 60870-5 was developed in a hierarchical manner in five core sections alongside four companion standards in order to define an open standard for SCADA communications and wide area processes. The IEC 60870 protocol is mainly used in the electrical industries of European countries and has data objects that are specifically provided for such applications. However, it is not limited to electrical industries and has data objects that can be applied for general SCADA applications in any industry [41].

Primarily, the three-layer Enhanced Performance Architecture (EPA) was adopted as the basis for data transmission in the IEC 60870 standard. The EPA is the simplified three-layer sub-set of the OSI seven-layer model and consists of Application, Data Link and Physical Layers. One layer is normally added to the top of the EPA model, which is defined as the "user process" layer. This extra layer represents the various functions or processes that must be specified to provide telecontrol system operations. Generally, the IEC 60870-5 document determines four frame formats that are used for telecontrol applications. These four frame formats are FT1.1, FT1.2, FT2 and FT3 [37, 42].

The companion standard IEC 60870-5-101 which is called 'Companion Standard for Basic Telecontrol Tasks' uses the FT1.2 frame format. In fact, when it is discussed about IEC 60870 in the context of SCADA system, the IEC 60870-5-101 part of the protocol has the key role. It provides the application level data objects that are required for SCADA operations. The IEC 60870-5 set of standards was initially published on the basis of IEC 60870-5-101 profile, as shown in Figure 10 [37]. It covered only transmission over relatively low bandwidth bit-serial communication circuits. However, after increasing of network communication applications, the fourth companion standard IEC 60870-5-104 was introduced in order to define the transport of IEC 60870-5 applications messages over networks using the TCP/IP protocol. As Figure 11 shows [37], IEC60870-5-104, entitled 'Network Access using Standard Transport Profiles', provides a very different physical and data transport procedure compared to IEC 60870-5-101. In this protocol, the lower levels have been completely replaced by the TCP and IP transport and network protocols, respectively. However, it retained most of the

Layer	Source	Description
User Process	IEC 60870-5-5	Application functions
Application	IEC 60870-5-4 IEC 60870-5-3	Application information elements ASDUs
Link	IEC 60870-5-2 IEC 60870-5-1	Transmission procedures Frame formats
Physical	ITU-T	Interface specification

Figure 10 IEC 60870-5-101 communication stack

Layer	Source	Description
User Process	IEC 60870-5-101	Application functions
Application	IEC 60870-5-101	Application information elements and ASDUs
Transport	TCP/IP Protocol Suite	
Network		
Link		
Physical		

Figure 11 IEC 60870-5-104 communication stack

higher application level functions and data objects. TCP and IP protocols are applied for the transport of Application Service Data Units (ASDUs) over local area and wide area networks [37]. IEC 60870-5-102 and IEC 60870-5-103 companion standards provide data types and functions to support electrical protection systems. However, here the main focus is on the T101 and T104 companion standards.

Whereas T101 provides full definition of the protocol stack right down to the physical level, this is not provided under T104 as existing and varied Physical and Link Layer operations are employed. IEC 60870-5-101 supports point-to-point and multidrop communication links carrying bit-serial low-bandwidth data communications. It also provides the choice of using balanced or unbalanced communication at the link level. Under unbalanced communication, only the master can initiate communications by transmitting primary frames. As the slaves are not able to initiate a transaction, the collision avoidance process is not required. Under the T101 profile, balanced communication can be used only for point-to-point links. This means that the T101 profile cannot support unsolicited messages from slaves to send data directly to the master for multidrop topologies. Therefore, it must adopt a cyclic polling procedure to inquire about secondary stations [37].

The IEC 60870-5-101 message structure is formed by the Data Link Layer and includes link address, control information, user data and so on. Each frame cannot carry more than one ASDU. Figure 12 shows the Data Link Layer frame and the structure of the ASDU carried by it [37].

It should be noted that for the network version, T104 profile, the ASDU is carried by the TCP/IP protocols instead of the T101 Link Layer. Therefore, the link frame of Figure 12 does not cover this part. This frame format will be briefly described in the following paragraphs.

The length section is repeated twice, and the two values must be equal so that the whole frame can be considered as a valid one. The maximum frame length is 261 octets. However, a lower maximum frame length can be specified.

The control field of the data frame has a key role in the operation of the transmission procedure. It depends on the modes of the transmission, balanced or unbalanced. In addition, the interpretation of the control field is dependent on whether the communication is a primary or secondary message [37].

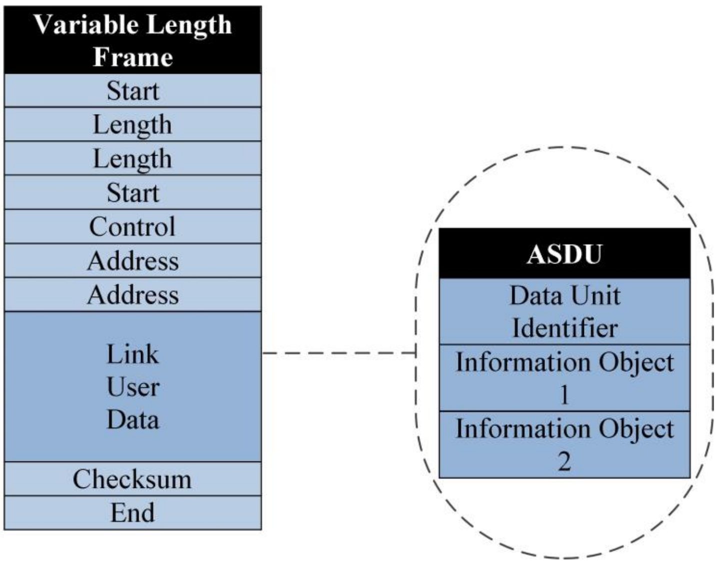


Figure 12 Data link frame format

Under the T101 profile, addressing is both at the link and application level. The link address field may be 1 or 2 octets for unbalanced and 0, 1 or 2 octets for balanced communication. Because balanced communication is only applied for point-to-point architectures, the link address is not necessary and can be used just for security purposes. For addressing all stations, the link address FF or FFFF is used as a broadcast message [41]. The structure of ASDU is divided to two main sections, the data unit identifier and the data itself (one or more information objects). Finally, for security provisions, T101 uses an eight-bit checksum.

2.5 Distributed Network Protocol Version 3 (DNP3)

During the same period that IEC 60870-5 was being published, the DNP3 protocol was developed and introduced in North America. In fact, they originated from a common point provided by the early IEC 870 document. For instance, DNP3 uses FT3 format, which is one of the four frame formats defined by the IEC 60870 [37]. Nevertheless, they differ in many aspects of physical, data link and application functions. Initially, Harris Control Division created DNP3 as a proprietary protocol for electrical industry applications in the early 1990s. However, in November 1993 the protocol ownership was transferred to the DNP3 User Group in order to use it as an open standard in industry [31]. Both DNP3 and IEC 60870-5 were developed fundamentally for SCADA applications. These entail the acquisition of information and sending of control commands between master stations, RTUs and other IEDs. They are designed in a way to transmit relatively small packets of data in a deterministic sequence and reliable manner. Hence, they are distinct from more general purpose communication protocols, such as FTP. Whereas FTP and similar protocols can send quite large files, they are not suitable for SCADA applications [31].

DNP3 supports multi-slave, peer-to-peer, and multiple master communications. It uses only balanced communications so it supports report by exception as well as polled operational mode. Report by exception capability enables outstation devices to send unsolicited messages to the master station. This provides efficient use of the communication system capacity and greater flexibility. It should be noted that although the outstation devices can initiate the communication in DNP3, only the master station could initiate a request for data or send commands [37].

DNP3 is based on the EPA model, same as IEC 60870-5. However, it adds number of transport functions, which are represented as a layer named 'Pseudo-Transport'. This layer is located below the Application Layer and provides the transmission of larger data blocks than Data Link Layer. Figure 13 shows the modified EPA model for DNP3 implementation alongside the message build up structure [37]. Each layer offers a number of services to the layer above it and adds information header to the message blocks that are transferred to the lower layers. In the following paragraphs, the overall messaging sequence of the DNP3 protocol will be briefly described.

At the highest layer of the stack, the Application Layer breaks down the data into smaller sized blocks, which are called Application Service Data Units (ASDUs). This layer then adds the application header, Application Protocol Control Information (APCI), to each chunk and builds the Application Protocol Data Unit (APDU). The maximum size of each APDU is 2048 bytes, but the number of APDU required to present an ASDU is not limited. The APDU passed to the Pseudo-Transport Layer are called Transport Service Data Unit (TSDU). TSDUs are broken down into smaller blocks, which are called Transport Protocol Data Units (TPDUs). Each TPDU is made

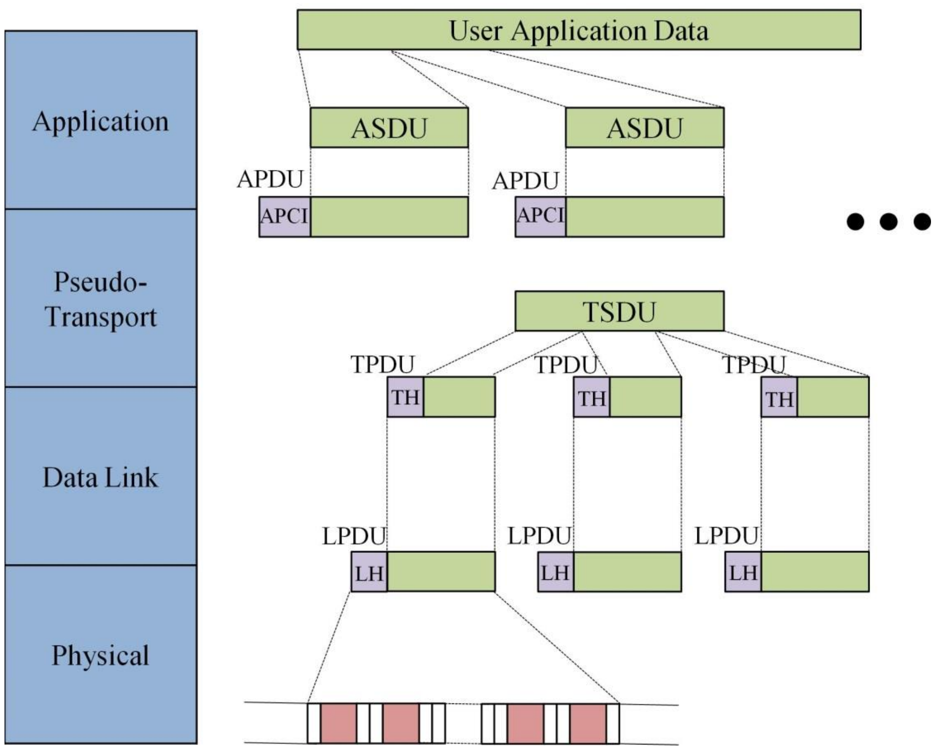


Figure 13 DNP3 communication stack and data unit structures

up of one byte of header and a maximum of 249 bytes for data. The Data Link Layer receives the overall 250 bytes of TPDUs from the Pseudo-Transport Layer [37].

According to the FT3 frame format, a 10-byte header is added, including 2 bytes of Cyclic Redundancy Code (CRC) for providing error detection. These 2 bytes CRC will be repeated for each block of data in LPDUs. The maximum number of data blocks in LPDU is 16. Each block consists of 16 bytes of data (except the last block that may have less than 16 bytes according to the data size) and 2 bytes of CRC. The LPDU maximum size is 292 bytes, of which 250 bytes are data. Finally, the Physical Layer sends data as bit stream over the determined physical media [31].

Due to the need to operate over larger geographical areas, it has been proposed to use the Internet Protocol suite and Ethernet for DNP3. In this case the Transport, Network and Data Link Layers related to the TCP/UDP, IP and Ethernet LAN will be added at the bottom of the Pseudo-Transport and Data Link Layers of DNP3 [31].

2.6 IEC 61850 for Substation Automation Systems

IEC 61850 is a communication standard released by the Technical Committee (TC) 57 of IEC [43]. The goal of this standard is to provide interoperability between the IEDs from different suppliers or, more precisely, between functions to be performed for power utility automation. It was originally introduced for the design of Substation Automation Systems (SAS). It defines communication between IEDs in substations and related system requirements. As a consequence of employing advanced and fast devices, such as protection and control IEDs, the efficient and high-speed communication infrastructure has become an important issue in substations [43]. The IEC 61850 standard has enabled IEDs and devices in a substation to be integrated on a high-speed peer-to-peer communication network as well as client/server. In this standard, the application is independent from the communication protocol by specifying a set of abstract services and objects. IEC 61850 applies Object Oriented (OO) data and service models to support all substation functions. This provides more flexibility to the developer and users, as well as simplifying engineering tasks [44].

The IEC 61850 set of documents is comprised of 10 parts, where each part defines a specific aspect of the standard.

- **IEC 61850-1**: Introduction and overview
- **IEC 61850-2**: Glossary of specific terminology and definitions
- **IEC 61850-3**: General requirements of the communication network with regard to the quality requirements, environmental conditions, and auxiliary services
- **IEC 61850-4**: System and project management with respect to the engineering process, the life cycle of the SAS, and the quality assurance
- **IEC 61850-5**: Communication requirements for functions and device models
- **IEC 61850-6**: Configuration description language for communication in electrical substations related to IEDs
- **IEC 61850-7**: Basic Communication structure:
    - **IEC 61850-7-1**: Principles and models
    - **IEC 61850-7-2**: Abstract Communication Service Interface (ACSI)
    - **IEC 61850-7-3**: Common Data Classes
    - **IEC 61850-7-4**: Compatible logical node classes and data classes
    - **IEC 61850-7-5**: Application guide and usage of information models

- **IEC 61850-8**: Specific communication service mapping (SCSM)
    - **IEC 61850-8-1**: Mappings to MMS and to ISO/IEC 8802-3
- **IEC 61850-9**: Specific communication service mapping (SCSM)
    - **IEC 61850-9-1**: Sampled values over serial unidirectional multi-drop point to point link
    - **IEC 61850-9-2**: Sampled values over ISO/IEC 8802-3
- **IEC 61850-l0**: Conformance testing

Parts 1 to 4 provide general information about the standard. Parts 6 and 10 are about configuration description language and conformance testing, respectively. This section focuses on Part 5, 7, 8, and 9 of the IEC 61850 standard, which are directly relevant to the objectives of this thesis.

IEC 61850-5 defines the communication requirements for functions and device models for power utility automation systems. Power utility functions refer to tasks which have to be performed by the automation system. These are functions to monitor, protect, control and maintain the system for reliable and economic operation. For specifying the communication requirements, all the functions need to be identified. Each IED includes various simple and complex functions that can be different in terms of supplier. In IEC 61850, functions are split into indivisible pieces called Logical Nodes (LN), which are then used to communicate. In fact, these virtual units are the objects specified in the OO approach of the standard. For example, a virtual representation of a circuit breaker class as a LN with the standardised class name XCBR. This is one of the important advantages of the standard over legacy protocols. In other words, each individual function can be built up by integrating the required LN from the standard [45]. This allows identification of all functions independently from IEDs and supporting future implementations. These core pieces are used to exchange information and contain all data to be exchanged (Piece of Information for Communication, PICOM) between these core functions and respectively between the IEDs where the functions are implemented. Functions may be implemented in a single IED or can be hosted by different IEDs. The LNs are modelled and their requirements are defined from the conceptual application point of view in IEC 61850-5 [46].

A logical device is mainly a composition of several LNs and additional services for communication purposes (for example, a representation of a bay unit). Logical devices provide information about the physical devices they use as host or about external devices that are controlled by the logical device. The grouping of LNs in logical devices is based on the common features of the LNs. For example, the modes of all these nodes are normally switched on and off together, or in the test mode. A logical device is always implemented in one IED; therefore, logical devices do not contain logical nodes from different IEDs [46].

Part 7-1 of the IEC 61850 series provides an overview of the architecture for communication and interaction between systems for power utility automation. It introduces the modelling methods, communication principles, and information models that are used in the various parts of the IEC 61850-7-x series. In addition, it describes the relationships between different parts of the IEC 61850 series. The modelling and implementation approaches applied in the different parts of the standard and their relations are shown in Figure 14 [47].

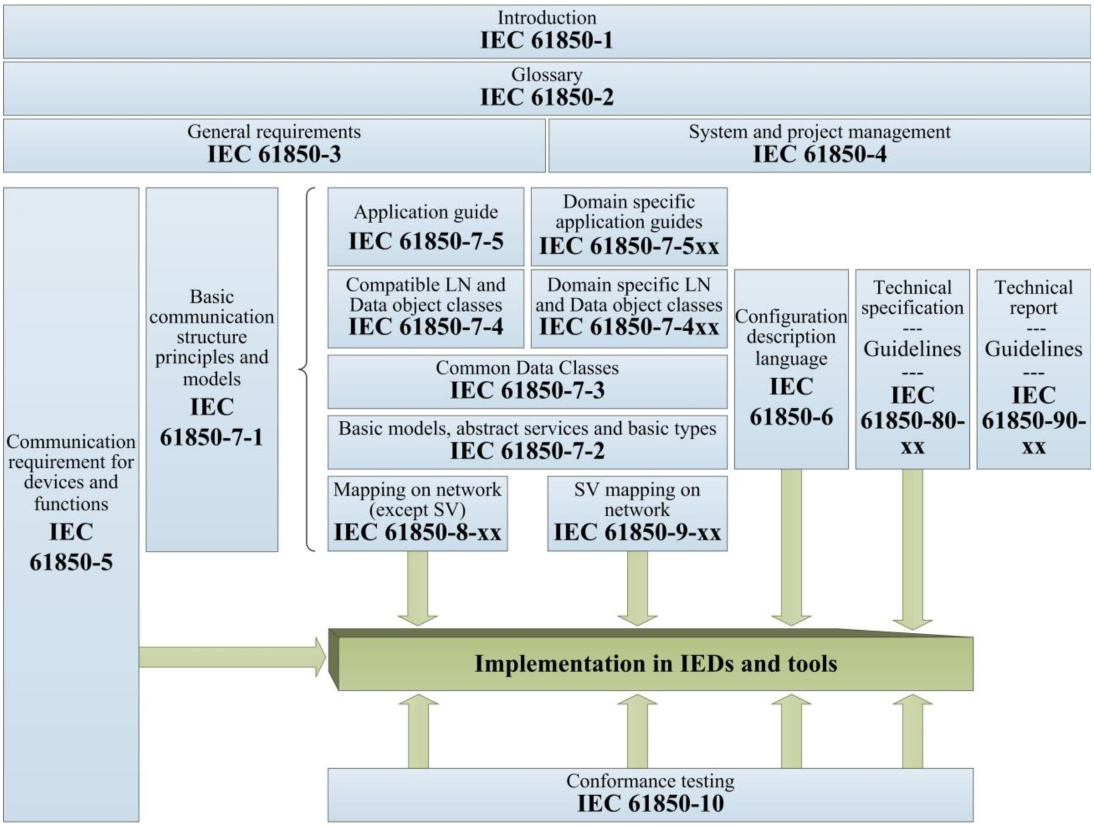


Figure 14 Relations between IEC 61850 parts

IEC 61850 documentation is quite extensive. There are also normative and informative documents in the standard, as shown in Figure 14. Technical Specifications provide guidelines for applying the standard for various applications areas and communication mapping. For example, using IEC 61850 between the control centre and substations together with IEC 60870-5-101 or 104 (specified in IEC 61850-80-1). Technical reports provide recommendations about applying the standard and for further enhancements or extensions. For example, using IEC 61850 to transmit synchrophasor information according to IEEE C37.118 (specified in IEC 61850-90-5).

The LNs, data, data attributes and service parameters are defined in order to provide the information required to perform an application as well as exchange information between IEDs. A logical node groups a number of data classes to build up a specific functionality. Over one hundred logical nodes covering the most common applications of substation and feeder equipment are defined in IEC 61850-7-4 [48]. The applications include various functions for measurement, monitoring, protection, control, etc. The whole set of all data attributes defined for the data is called Common Data Class (CDC). IEC 61850-7-3 defines CDCs for a wide range of applications [49]. The names of the logical nodes, data objects, and data attributes are designated in a standard way to achieve interoperability [50].

Information exchange is defined by means of services and the categories of services are presented in IEC 61850-7-2 [51]. The provided services are called abstract services. Abstract means that only those aspects that are required to describe the relevant actions on the receiving and sending side of a service request are defined. The abstracting technique is the dominant architectural construct adopted by IEC 61850. This feature provides the definition of objects that are independent of any underlying communication protocols. In other words, abstract means that the standard only determines what the services are intended to provide, rather than how they are built. Therefore, abstraction allows various mappings of services appropriate for different requirements. Furthermore, the system will be compatible with future developments in the communication technology as there is no need to change models, databases, etc [52]. Additional mappings to other communication stacks are possible. However, in order to maintain interoperability efficiently, the number of adopted mappings in the standard should be limited [51, 53].

The semantic of the service models with their attributes are defined in IEC 61850-7-2 based on the functional requirements in IEC 61850-5. The communication services can be categorised into two groups. One group is based on the client-server model and the other one uses the peer-to-peer model. Figure 15 shows the five types of communication services provided by IEC 61850. Generic Object Oriented Substation Event (GOOSE) and Sampled Value (SV) are mapped directly to the Data Link Layer. Therefore, they eliminate the processing of any middle layers and increase performance. Generic Substation State Event (GSSE) is mapped to its own protocol profile. Client-server communication uses the mapping of the application model to Manufacturing Messaging Specification (MMS) [53].

As shown in Figure 15, the information models (logical device, logical node, data, and data attributes) defined in IEC 61850-7-4 and IEC 61850-7-3 communicate using services provided in IEC 61850-7-2. Subsequently, the information exchange service models defined as abstract services (ACSI) in IEC 61850-7-2 are mapped to a specific protocol stack that can meet the data and services requirements.

Among the IEC 61850 services, the focus is on the GOOSE and SV messages in this thesis. The corresponding peer-to-peer communication provides services for the

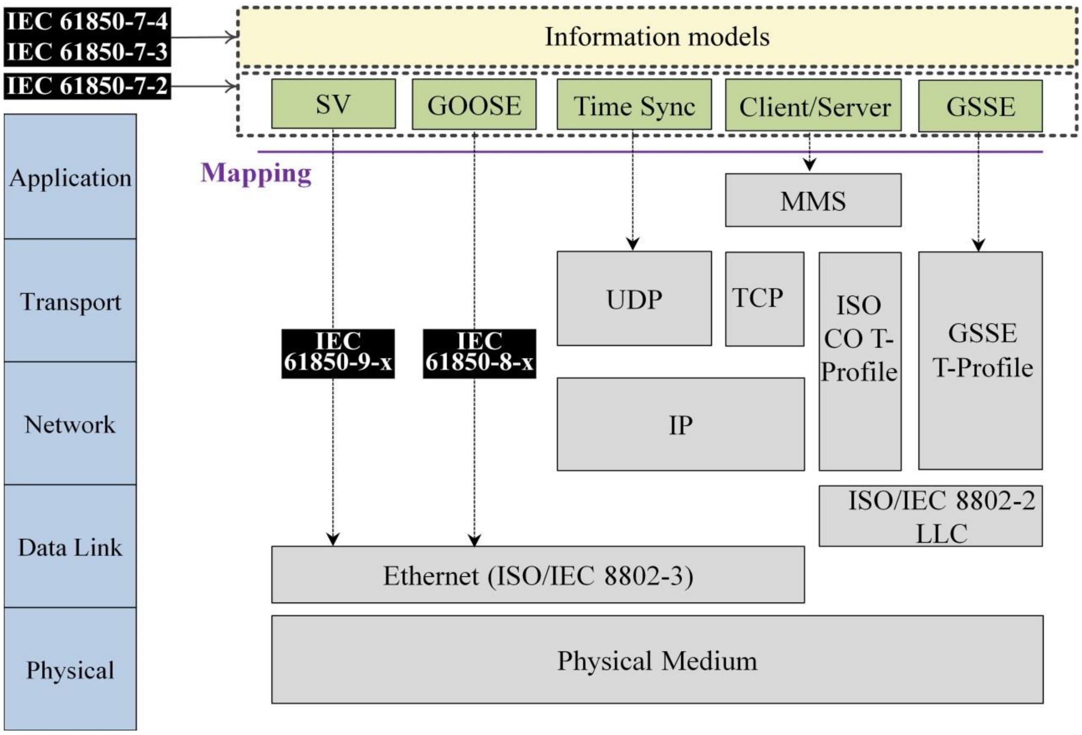


Figure 15 Communication services defined in IEC 61850

exchange of GOOSE based on multicast, and SV based on unicast or multicast. The GOOSE service is used for time-critical purposes (such as fast transmission of data between protection IEDs), and the SV service is used for the transmission of data on a periodic basis (such as transmission of measured values from merging units). Figure 16 shows the structure of a GOOSE message. A GOOSE message should at least be generated each time when a value from members referenced by the data-set varies. Figure 17 shows the format used for the sampled value message. The transmission of SVs also requires special consideration with regard to time constraints.

The syntax (format) and encoding of the messages that carry the parameters of a service, as well as the way that they are passed through a network, are defined in a Specific Communication Service Mapping (SCSM). In this regard, Part 8-1 of the standard specifies a method of exchanging GOOSE messages through LANs and using Ethernet. Furthermore, Part 9-2 is an extended mapping specification of IEC 61850-8-1 to cover Sampled Values. As previously described, it should be noted that the new mappings of abstract services (IEC 61850-7-2) to a specific protocol or technology can be also defined.

GOOSE message		
Parameter name	**Parameter type**	**Comments**
DatSet	ObjectReference	Value of the attribute DatSet of the GOOSE control block (GoCB)
GoID	VISIBLE STRING129	Value of the attribute GoID of the GoCB
GoCBRef	ObjectReference	Reference of the GoCB
T	TimeStamp	Time at which the attribute StNum was incremented
StNum	INT32U	Counter that increments when a GOOSE message has been sent and a value change has been detected within the data-set specified by DatSet
SqNum	INT32U	Counter that increments when a GOOSE message has been sent
Simulation	BOOLEAN	Indicates with the value TRUE that the message and its value have been issued by a simulation unit
ConfRev	INT32U	Value of the ConfRev attribute of the GoCB
NdsCom	BOOLEAN	Value of the attribute NdsCom of the GoCB
GOOSEData [1..n]		
Value	(*)	Value of a member of the data-set referenced in the GoCB (*) type depends on the appropriate common data classes (CDC)

Figure 16 GOOSE message definition

Sampled Value format		
Parameter name	**Parameter type**	**Comments**
MsvID or UsvID	VISIBLE STRING129	Values of the attributes MsvID or UsvID of the multicast sample value control block (MSVCB) or unicast sample value control block (USVCB)
OptFlds	[a]	Specifies which of the optional fields (RefrTm, SmpRate and SmpMod, and DatSet) are included in the sampled value message [a] It is derived from the attribute OptFlds of the respective USVCB or MSVCB
DatSet	ObjectReference	ObjectReference of the data-set whose values of the members are transmitted in the message (taken from the MSVCB or USVCB)
Sample [1..n]		
Value	(*)	Value of a member of data-set referenced by the MSVCB or USVCB (*) Type of the value typically belongs to the common data class SAV (sampled analogue value), but can be any other CDC's process values
SmpCnt	INT16U	Values of a counter, which is incremented when a new sample of the analogue value is taken
RefrTm	TimeStamp	Time when the transmission buffer has been refreshed locally
ConfRev	INT32U	Value of the attribute ConfRev of the MSVCB or USVCB
SmpSynch	INT8U	Indicates whether the sampled values are synchronized by clock signals
SmpRate	INT16U	Value of the attribute SmpRate of the MSVCB or USVCB
SmpMod	ENUMERATED	Value of the attribute SmpMod of the MSVCB or USVCB
Simulation	BOOLEAN	Indicates with the value TRUE that the message and its value have been issued by a simulation unit

Figure 17 Sampled Value (SV) format definition

2.7 Concluding Remarks

As there are many manufacturers in the power market, open standards should be employed to provide interoperability between equipment from different manufacturers. In this chapter, a number of common open standards in power systems were investigated, including synchrophasor standards as well as specific standards for communications. Among the communication standards, IEC 61850 has features that make it dominant, especially in time-critical applications. IEC 61850 was originally designed in a way to operate over Ethernet and modern networks. The legacy protocols that were described in this chapter were basically designed for traditional serial link technologies. Hence, due to the low bandwidth available at the time, they adopted a procedure to reduce the transmitting data bytes. Despite the fact that they were equipped with an Ethernet Layer, they could not benefit efficiently from the wider bandwidth as they are using the same procedure for data structure [53].

Although the scope of IEC 61850 was initially limited to the inside of substations, it is believed that the capabilities of IEC 61850 can be used to improve wide area communication applications. The integration of IEC 61850 for PMU communications is one of the proposed applications that will be investigated in this thesis [54].

Chapter 3

Wide Area Monitoring Systems

3.1 Introduction

Employing WAMS based on PMU functionalities enables dynamic view coverage of grid behaviour and, in turn, improves the stability and reliability of power system operations [35]. WAMS consists of three layers, similar to the traditional SCADA system. The first layer is the section that WAMS interfaces with power systems to measure required parameters. This layer is called the Data Acquisition Layer and PMUs are located in this section. Layer 2 is where PMU measured data are collected and time-aligned. This layer is known as the Data Management Layer and PDC is placed at this layer. Finally, layer 3 is the Application Layer where the sorted PMU measurements are used by the different kinds of functions for the monitoring, control and protection applications [22]. These three layers are connected through communication networks. Therefore, WAMS is comprised of four main parts: PMUs, PDCs, application software, and communication networks. A successful implementation of WAMS needs an elaborate planning and designation of equipment and methods to fulfil the requirements of these four parts. Figure 18 illustrates the simple structure of WAMS and the four components discussed [55]. In this chapter, the working principles of PMUs and their installation requirements are described. Details regarding PDCs and their technical challenges are provided. Communication networks and related technologies are discussed. Common applications that benefit from synchrophasor measurements are addressed. In addition, information about WAMS deployment on the GB transmission

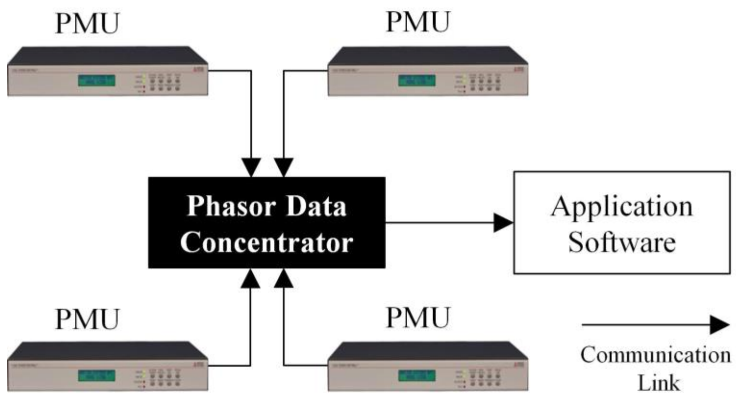


Figure 18 WAMS structure

system and laboratory-based WAMS in Brunel University London as well as examples of events captured are presented.

3.2 Phasor Measurement Units

3.2.1 Phasor Definition

Phasor representation of sinusoidal signals is commonly used in the AC power system concept. A phasor is a mathematical representation of an electrical waveform based on its amplitude and phase angle. A sinusoidal signal of a known frequency (f) is described by its magnitude (X_m) and angular position ($\emptyset$) with respect to an arbitrary time reference, as defined in Equation (3):

$$x(t) = X_m \cos(\omega t + \emptyset) = X_m \cos(2\pi f t + \emptyset) \quad (3)$$

The phasor representation of the sinusoid is given by Equation (4):

$$X \equiv \frac{X_m}{\sqrt{2}} e^{j\emptyset} = \frac{X_m}{\sqrt{2}} (\cos \emptyset + j \sin \emptyset) = X_r + jX_i \quad (4)$$

where the magnitude of the phasor ($\frac{X_m}{\sqrt{2}}$) is the root-mean-square (rms) value of the sinusoid waveform. Its phase angle ($\emptyset$) is the instantaneous phase angle of the sinusoid in Equation (3) relative to a cosine function at the nominal system frequency synchronised to UTC. The subscripts r and i signify the real and imaginary parts of the complex value in rectangular components, respectively. It should be noted that the signal angular frequency (ω) is not explicitly stated in the phasor representation [56]. The sinusoidal signal and its phasor representation are illustrated in Figure 19 [57].

The value of $\emptyset$ depends on the time scale, particularly where $t = 0$. In addition, the frequency of the sinusoid is implicit in the phasor definition. Therefore, phasors can be evaluated and compared with each other if they have the same time scale and frequency [32].

Phasor representation compared to the time-domain has the benefit that the time dependant frequency factor can be factored out [58]. Therefore, Using phasor notation considerably simplifies not only the mathematics but also the electronics and processing power requirements [59].

3.2.2 Phasor Measurement Concept

The most common way to determine the phasor representation of AC waveforms is to take data samples from the waveform using an analogue to digital (A/D) converter and apply the Discrete Fourier Transform (DFT) [57]. Assuming that the signal is sampled

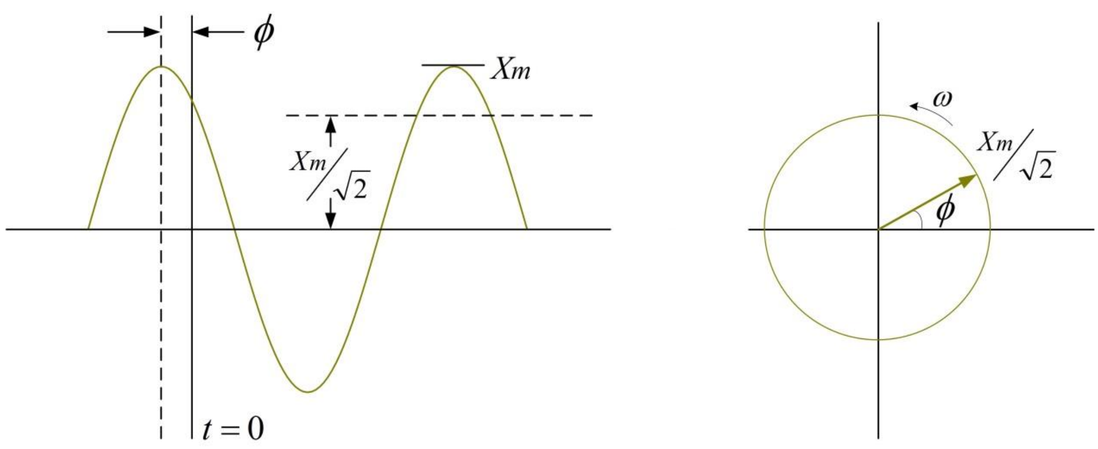


Figure 19 Phasor representation of a sinusoidal signal

with the sampling frequency $F_s = Nf$, meaning N samples per cycle of the signal, the sampling period is $T = {}^{1}/_{F_s}$. Accordingly, $\omega T = {}^{2\pi}/_{N}$. If $x_k\{k = 0, 1, \dots, N-1\}$ are the N samples of the input signal taken over one period, then the DFT-based phasor calculation is performed as in Equation (5) [60]:

$$X = \frac{\sqrt{2}}{N}\sum_{k=0}^{N-1} x_k e^{-j\omega T k} = \frac{\sqrt{2}}{N}\sum_{k=0}^{N-1} x_k e^{-jk\frac{2\pi}{N}} \tag{5}$$

where x_k is the k^{th} sample of the analogue signal.

3.2.3 Phasor Measurement Units

PMUs are installed at selected power system substations where they measure voltage and current phasors as well as frequency. There is a wide variety of phasor measurement equipment available. Many PMUs are produced as dedicated devices, while there are also vendors that offer PMU functionality as a supplementary feature on their other products, such as relays and Digital Fault Recorders (DFRs) [61]. Figure 20 shows the functional block diagram of the elements in a typical PMU [62, 63]. The general structure is similar to many power system relays and DFRs [64].

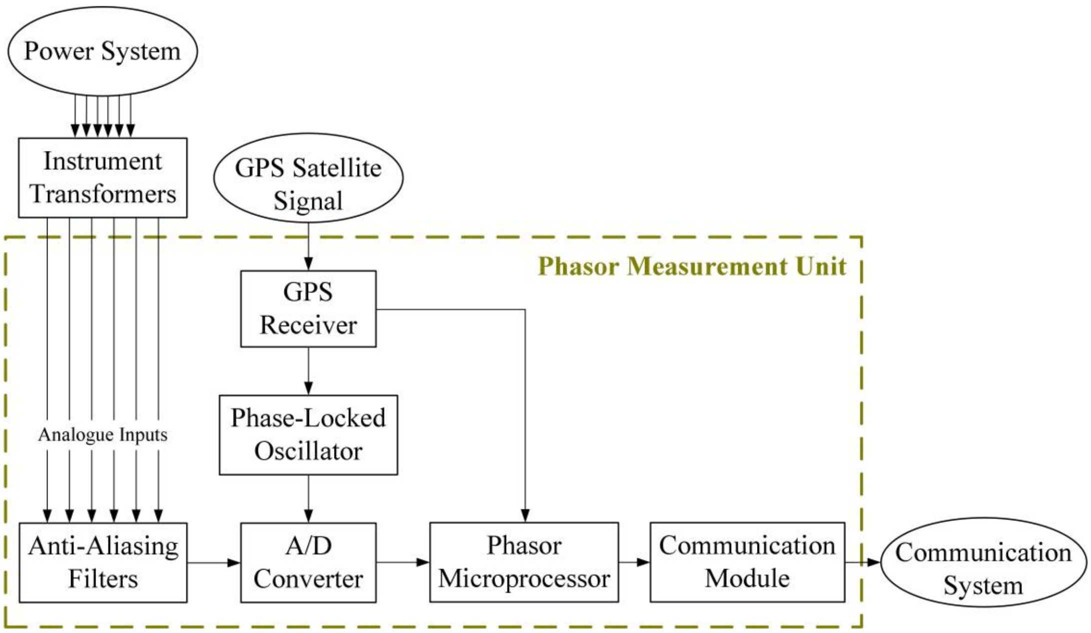


Figure 20 Functional block diagram of the elements in a typical PMU

PMUs need to have access to the voltage and/or current signals to be measured. In some substations these signals are available in a single location, while in others the signals are brought to different buildings or cabinets. Given this, it may be necessary to include several PMUs or use a PMU that has distributable input modules to cover the whole substation [65]. Analogue input signals corresponding to power grid voltages and currents are obtained from instrument transformers at substations, as shown in Figure 21 [13]. Several instrument transformer technologies are available that can be used to transform signals to an appropriate level for PMU applications. It should be noted that the measurement accuracy of a PMU is directly affected by the instrument transformers [66].

Since sampled data are used to represent the input signal, it is required to apply an antialiasing filter to the signal before data samples are taken. Antialiasing filters are analogue devices which limit the bandwidth of the pass band to less than half the data sampling frequency (Nyquist criterion). Therefore, the unnecessary high frequency signal components are removed before digital sampling occurs in the A/D converter [57]. Meanwhile, the PMU receives GPS signals that provide precise timing data. The timing data serves as (a) the reference creating clock pulses for the phase-locked oscillator that determines sampling times in the A/D converter, and (b) the time-stamp for synchrophasor data [63].

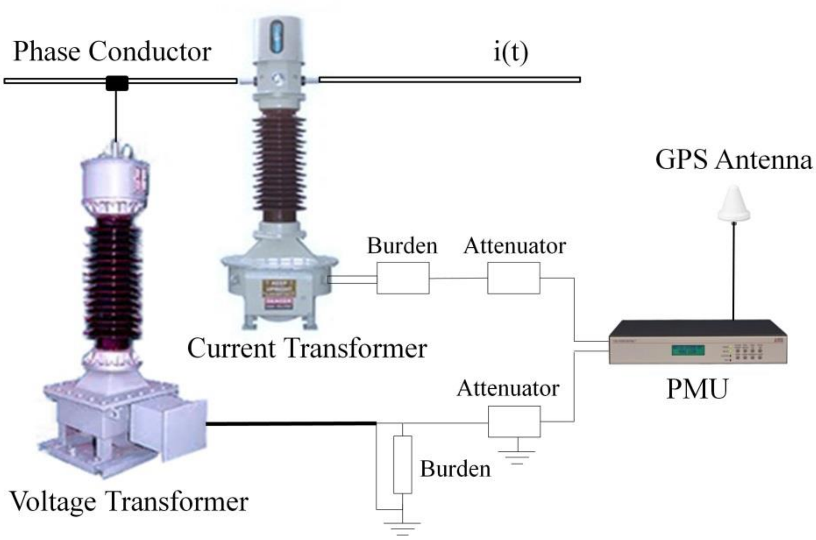


Figure 21 Typical PMU installation and interconnection in a substation

Time synchronization of phasors is necessary in order to obtain a complete view of the grid at specific times and to make the comparison of measurements from PMUs installed at different geographical locations more accurate. Synchronised phasors are known as synchrophasors. In this regard, PMUs require a precise time input. This synchronization is achieved by using the described sampling clock which is phase-locked to the one-pulse-per-second signal provided by a GPS receiver. The receiver may be built into the PMU or can also be installed as a separate unit in substations that distribute synchronizing pulses to the PMU and to other devices [57]. Most PMUs use a direct GPS input from an antenna or an Inter-Range Instrumentation Group (IRIG-B) time code. It is possible to use one GPS antenna for more than one PMU by using a GPS antenna splitter. It should be noted that if one of the PMUs provides antenna power, the splitter must have DC blocks on the other PMUs that do not supply power. The type and length of cable are important as the signal attenuates rapidly while passing through it. It is necessary to make sure that each PMU gets a strong enough signal from the antenna. The amplifier can be used to step up the low level signal to the acceptable level for PMUs [67].

The phasor microprocessor in Figure 20 computes synchrophasor data from the digitised signal using the DFT algorithm. Finally, time-tagged data are sent to the communications module where they are formatted for transmission.

In most cases, PMU installation is for a permanent operation so all aspects should be considered in order to have a well-established measurement system. PMUs can be different in terms of algorithm selection, timing input, number of voltage and current inputs, communication interface, accuracy, etc [68]. However, they have a number of common requirements including access to signals to be measured, a timing signal to synchronise the measurements, a power supply, etc. [65]. The power supply for PMUs comes from either an AC or DC source. However, it should be noted that PMUs need to operate continuously, especially during power system disturbances. Thus, they must be connected to an uninterruptible power source [65]. In addition, to assure that the measurements from all PMUs are comparable under various power system operations and for the advancement of connectivity and interoperability, standardization is an important requirement. Most PMUs on the market today use the IEEE C37.118 standard, as described in Chapter 2. Synchrophasor and frequency values must meet the general definition as well as minimum accuracy requirements given by the standard [69].

3.3 Phasor Data Concentrators

Typically, the PMUs located at various key substations generate and send data in real-time to a PDC at the control centre where they are aggregated. The overall architecture of WAMS can be different from utility to utility. It may consist of hierarchical organised sets of PDCs. The top level PDC in the hierarchical structure is called SuperPDC (SPDC) and plays a similar role to the PDCs in the lower levels. If multiple IEDs in a substation provide synchrophasor measurements, a local PDC may be deployed. Between the SPDC and local PDCs, a number of regional mid-level distributed PDCs may be present that gather data from local PDCs and send them to the SPDC. Data from all of the PMUs in the network are not necessarily required at the SPDC. Since local PDCs represent a local point of failure for the data stream, backups and bypass options are needed for mitigating such failures.

As described in Chapter 2, the IEEE C37.118 standard defines four message types: data, configuration, header and command. The first three are transmitted from the data source, either PMU or PDC, and the last one is received by the data source. It should be noted that PDC itself can be considered as a data source when data from the PDC are transmitted to another PDC [33]. Data messages cannot stand alone, as they do not describe the data they contain. Configuration messages contain information required to determine the meaning of each individual field with the data message [70]. A typical exchange between a PMU and a PDC is as follows [71]:

- The PDC sends a command message to the PMU to request human-readable description information;
- the PMU replies with a header message;
- the PDC sends a command message to the PMU to request configuration information;
- the PMU replies with a configuration message;
- the PDC sends a command message to the PMU to request data;

- the PMU replies with data messages until the PDC sends a command message to terminate its request.

A PDC collects data from multiple PMUs or other PDCs and time-aligns them according to their time-stamps to create a system-wide measurement set. In fact, it forms a data packet with a given time-stamp, and then assembles all the data received with that time-stamp into the single packet. The produced real-time and synchronised output data stream can be exploited by smart grid applications and is also stored for future analysis. A high number of PMUs are installed in the entire power system and depend on a limited number of PDCs to process and store their data. Therefore, each PDC needs to deal with a huge amount of data and the required data storage capacity should be considered [72]. As more PMUs are deployed in the system, the number of measurement samples increases and the storage requirement accelerates [73]. Storing and processing a huge volume of PMU data and scanning through terabytes of information to find the particular event will be a big challenge for WAMS. Currently available storage and processing systems, such as Storage Area Network (SAN) and Relational DataBase Management System (RDBMS), have low read rates and do not work well with the high resolution time-series data of WAMS. Thus, an efficient platform is required to interact with a huge amount of high-resolution data, such as Hadoop [74, 75].

3.3.1 Hadoop Framework

Hadoop is a framework provided by the Apache Software Foundation [76] as an open source project for running applications on large clusters of commodity hardware. Whilst data concentrators such as openPDC [77] do not offer a cloud computing platform, they can utilise this scalable fault-tolerant distributed system for data storage and processing. Hadoop has two primarily parts: the Hadoop Distributed File System (HDFS) and MapReduce programming model [78].

HDFS is the storage system used by Hadoop and has master-slave architecture. Accordingly, each cluster consists of a single NameNode and a set of DataNodes. Figure 22 provides an illustration of the high-level architecture for the HDFS working principle [79]. When data is transferred to the Hadoop cluster, HDFS creates user-definable replications of the data and stores them in blocks on the various DataNodes.

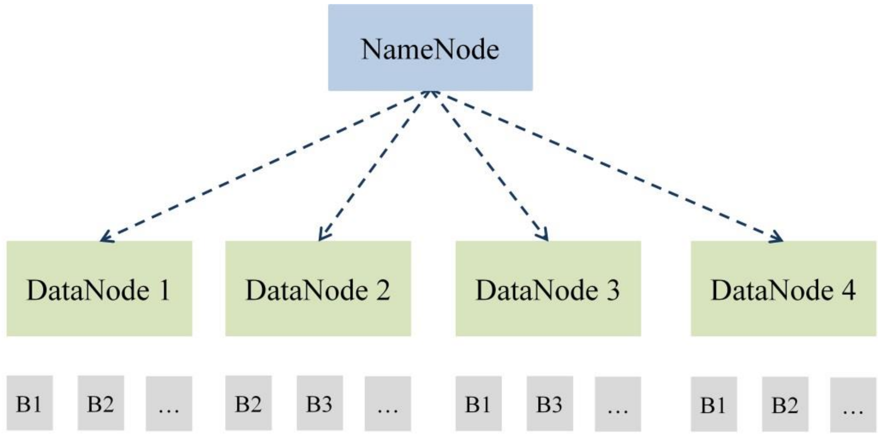


Figure 22 High-level architecture for HDFS working principle

NameNode will retain and index all locations. In this case, any node failure will never cause data loss. Furthermore, this replication of data also enables parallel data reading, which in turn reduces the required time for pulling large data [80, 81].

MapReduce is a programming framework designed for the parallel processing of huge datasets on distributed sources [82]. This computing model is divided into two parts, Map and Reduce. In the Map step, input is divided into smaller segments and distributed to the nodes. Then nodes will process the related segments and produce intermediate outputs separately. In the Reduce step, the individual outputs are collected from the nodes, and after aggregating, they form the main output. Therefore, by running parallel processes, analysis can be conducted in less time. In fact, Hadoop transfers the processing to the data instead of the conventional procedure of transferring the data to the processing [82].

3.4 WAMS Applications

WAMS have great potential to improve the reliability and stability of grids based on the operational feature of PMUs. In the literature, there are a large number of WAMS applications; however, they can be divided into the three main groups of monitoring, protection, and control applications [83, 84]. Furthermore, the applications are also categorised as on-line or off-line. On-line applications process real-time data as it arrives to the client system. In contrast, off-line applications process data that are archived [85].

3.4.1 Power System Monitoring

PMU-based monitoring systems offer various kinds of functions, such as wide area visualisation, model validation, state estimation, near real-time event replay, post event analysis, early warning of potential problems, etc. These functionalities will significantly improve situational awareness. When power systems operate under normal conditions, providing applications with reduced resolution synchrophasor measurements is sufficient. However, for the near real-time event replay mode and post event analysis, measurements with full resolution are required [86, 87].

State estimation is an important method for the monitoring of power systems. It uses measurements of real and reactive power in line flows and injection points in order to estimate the bus voltage angle and magnitude. Each measurement cycle may take couple of seconds to minutes, and during this period, system is assumed to be static. However, the real system condition is dynamic and oscillation occurs on the flow. By using PMUs, the time-stamped measurements can be relayed on a continuous basis and the state vector can follow the dynamics of the system [16, 88]. PMUs offer a number of possible benefits to the state estimation application including direct calculation using phasors, faster solution convergence, enhanced observability, improved solution accuracy and robustness, bad data detection and topology error correction, etc [89].

A large amount of technology that is new to the GB system has already been deployed in other areas of the world. In this regard, the Chinese are building one of the biggest and most complex power systems. To date China is the leader in the deployment of PMUs with over 2500 active PMUs. Due to long transmission lines running across relatively weak interconnections in China, the WAMS network is primarily concerned with monitoring low frequency oscillations. Also model validation and wide-area data recording and playback, with applications such as state estimation and adaptive protection schemes are currently undergoing development [90].

3.4.2 Power System Protection

Power system protection applications work based on the measurements obtained from monitoring applications. The fast evolution of WAMS enables real-time processing of wide-area measurement data for the use in system protection applications [91]. These applications analyse the measured data and evaluate the status of the network in order to guarantee the safe operation of the grid. Currently, most of the decision-making and protection actions are performed locally. However, WAMS can enhance the dependability and security of system protections [92]. Synchronised phasor measurements offer solutions to a number of complex protection problems and improve the performance of protection applications. It should be noted that the communication needs for various protection applications are different. Phasor measurements are particularly effective in enhancing power system protection functions that have a slow response time requirement. Some protection systems that could benefit from PMUs include adaptive dependability and security, back up protection of distance relays, adaptive out-of-step, angular voltage stability of network, etc [57].

3.4.3 Power system control

If by means of communication regional or system-wide data is available, wide area control systems can be deployed that enhance the functionalities of local control. Besides the benefit of fast control in contingency cases, dynamic control is of growing importance along with the rise of fast controllable equipment such as HVDC and FACTS devices [91]. Prior to the emergence of real-time phasor measurements, most control systems were processed locally due to low time delays. Controllers like Variable Series Capacitors (VSCs), Universal Power Flow Controllers (UPFCs), and Power System Stabilizers (PSSs) regulate the grid based on local feedback. In addition to remote control of the power systems, synchrophasors can provide direct feedback to these controllers and enable dynamic control of power systems. Using PMUs to damp the low frequency inter-area oscillations is one of the effective applications of WAMS [57, 88].

3.5 Communication Infrastructures

In developing a WAMS, reliable and high-speed communication infrastructures that enable secure sharing of data among PMUs, PDCs and smart grid applications play an important role. IEEE C37.118 frames are typically not sent directly over networks, rather, they are based on the concept of layered protocols and encapsulated within the frames of other communication protocols [70]. The speed of data transfer is less critical for off-line applications; however, for on-line applications faster data transfer is required and depends on the type of application. For example, the latency requirement for state estimation is around 1 s, transient stability is 100 ms and voltage stability is 1-5 s [18]. The communication infrastructure should therefore be able to support different Quality of Service (QoS) classes for traffic and should be able to prioritise one class over another [12]. Utilities can use Multi-Protocol Label Switching (MPLS) or frame relay technology for WANs. These communication media provide a guaranteed bit rate but are not guaranteed to be error free [70]. Since data may be shared with multiple entities at the same time and for communication redundancy, WAMS should also support multicast data sharing. It is also crucial to secure WAMS in order to ensure the availability, integrity, and confidentiality of the data transmitted over a network [12]. Most PMUs have an Ethernet interface, although there are some models that only use asynchronous serial (RS 232). An interface device (modem, router, etc.) is required between the PMU communication link and the communication system.

3.5.1 Internet Protocol

For transmitting data over networks using Internet Protocol (IP), each node in the substations of a WAMS is given a unique IP address. The source node sends packets to the destination node through the intermediate routers based on the destination IP address. In IP routing, each router takes an independent routing decision on each incoming packet to identify the next hop, to which the packet has to be sent. To make such a decision, each router maintains a routing table. In conventional IP, the building of routing tables is performed by routing algorithms like Open Shortest Path First (OSPF), Routing Information Protocol (RIP), Border Gateway Protocol (BGP), Interior Gateway Protocol (IGP) or Intermediate System-to-Intermediate System (IS-IS) [93]. Depending on the destination address in the packet header and routing table, the router forwards the packet to the next planned hop. This process is continued by the following routers until the packet reaches its destination [25].

Communication over networks using IP can be connection-oriented (TCP) or connectionless (UDP).

TCP (Transmission Control Protocol) is a transport mechanism over IP, which offers connection-oriented communication. It supports retransmit capabilities, flow control, buffer handling and traffic shaping properties. TCP/IP is used by common services like FTP, Database, HTTP, etc. TCP rearranges data packets in the specified order and retransmits lost or corrupted data. In order to handle packet drops, every packet being received is acknowledged back to inform sender the successful transmission of packet. Afterwards, the sender will release the “transmit buffer” for new data to be transmitted [94]. Although TCP provides reliable communication, it is not suitable for real-time communications since the acknowledgment and retransmission feature lead to excessive delays [25].

On the other hand, UDP (User Datagram Protocol) is a transport mechanism over IP, which offers connection-less communication. It does not provide a mechanism for flow control and rate adaptation that otherwise is associated with TCP. UDP can be used for unicast, multicast, broadcast and anycast applications. It is used by services like VOIP, DNS, DHCP, etc [94]. In the case of UDP, there is no built-in ordering and recovery of data, but the transmission speed is higher than TCP. Therefore, time-sensitive applications often use UDP, since a small amount of lost data is preferable over delayed data in many real-time applications [65].

3.5.2 Quality of Service (QoS)

The communications infrastructure in smart grid carries traffic for various applications. These applications have different delay requirements from a few milliseconds to several seconds. Allocating exclusive bandwidth for each application is not practical and requires a large overall link bandwidth, which is not cost-effective. Basically, communication links are selected in a way to support the average expected data rates with an additional margin to accommodate traffic variations. However, this margin may not be sufficient for the dynamic traffic load of a congested network and causes packets to be temporarily stored at routers. In addition, without adopting an appropriate approach to manage the traffic, the packets exit routers based on the First-In-First-Out (FIFO) order. In this case, a packet of a time-critical application may need to wait behind a number of packets of applications that can tolerate large delays. In this regard, Quality of Service (QoS) policy can be used to ensure that excessive delay does not occur for time-critical application packets in a shared network. QoS refers to the set of tools and techniques that are needed to manage network resources and provide preferential treatment to data from certain priority applications over data from other applications [95, 96]. Figure 23 illustrates how this classification is implemented in a router [94].

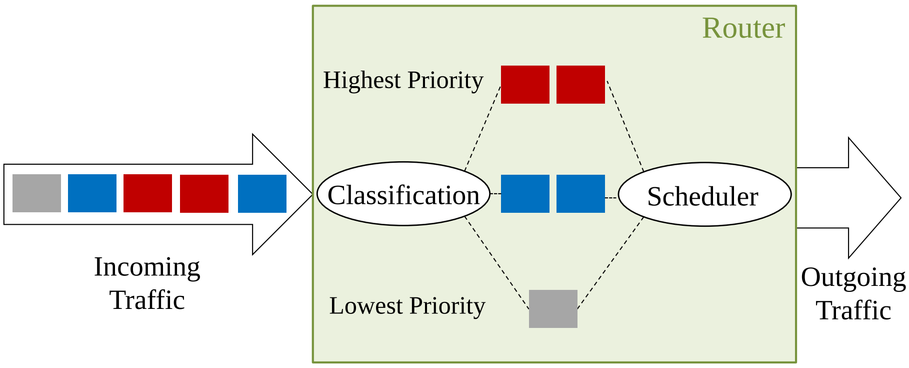


Figure 23 Classification of traffic based on priority

The second byte in an Internet Protocol version 4 (IPv4) packet is the Type of Service (ToS) byte, which allows different types of IP packets to be distinguished from each other. Using the content of the ToS byte, the router then can provide a specific level of service in accordance with the determined priority [95].

3.6 WAMS Deployment on the GB System

3.6.1 WAMS Deployment on the Transmission System

The first WAMS was deployed in the GB Electricity National Control Centre (ENCC) in 1998. This system was developed by Psymetrix and is running PhasorPoint application to carry out continuous analysis of the dynamics of the GB system [97]. To effectively monitor the inter-area modes between Scotland and England, information is required from the respective centres of inertia for both areas [98]. In the absence of data from the Scottish system, one PMU was installed in the North of England, close to the Anglo-Scottish boundary and another PMU was installed close to the centre of inertia for England and Wales as shown in Figure 24. By comparing the level of oscillations between the two locations it is possible to determine whether the source of the oscillation is in the north or the south of the network. Also the provided information enables operators to identify whether the oscillation damping on the system has fallen below the predefined stability margins. In addition to the two PMUs configured for detecting inter-area modes, a total of 40 PMUs have been installed to the transmission network of England and Wales. The majority of them have been configured to report back to the central PDC at the ENCC, using the internal Business LAN.

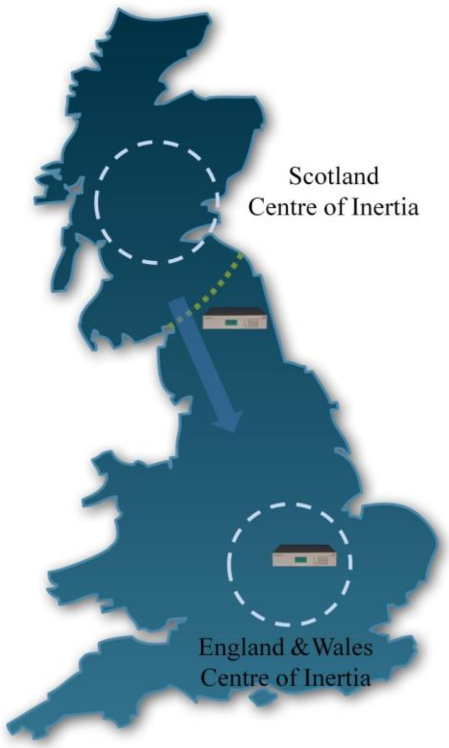


Figure 24 PMU placement for monitoring of the Anglo-Scottish interconnection

3.6.2 Brunel University Laboratory-Based WAMS

The high cost of early PMU devices historically restricted their use to the transmission systems. However, due to recent developments, the cost of the components from which PMUs are assembled decreased dramatically. Hence, deploying PMUs has become prevalent across the utility environment, including distribution systems [61]. Moreover, employing PMUs in a laboratory-based and domestic level simplifies the investigation of WAMS compared to the more complicated case of installing them in substations. More equipment is required inside a substation for deploying PMUs, such as step-down transformers that bring the three-phase voltage or current level to the instrumentation level. Brunel University London installed a PMU that is connected to the 3 phase 415 V AC domestic supply level and joined a laboratory-based WAMS as a part of the EPSRC project "FlexNet" [99]. Currently, PMU measured synchrophasors from 4 UK Universities (Brunel, Birmingham, Manchester, and Strathclyde) are transmitted via the Internet to a server in Ljubljana, Slovenia. As the PMUs are well geographically distributed across the Scottish to England system, as depicted in Figure 25, they provide a relatively good visibility of events through the covered area. The installed PMU at Brunel for this project is an Arbiter 1133a [67], which has been configured to measure and send 50 samples of the required parameters per second. The number of measured parameters in the PMU output determines the size of data packet. Each data stream consists of measurements such as voltage magnitude, voltage angle, frequency, frequency delta ($^{df}/_{dt}$) etc.

In addition to the Arbiter PMU installed for the "FlexNet" project, Brunel has also deployed and investigated other types of PMUs. The Frequency Disturbance Recorder (FDR) is one of them. The FDR is the data acquisition device of the FNET (Frequency Monitoring Network). FNET is a low-cost wide-area power system frequency measurement network. The FDR, which is a single phase PMU, computes power system parameters using phasor techniques developed specifically for single phase measurements. The measured data are then continuously transmitted over the Internet to the FNET server housed at the University of Tennessee [100]. This system also uses a triangulation method based on the travelling wave of system events to determine the approximate source of an event or incident in the grid [90]. National Instruments (NI) CompactRIO is another measurement device that includes the core hardware and

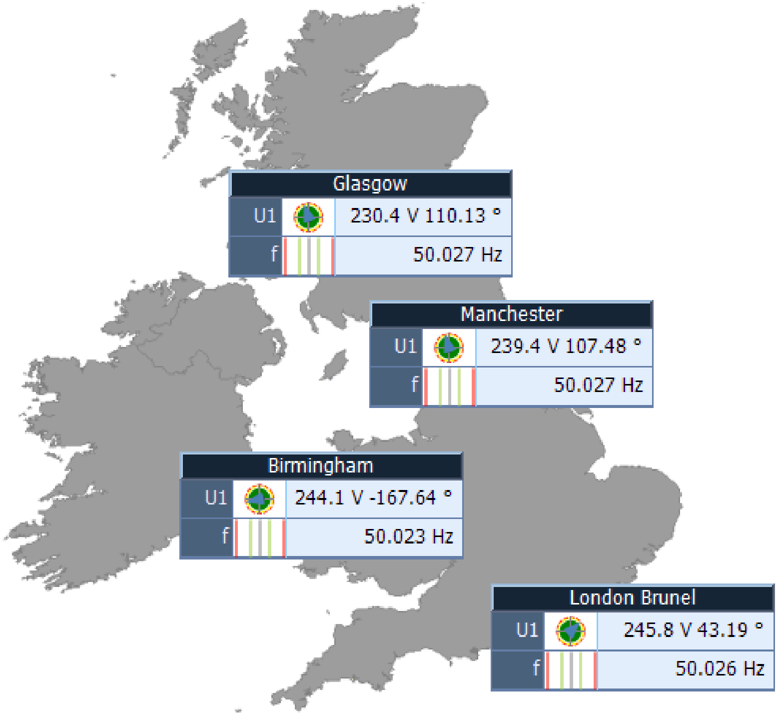


Figure 25 The laboratory-based WAMS PMUs locations across the UK

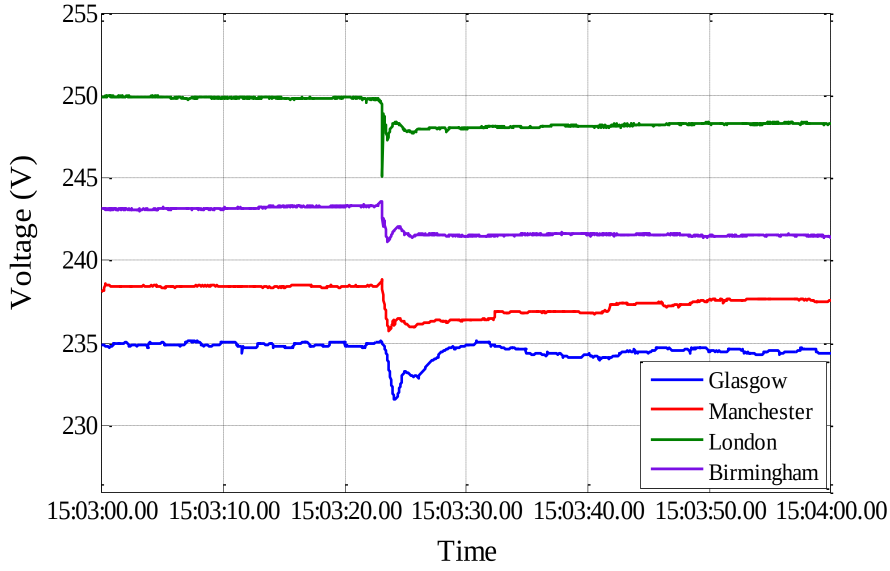
software components to design an advanced PMU. CompactRIO is a reconfigurable embedded control and acquisition system that is programmed with NI LabVIEW graphical programming tools [101] and can be used in a variety of control and monitoring applications [102].

A number of different data concentrator packages have also been employed and investigated, and these are described in the following subsections.

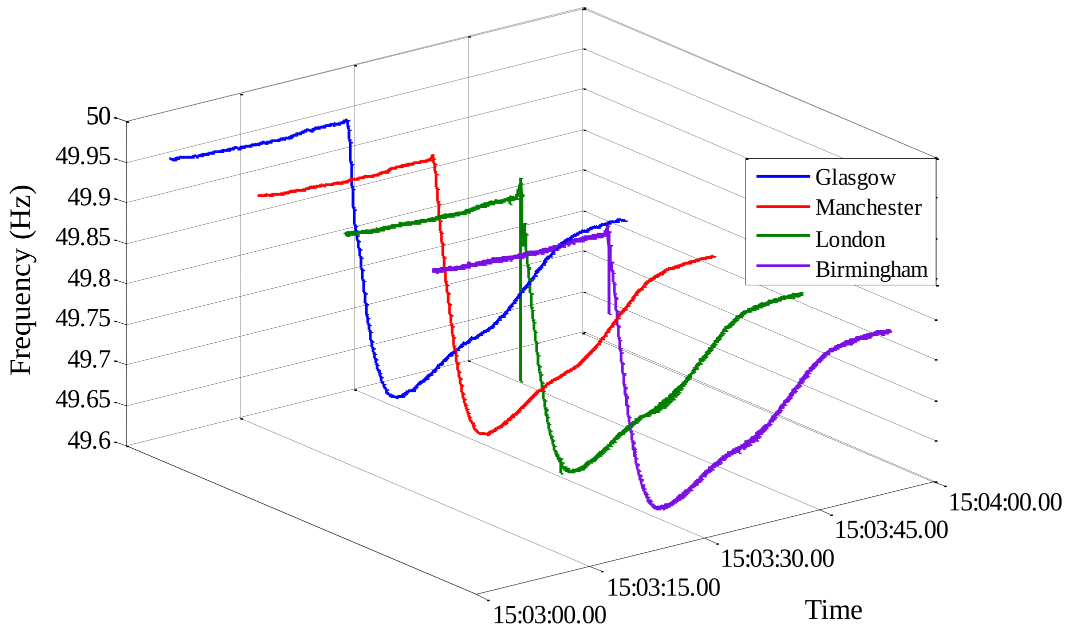
3.6.2.1 ELPROS

The PDC in Slovenia is running WAProtector, which is a system for wide area monitoring, protection and control provided by the ELPROS [103]. This application presents various details from the collected PMU data such as phasor representation of voltages, phase angle geographic charts, two dimensional frequency, voltage magnitude and phase angle trending charts, angle difference and oscillation graphs, and so on. The event details including time, location, and type of events, are shown on the main display and are also stored for future analysis.

Figure 26 shows an example of identifying voltage and frequency deviations across the UK network happened on 30 September 2012 using data from the four laboratory-based PMUs. Frequency is a good indicator of the condition of power systems and the size of frequency deviation is well correlated with the severity of the event [13]. The voltage phase angle difference between nodes is another key factor in monitoring. Power flows



(a) Voltage magnitude measured by the 4 PMUs

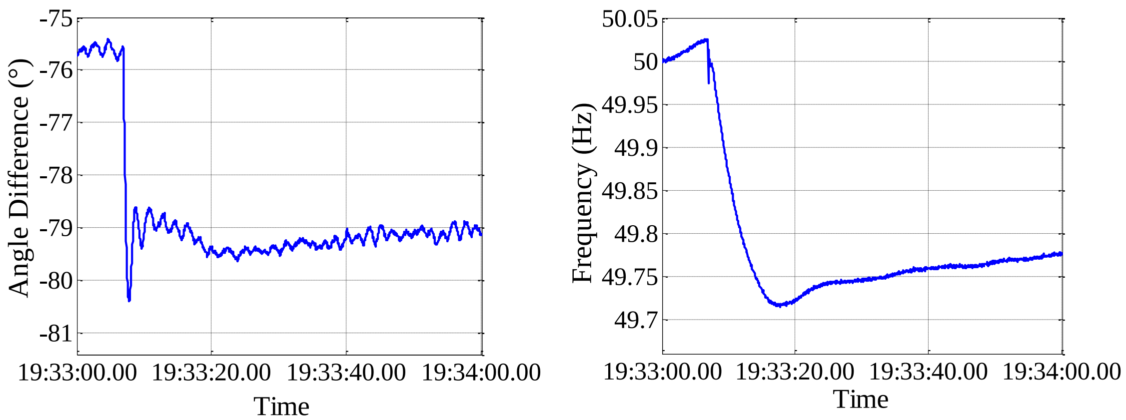


(b) Frequency measured by the 4 PMUs

Figure 26 Voltage and frequency across UK on 30 September 2012 from nodes with higher phase angle toward nodes with lower phase angle. The larger the phase angle difference between the two nodes, the greater the power flow between them. Exceeding the power flow from a certain level can make the power system unstable. Therefore, a significant divergence in phase angle can be a sign of instability risk [104]. Figure 27(a) shows the phase angle deviation which occurred between Glasgow and London on 22 February 2013.

3.6.2.2 Schweitzer Engineering Laboratories (SEL) PDC

A local PDC was also been developed by using SEL-5073 PDC, which collects measurements locally from the PMU in the laboratory [105]. SEL-5073 PDC software with integrated built-in archiving runs on a windows-based computing platform and is able to receive synchrophasor messages using Ethernet or serial communication. It can process incoming data from more than 500 PMUs at a maximum data rate of 240 messages per second. The processed data can be transmitted to up to six external clients as well as internal archive. The PDC Assistant software, a user-friendly interface, provides the ability to view the PDC real-time status, configure the PDC inputs, outputs, archives and so on. SEL-5073 has high-speed calculation capability that can perform various phasor and analogue calculations. This real-time measurement calculation function uses the measured parameters of the PMUs to calculate new parameters that are not directly collected, such as the calculation of real and reactive power, derivatives,



(a) Angle between Glasgow and London captured by ELPROS

(b) London frequency captured by openPDC at Brunel University

Figure 27 Angle and frequency of UK network on 22 February 2013 network latency, etc. These calculations can be archived with other PMU data or sent as an output stream. SEL-5073 offers two types of archiving modes, triggered and continuous. The triggered archive stores data whenever an event happens, while the continuous archive stores all the data received. Another feature of SEL-5073 is the archive retention setting, which enables archive data to be deleted after a specified duration. However, it offers Archive Collection Service (ACS) to back up the archive data and store data on a local or network storage drive automatically. For visualising and analysing real-time streaming and archive data SEL-5073 can be integrated with SEL-5078-2 Central software. The SEL Central allows a quick translate of synchrophasor data into visual information [105, 106].

3.6.2.3 Open Source PDC (openPDC)

An open source PDC has also been employed for further investigation. The previously discussed PDCs were specialised standalone units and not openly available. However, openPDC is an open source PDC developed and made available to public by the Tennessee Valley Authority (TVA) in October 2009. OpenPDC architecturally consists of three layers: the Input, Action and Output Layers. Each layer performs a specific set of functions [14, 77].

The Input Adapter Layer reads streaming data from the measurement devices that may use different protocols. In fact, it allows the parsing of protocol and provides a generic data format. After assigning an ID to the measurement, it will transfer them to the Action Layer. Currently openPDC supports different kinds of protocols including IEEE C37.118-2005 and 2011, IEEE 1344, BPA PDCStream, Virginia Tech FNET, Macrodyne, SEL Fast Message, etc. However, custom Input Adapters can be written to collect data from user desired input sources [73, 80].

The Action Adapter Layer deals with concentration and processing of the input measurements. An important function of this layer is the phasor time alignment adapter. In this function the measurements received from the Input Layer are sorted by their associated GPS time-stamps and time-aligned before transferring them to the next layer. The Action Adapter Layer also provides two more essential functions, which are real-time measurement calculation and real-time event detection. The real-time measurement calculation function uses the measured parameters of the PMUs to calculate new parameters that are not directly collected; For instance, the calculation of active and reactive power. It is evident that all the required parameters for the calculation of new parameter must be measured and available by the PMU. The real-time event detection function monitors the incoming measurements and ensures that they are within the specified limits. Otherwise, it will notify of such an occurrence [73].

Finally, the Output Adapter Layer of the openPDC receives all measured and calculated parameters at the end and queues up and forwards the data to either historian system to be archived for future off-line analysis or to any other defined client systems. The Output Adapter can re-encapsulate the data in several protocols. Examples of openPDC output are IEEE C37.118 concentrator output stream, Inter Control Center Protocol (ICCP), Comma Separated Values (CSV) file export, and historian archiving output [73, 77].

OpenPDC has various features that make the monitoring of power systems more convenient. One of them is the ability to replay a data stream from a specific time in the past. In this mode, the stored data from the historian will be retransmitted to the openPDC software. The data is shown as if it were coming from the PMU. The user can also speed up or slow down the replay speed. This near real-time event replay facilitates event analysis and helps the system operator to take appropriate corrective or protective control actions quickly. Another feature of openPDC is that each of the Adapter Layer's functionalities can be improved or extended by the user or developer. For example, a new model can be written for Input Adapter to enable support of new protocols, or a new Action Adapter can be defined to provide a particular function, detection of specific event, etc [80, 86].

Figure 27(b) shows the frequency graph for the Brunel University PMU captured by openPDC on 22 February 2013.

3.6.3 Challenges and Future Developments

The main challenges in developing WAMS include:

Having more PMUs installed across the power system provides a better view of the event propagation in the network. Therefore, more PMUs are required to send data to the ENCC. Furthermore, there should be sufficient numbers of PMUs to test the applications on the openPDC platform at Brunel.

In the laboratory-based deployment of WAMS, a few PMUs transmit data to the PDC. While a high number of PMUs are installed for the entire GB power system, they depend on a limited number of PDCs to process and store their data. Therefore, each PDC needs to deal with a huge amount of data and the required data storage capacity should be considered. In the case of Brunel University, the PC hard drive works as a server for storing streams of data locally. However, the capacity should be extended for future developments. As more PMUs are deployed in the system, the number of measurement samples increases and the storage requirement accelerates [73][22].

Storing and processing huge volumes of PMU generated measurements and scanning through terabytes of information to find particular events will be a big challenge. Thus, efficient platforms should be employed to interact with huge amounts of high-resolution data. Hadoop is a proposed computing and storage framework to be used with data concentrators and handle these concerns. More information about Hadoop has been provided in Subsection 3.3.1 [74].

Advanced applications that can analyse data efficiently and recognise potential problems quickly need to be developed and implemented. These applications provide useful information for operators to identify sequences of events and their causes during a power system disturbance. Hence, operators would have more time and better understanding to evaluate the simulation and adopt appropriate control actions [86]. Common smart grid applications that can exploit the measurements have been provided in Section 3.4.

3.7 Concluding Remarks

WAMS is an invaluable technology to enhance the reliability of power grids. In this chapter, the components of a WAMS were divided into four main parts. Each part, alongside its requirements, technical challenges, and related technologies was discussed in detail. A successful implementation of WAMS needs an elaborate plan and design of these components. Furthermore, the WAMS deployment on the GB system was divided into two parts, the transmission system and laboratory-based, and the relevant details for each were provided. Samples of events captured by laboratory-based employment of WAMS across the UK network were presented. A number of data concentrator software and their features were also investigated. Among them openPDC source codes are openly available, which enables users to extend and modify functionalities of the data concentrator.

Chapter 4

Performance Evaluation of Substation Communications Infrastructure

4.1 Introduction

Changes in the wholesale electricity market alongside the difficulties in upgrading the transmission system have increased the complexity of power network operations [107]. This fact has placed heavier demands on developing new technologies to manage power systems reliably. Substations are key nodes in the power system, where information from the system is retrieved and used for reliable operation and management of the network. Substation Automation Systems (SASs) are now being implemented using IEDs interconnected through communication network technologies to facilitate substation monitoring, control and protection. Interest in SAS has increased rapidly due to its numerous benefits to utilities. Digital data acquisition affords a level of visibility never considered possible in the electromechanical era of substations. Moreover, SAS provides additional capabilities and information that can be used to further improve the operations, maintenance, and efficiency of substations [44, 108].

As a consequence of employing advanced and fast devices, the efficient and high-speed communication infrastructure has become an important issue in the design of substations. In this regard, the state-of-the-art IEC 61850 standard, released by the International Electrotechnical Commission (IEC), has enabled IEDs and devices in a substation to be integrated on a high-speed communication network. Furthermore, IEC

61850 has the objective of enabling interoperability between IEDs within a substation [109]. Interoperability is defined as the ability of two or more IEDs from the same vendor, or different vendors, to exchange information and use it for the correct execution of specified functions [110]. By applying object oriented (OO) data and service models, IEC 61850 supports all substation functions and provides more flexibility to the developer and users [69].

Due to the criticality of some of the smart grid applications, the communication infrastructure performance in such networks needs a thorough analysis to ascertain that the required specifications will be met. In this chapter, a laboratory-based IEC 61850 analysis is provided. Afterwards, the simulation and modelling of a typical power system substation communications infrastructure will be presented. The purpose of this research is to create IEC 61850-based IED models and setup a simulation framework for substation communication networks. One of the important aspects of communication network performance analysis is the delay characteristics, especially for the smart grid's control and protection functions that have a fast response time requirement. By simulating the substation communications network using DES, the End-to-End (EtE) delay of the specific transmitted information can be investigated in detail.

Although IEC 61850 was originally introduced for the automation of substations, the application of IEC61850 is expanding rapidly. The deployment of IEC 61850 for Wide Area Network (WAN) applications such as PMUs is one of the proposed applications. Basically, PMUs are deployed for WAMS. Although PMUs transmit data from substations to PDC through WAN, investigating their behaviour inside the substation can be an effective step in introducing new protocols for their communications [75]. Hence, in this research, a preliminary analysis on introducing the IEC 61850 protocol for PMU communications at the substation level has been performed.

4.2 Laboratory-Based IEC 61850 Analysis

As discussed in Chapter 2, IEC 61850 is a complex standard and the development of a system capable of communicating based on this standard can involve a huge investment as well as considerable development time [111]. In this regard, the Beck DK61 kit [112] contains all the hardware and software components required for the fast development of custom applications, including the IEC 61850 stack. This protocol stack is developed and maintained by SystemCORP [113] and enables users to quickly develop and test IEC 61850-based applications. The Beck DK61 development kit runs over the @CHIP-RTOS, which is a proprietary Real Time Operating System compatible with most basic DOS commands. The kit is also equipped with the embedded IPC@CHIP SC143, which is an advanced web microcontroller used mainly in the telecommunication industry. Using the SC143 chip allows for deployment of embedded software in C/C++ as well as Programmable Logic Control within the DK61 development environment [114]. Figure 28 shows the hardware architecture of the DK61 board [115].

The laboratory experiment in this section complements the theoretical background presented in Chapter 2 and provides a real insight into the fundamental performance of the IEC 61850 standard. The DK61 board can be configured to act as a server or client. For this analysis, DK61 is set up to be used as a server, which exchanges the status values (on or off) of DIP switches on the board with a client based on GOOSE messages. The lab PC is used as a client and runs an open source network analyser, Wireshark [27], to capture and visualise the IEC 61850-based generated packets and

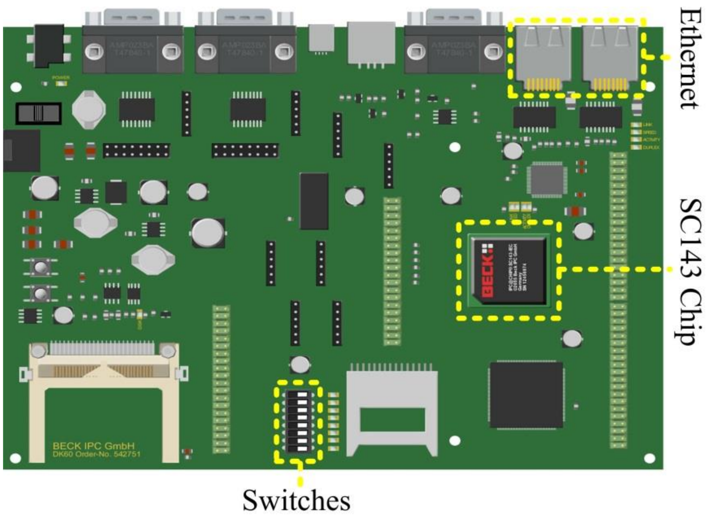


Figure 28 Hardware architecture of the DK61 board

investigate their characteristics.

For setting up the server, the CHIPTOOL [116] software needs to be installed on the PC and is used to configure the DK61 board. The CHIPTOOL application is the Beck IPC specific tool for communication with the SC143 on the DK61 board. It provides a number of services, such as the Ping function, Telnet, FTP, HTTP, IP configuration, etc. The required configuration files have been uploaded on the DK61 board using FTP and the server can be started by opening a Telnet session into DK61 using CHIPTOOL [114].

Using the ICD Designer application [117], the hierarchical structure of IEDs under IEC 61850 standard including Logical Nodes, Data Objects and Data Attributes can be depicted. ICD Designer is a tool that is used for the configuration of IEC 61850 enabled products. As can be seen in Figure 29, the so-called standardised Logical Node (LN) “GGIO” (Generic Process Input Output) is used to designate input and output signals. The LN has also a number (1 to 3) at the end in order to differentiate several LNs that have the same class name. Apart from common information Mod, Beh, Health and NamPlt, the Logical Node has a Data Object Ind for status information. For example, the Data Object DIPS_GGIO1.Ind1 of the corresponding LN specifies three Data Attributes: stVal (Boolean), q (Quality), and t (TimeStamp). The value stVal represents the status of a DIP Switch. The other two attributes q and t should also be specified and

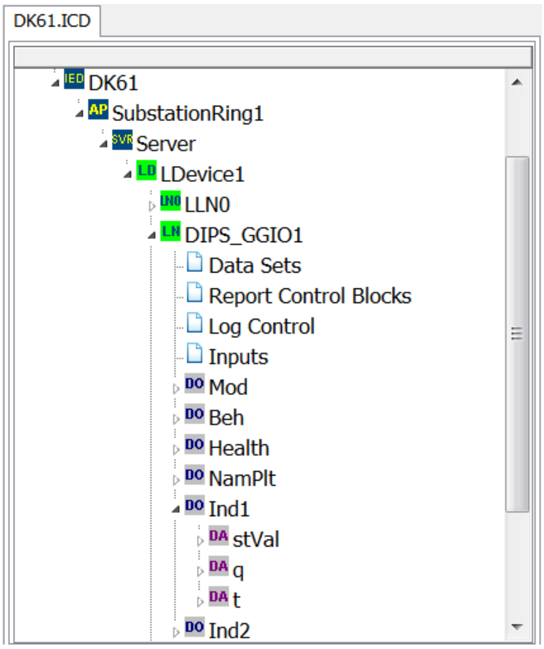


Figure 29 Hierarchical structure of DK61 under IEC 61850

need to be stored together with the status value. Each of the three attributes will be communicated when a client reads the Data Object Ind. The server logical device structure shown in Figure 29 contains information about these three Data attributes. The first one represents the stVal and is of type Boolean. The second type is a Bit-string that represents the quality information. The last component is the UTC time stamp; it should be noted that the time of the clock was not synchronised during the test [115].

The positions of the DIP Switches can be changed manually. By operating DIP switches on the server, the positions (information) are intended to be communicated by IEC 61850 services. In fact, the DK61 acts as a server and publishes the status of DIP switches in GOOSE messages and the PC acts as a client and subscribes to that GOOSE message [111]. Various client test applications such as IEDScout can be also connected to this server. The status of the switches is represented by Booleans. The ON position will be represented by Boolean true and the OFF position by Boolean false. After toggling a DIP switch the published GOOSE message from the DK61 board was captured on the PC using Wireshark. Figure 30 illustrates the captured GOOSE message, which shows the updated status of the DIP switches. As can be seen from Figure 30, the GOOSE message has only the Data Link (Ethernet) layer among the Application and Physical layer, while the transmitted UDP message comprises all layers including Data Link, IP, and UDP.

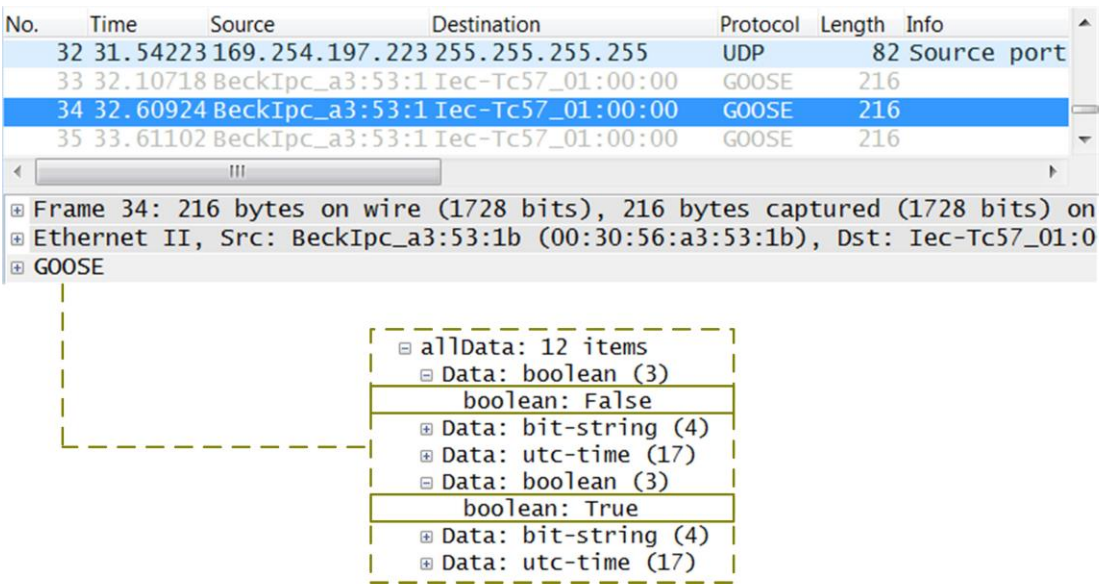


Figure 30 The captured GOOSE message using Wireshark

4.3 Network Simulators

Establishing a network for any experiment and testing a simple problem takes a large amount of time and expense. Therefore, it is not quite possible to implement the entire network scenarios for analysis in the real world. There are many tools which help network developers to test their network scenarios virtually. These network simulators are used for performance analysis in the field of communication. With the help of these simulation tools, both the time and cost of testing the functionality of proposed networks can be reduced and implementations are made straightforward. Generally, network simulators include a wide range of networking technologies and protocols which help users to build complex networks from basic building blocks. Users can simply design different network topologies using various types of basic building blocks, such as end host, hubs, routers, switches, etc. There are a large number of network simulators including OPNET, QualNet, ns-2, ns-3, OMNET++, GloMoSiM, SWAN, Jist, NetSim, J-Sim, SSFNet, etc. Therefore, selection of a suitable network simulator for specific research work can be a crucial task [118].

Network simulators can be categorised into the two types of free and commercial software. Apart from providing the affiliated packages to the user for free, the free network simulators may provide their source codes. This is an important advantage of this type of network simulator and they are also called open source simulators based on this feature. In these simulators, everyone can contribute to their development and help fix bugs. There are no limitations on the interfaces, so they are also open for future improvement. Because of their flexibility, recent developments and new technologies are implemented in a faster way than in commercial network simulators. Typical open source network simulators include OMNeT++ and NS-3 [118].

The commercial network simulators do not provide the licensed version for free. Users need to pay for the complete software or specific packages that fulfil their specific requirements. OPNET is a commonly used commercial simulator and QualNet is another example of this type. Commercial simulators have a number of specific advantages. The main advantage is that they are managed and maintained consistently by specialised staff of the company and generally have comprehensive and updated documentations. Open source network simulators are weak in this regard since there are not enough specialists working on their documentations. This causes serious problems when different versions are issued with new or modified functionalities. Hence, without any proper documentation, it will become more difficult to trace or understand the updated features [118].

The question of which simulator to be used is not an easy one and the answer is largely dependent on the specific use case. Existing computer network communication simulators have been studied on the basis of availability, simplicity, scalability, data manipulation, graphical display, and other important properties in order to be used in this research. The following subsection gives an overview on three common network simulators. These network simulators are also called Discrete Event Simulation (DES) tools as the network behaviour is simulated by modelling the events in a system as per order of the scenarios that the user has setup [119]. In fact, prior to the execution of the simulation, the user defines a list of events to be triggered at particular time periods or some conditional events. These stored events are then processed in order when the command to run the simulation is given. DES can provide a flexible, scalable and highly repeatable way to analyse the performance and behaviour of the communication networks under different conditions [120].

4.3.1 OPNET Modeler

OPNET Modeler [23] (Optimized Network Engineering Tools) is a well-established commercial DES tool that provides advanced communications network modelling and simulation capabilities. It was first proposed in 1986 and initially developed by Massachusetts Institute of Technology in 1987 using C++. Currently, OPNET is a very expensive package with powerful capabilities for developing different scenarios and is widely used by network industries [118, 121].

Generally, it is a comprehensive tool for simulation with a high level of modelling details and customizable presentation of simulation results [118]. OPNET consists of a high level user interface constructed from C and C++ source code blocks with a library of OPNET specific functions. Devices, network protocols, algorithms, applications, queuing policies, etc. can be modelled in detail using OPNET Modeler's powerful object-oriented modelling approach [119]. It provides a huge library of models and commercially available network technologies. Its friendly Graphical User Interface (GUI) and flexibility make the model building and implementation phases easier. OPNET Modeler has a hierarchical modelling procedure that is divided into the three main scopes of network, node, and process models [122]. Network devices such as workstations, switches and routers are called nodes. A node model consists of modules connected by packet streams or statistical wires, and each module is assigned to a process model to achieve the required behaviour [123]. A hierarchical structure helps users to organise the networks. OPNET simulator is very efficient when working with complex networks with a high number of devices and traffic flows, or in networks where small changes could be critical. In addition, it benefits from a fast discrete simulation engine [119].

4.3.2 OMNeT++

The open source DES tool OMNeT++ [21] (Objective Modular Network Testbed in C++) has been available to the public since 1997 [124]. Although OMNET++ is most commonly used for communication network simulations, it can be used for the simulation of complex IT systems, hardware architectures, and queuing networks as well [124]. It should be noted that OMNeT++ is not a simulator itself but rather a simulation framework. In fact, it provides infrastructure and tools for writing simulations [125]. Currently, OMNeT++ is gaining widespread popularity as a network simulation platform in academia as well as industry [120].

It is a modular component-based simulation package with extensive GUI support. Components are also called modules and are programmed in C++. The components are then assembled into larger components and models by using a high-level language called Network Description (NED) [120]. Using NED Editor, the communication network's topology is created. NED can be edited both graphically and in text mode. The network description consists of a number of component descriptions such as channels, simple and compound module types. In addition, introducing communications network traffic for each workstation takes place in ini files that also carry configuration options for the simulator. OMNeT++ simulations can be executed using two different interfaces. The graphical Tkenv user interface is extremely useful for demonstration and debugging purposes. The command-line Cmdenv user interface is the best for batch execution [119].

OMNeT++ has generic and flexible architecture that enables various modules to be easily integrated [126]. Along with the OMNeT++ widespread application more models, networks, protocols etc. are contained in model library. The INET framework, an open-source communication network simulation package for OMNeT++, contains the common node models and protocols [127].

The online documentation for OMNeT++ is extensive. However, more protocols and communication technologies need to be implemented and included in order to avoid having to perform significant background work. In addition, participation and contribution of more organizations are required for further development [118, 119].

4.3.3 ns-3

The ns-3 [128] project, initiated in 2006, is also an open source DES tool and has been primarily targeted for research and educational use [124]. It is licensed under the GNU GPLv2 license and is freely available for developments. ns-3 is a new simulator that has been designed to replace the current popular ns-2. It is not an updated version of ns-2 and also not backward-compatible with ns-2 [118]. ns-3 is written in the C++ and Python programming languages. However, ns-3 network simulations can be implemented in pure C++, or some parts of the simulations can also be written using Python [124]. It has a strong library which is useful for users to perform their simulation by editing the provided models. Animations are also used to visually display the obtained results. It should be noted that ns-3 is an active project and still under development. In addition, the simulation credibility needs to be improved. It has a community-based development and maintenance model, requiring the participation and contributions of more users and organizations [119].

In this chapter, OMNeT++ DES tool has been selected for simulation of a typical substation as its open source and also provides GUI supports. In Chapter 5, apart from OMNeT++, OPNET Modeler has also been employed for simulation as the OPNET’s extensive library enables to simulate and model the exact communication devices in the existing GB WAMS.

4.4 Substation Automation Systems

It is not sufficient that substations operate properly; they must also operate reliably under credible contingency situations [129, 130]. Fast and reliable information about the current state of power systems leads to better operation and management. In this regard, SAS can provide a powerful, fast, and viable way to design and implement substation monitoring, protection, and control functions in modern transmission and distribution grids [131]. The deployment of SAS has also fulfilled a market requirement to decrease the total cost. For example, optimization of maintenance costs and, in turn, reducing the life cycle costs of substations, provides highly efficient operation or near-limit operation of substation equipment [132].

Automated substations consist of smart and advanced equipment, such as relays, circuit breakers, transformers, switches, etc. that are integrated and monitored by a graphical interface unit that can be remotely accessed [133]. During the last decades, electromechanical devices in SAS have been replaced by IEDs and they now perform most functions, including protection and control. The basic functions of a SAS can be categorised as described in Table 1. Most SAS have these functions even though they may vary in different projects [132, 134].

Table 1 Overview of the functions of a Substation Automation System

Basic Functions	Examples
Monitoring	• Monitoring of switchgear status, status of transformer and tap changer, status of protection and control equipment, etc. • Monitoring of electrical parameters; e.g. frequency, voltage, current, real and reactive power, etc. • Fault record of facility and device disturbance record
Control	• Control of switchgear and transformer tap • Synchronism check and interlocking • Load shedding, voltage regulation, reactive power control, etc.
Protection	• Protection for transmission line, transformer, busbar, feeder, etc. • Overcurrent, distance, differential protection, etc.

The architecture of a SAS can be mapped into three levels hierarchically as shown in Figure 31 [47]. *Station level*, provides an overview across the whole station and assures the supervision of all the substation equipment. This level includes Human Machine Interface (HMI) and engineering workstations as well as gateways to connect the substation control centre to WAN. *Bay level*, includes the protection and control IEDs of different bays, such as circuit breakers, transformers, and capacitor banks. Equipment in the bay level and station level are called secondary equipment. *Process level*, includes switchyard equipment (called primary equipment) such as CTs/PTs, remote I/O, actuators, Merging Units (MU) etc. The main purpose of this level is to acquire data from the electric processes and to make switching operations [43].

The communications of these three levels are carried out through the *Process Bus* and *Station Bus*. The *Process bus* is the communication network which connects the IEDs at the primary equipment level to other IEDs, such as MUs providing sampled measured values of current and voltage via the Local Area Network (LAN). The *Station Bus* is the Communication network which inter-connects IEDs at the *Bay Level*, IEDs at the *Station Level*, and connects the *Bay Level* to the *Station Level* [43].

The communication network is now considered the backbone of substation automation. Inappropriate configuration of the communication network may cause failure of

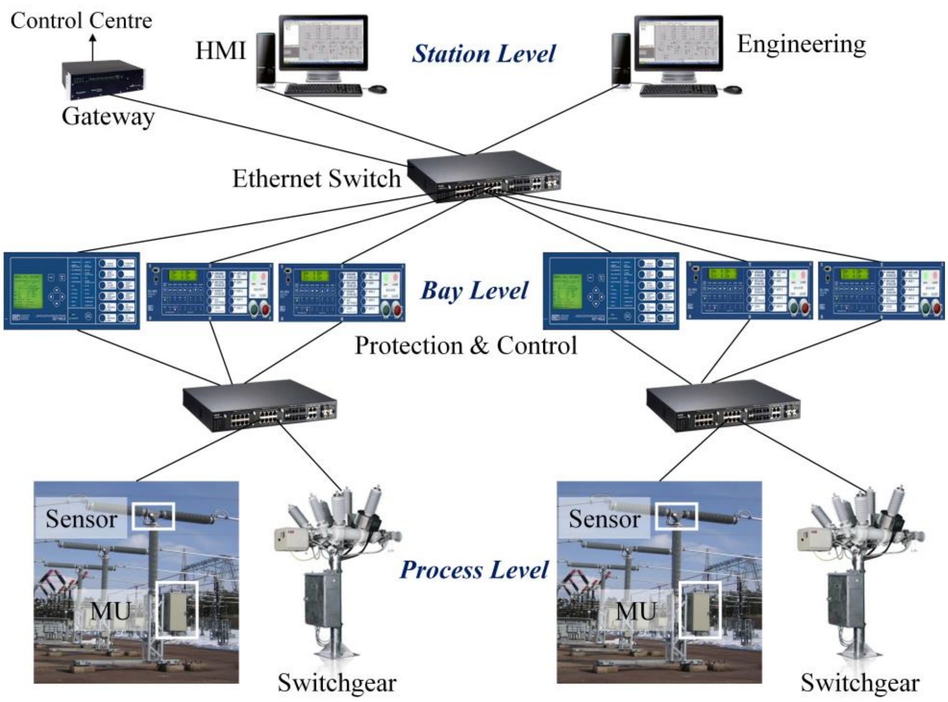


Figure 31   Substation Automation System (SAS) architecture

substation automation functions and could make the applications at best inefficient and at worse ineffective. The IEC 61850 standard has enabled IEDs and devices in a substation to be integrated on a high-speed peer-to-peer communication network, as well as client/server communication [44, 135].

4.5 Substation Communications Architecture Simulation

The open source OMNeT++ [21] has been used as a DES tool to simulate the proposed substation architecture in this section. The INET framework [127], an open-source communication network simulation package for OMNeT++, contains the common node models and protocols. However, some required models were designed and configured and will be discussed in the following subsection.

4.5.1 Simulation Model Configuration

The substation model that has been considered for simulation consists of one Transformer Bay, two Feeder Bays, a Station PC and Server. All of these nodes are connected via Ethernet Switch through star architecture. Figure 32 shows the communications architecture of the simulated substation in OMNeT++. The Transformer Bay model has two Protection and Control IEDs, two Breakers, one Merging Unit (MU), and is also equipped with one PMU. The two Feeders have similar architecture, which consists of two Protection and Control IEDs, one Breaker, and one MU. These IEDs are also connected via Ethernet Switch through star architecture.

The MU IEDs need to send Sampled Value messages so they are modelled based on a three-layer communication protocol stack, which Application Layer packets are directly mapped to the Ethernet Link Layer. The Protection and Control IEDs may require communicating with Station PC and Server using TCP/IP protocol, apart from receiving Sampled Values from the MUs and sending GOOSE Trip messages to the Breakers. Therefore, they should support both 5-layer Internet Protocol and 3-layer IEC 61850 communication protocol stacks. A new node model has been designed for this purpose in OMNeT++. This node model has two types of applications (TCP/IP and IEC 61850-based applications), which have a shared Link Layer. In the Link Layer, a new module has been designed, called Controller, to perform two required tasks. The first task is to provide two separate connections for the packets of two applications arriving to the

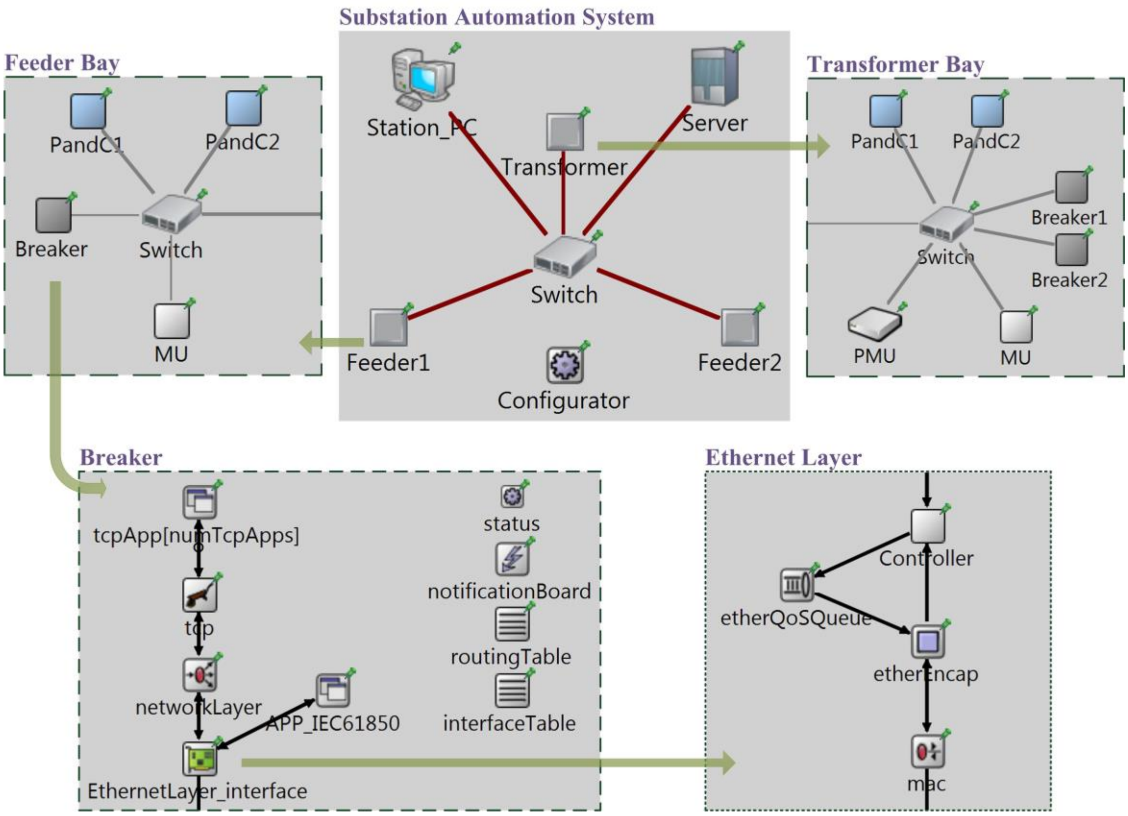


Figure 32 The communications architecture of the simulated substation

Queue and Ethernet Encapsulation modules. The second task is to classify the packet received by the node to determine whether it is a TCP/IP or IEC 61850 packet so that it can be passed to the relevant Application Layer. A similar node model has been created for the Breaker IEDs, since they need to send status information to the Station Server based on TCP/IP as well as communicate with Protection and control IEDs to receive or send IEC 61850-based commands or status information.

The generated traffic by the nodes has been configured based on the following assumptions in accordance with references [123, 136]. The MUs send Sampled Value messages to the corresponding Protection and Control IEDs at a sampling rate of 4800 Hz. For the MUs inside the two Feeders, the message size is 52 bytes, while for the Transformer Bay MU it is 98 bytes. This is because the Transformer Bay MU contains two datasets of current and voltage. The PMU IED generates 50 samples per second with the destination of Station Server. The PMU communicate based on the User Datagram Protocol (UDP) with the message size of 50 bytes. Communication over networks using the Internet Protocol (IP) can be connection-oriented (TCP) or connectionless (UDP). TCP rearranges data packets in the order specified and retransmits lost or corrupted data. In the case of UDP, there is no built-in ordering and recovery of data, but the transmission speed is higher than TCP. Therefore, currently UDP is used commonly with PMUs since a small amount of lost data is preferable over delayed data in real-time measurements [137] .The packet size depends on the number of synchrophasor parameters that a PMU measures. The 50 bytes message size has been chosen through capturing real PMU packets using Wireshark [27], an open source packet analyser, and analysing the packets specifications.

Furthermore, all the Protection and Control IEDs, as well as Breaker IEDs, send updated meter values or Breaker status information to the Station Server. These messages are sent at a rate of 20 Hz with a 32 bytes size using the TCP/IP protocol. It has been assumed that a fault happens in Feeder1 causing Protection and Control IEDs in Feeder1 and Transformer Bay to send GOOSE Trip messages to the corresponding Breakers. The Trip message size has been set to 16 bytes and is sent four times to ensure its delivery. One of the Protection and Control IEDs in Transformer Bay has been configured to send Trip messages continuously in order to introduce possible higher background traffic.

4.5.2 Simulation Results and Analysis

In the first scenario, 10 Mbps LAN has been considered for all the substation communications and Table 2 shows the obtained simulation EtE delay results for Sampled Value and Trip messages, respectively. The table provides statistical characteristics, including minimum, maximum, average, and standard deviation.

In the second scenario, the previous substation LAN has been replaced by 100 Mbps LAN while the other network configurations and design are the same as in the previous scenario. The obtained results show a great improvement from the latency point of view, as illustrated in Table 3.

Apart from the Sampled Value and Trip messages, delays of the PMU packets have also been analysed. In this analysis, four scenarios were performed to investigate the delay characteristics of the PMU inside the substation. The first scenario is that already described using the UDP/IP protocol. For the second scenario, the PMU has been modelled based on the created IEC 61850 node to communicate over the Ethernet. In

Table 2 Latency charactristics for 10 Mbps Scenario (millisecond)

(a) Sampled Value

Bay	Minimum	Maximum	Average	Deviation
Transformer	0.1985	0.2656	0.2019	0.0119
Feeder 1	0.1441	0.2108	0.1488	0.0131
Feeder 2	0.1249	0.1912	0.1287	0.0138

(b) Trip message

Bay	Minimum	Maximum	Average	Deviation
Transformer	0.1153	0.187	0.1225	0.0167
Feeder 1	0.1153	0.1734	0.1275	0.0214
Interbay	0.2306	0.3937	0.2618	0.0401

this scenario, the average EtE delays of the PMU packets were reduced by 10% compared to the UDP/IP scenario. However, as a large portion of this EtE delay is due to the relatively heavy background traffic on the Station Server, a new server has been added to the Station Level of the substation to work as PDC. The third and fourth scenarios were performed for more accurate comparison of the UDP/IP and IEC 61850-based PMU communication. From the obtained results shown in Table 4, the Ethernet-based IEC 61850 communications reduced the average delays of the PMU packets by 27% compared to the UDP/IP protocol.

In SAS, the propagation delays in the physical links are much smaller compared to the other latency factors associated with protocols, acknowledgement messages, processing delays etc. This is merely due to the relatively short distances that the packets need to travel between communicating nodes in the network [131].

In the next section, the recently proposed IEC 61850-90-5 technical report [138] is briefly investigated. This document enables IEC 61850 to transmit synchrophasor information according to IEEE C37.118 and over wide area.

Table 3 Latency charactristics for 100 Mbps Scenario (millisecond)

(a) Sampled Value

Bay	Minimum	Maximum	Average	Deviation
Transformer	0.0199	0.0266	0.0206	0.0019
Feeder 1	0.0145	0.0212	0.0152	0.0018
Feeder 2	0.0125	0.0189	0.0130	0.0014

(b) Trip message

Bay	Minimum	Maximum	Average	Deviation
Transformer	0.0116	0.0199	0.0129	0.0025
Feeder 1	0.0116	0.0173	0.0122	0.0014
Interbay	0.0232	0.0399	0.0273	0.0054

Table 4 Latency characteristics of PMU (millisecond)

Scenario	Minimum	Maximum	Average	Deviation
Station Server-UDP/IP	0.0548	0.0666	0.0602	0.0029
Station Server-IEC 61850	0.0455	0.0618	0.0540	0.0037
PDC Server-UDP/IP	0.0251	0.0317	0.0265	0.0022
PDC Server-IEC 61850	0.0183	0.0249	0.0192	0.0017

4.6 IEC 61850 for Synchrophasors over Wide Area

The technical report IEC 61850-90-5 [138], which has been published in 2012, provides a way of sending PMU data to PDCs and control centre applications. As the PMUs generate data based on the IEEE C37.118 standard, the data needs to be transmitted in such a way that is also compliant with the concept of IEC 61850. In addition, PMU data are transmitted over wide area where they need a routable profile. Accordingly, the

IEEE 61850-90-5 standard has been proposed to provide routable profiles for IEC 61850-8-1 (GOOSE) and IEC 61850-9-2 (SV) services, referred to as R-GOOSE and R-SV, respectively [138].

As described in Chapter 2, IEC 61850 is basically a layer 2 protocol and does not provide a Network Layer protocol. As such, this protocol does not inherently provide the routing capability required for wide area applications. The Internet Protocol (IP) is one of the options for communications over wide area. This is the protocol that the IEEE C37.118.2 standard uses for the transmission of data over networks. Although IEEE C37.118.2 allows communication over IP using both the TCP and UDP transport protocols, IEC 61850-90-5 focuses on UDP. Figure 33 illustrates the mapping of R-GOOSE and R-SV services. As can be seen, the Application Profile (A-Profile) consists of the GOOSE and SV as the Application and Presentation Layers encapsulated in the Session Protocol defined in IEC 61850-90-5. The A-profile in turn is bound to the Transport Profile (T-Profile), which provides a routing tunnel as specified by the Session Layer. In order to conform to IEC 61850-90-5, implementations should at least

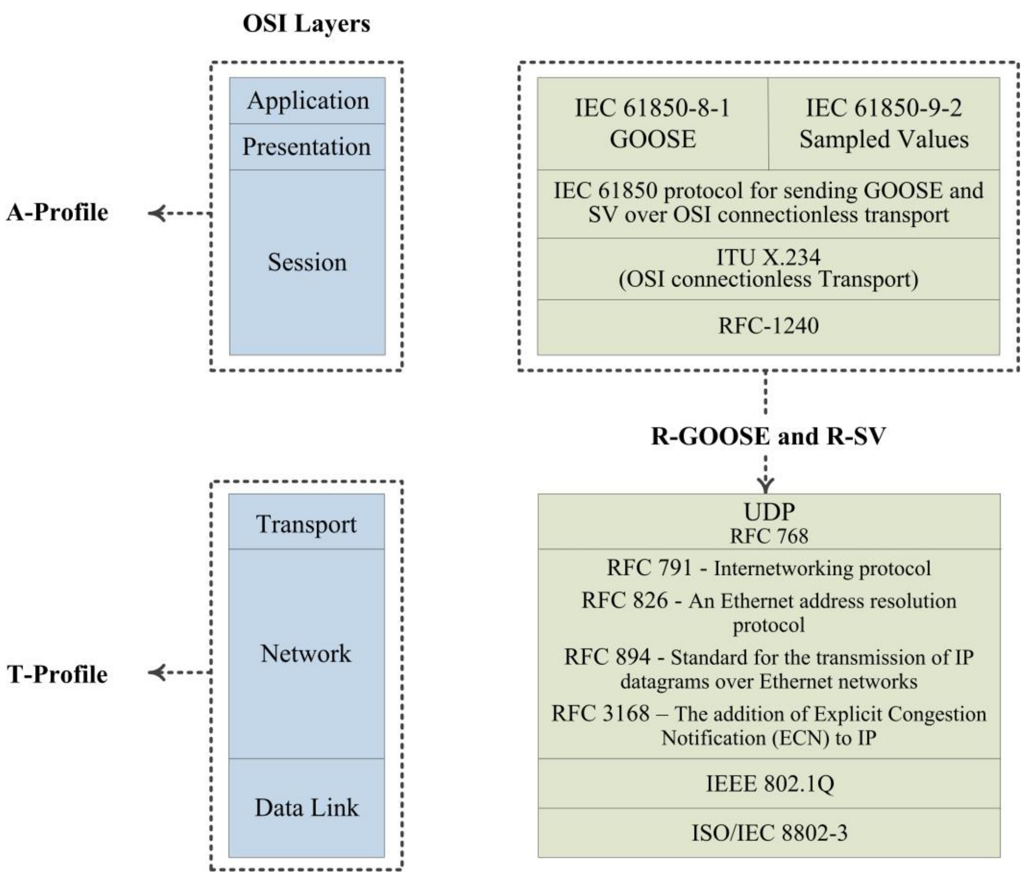


Figure 33 Mapping of R-GOOSE and R-SV services

support IPv4. Additionally, IPv6 can be used in parallel with IPv4 allowing higher wide area routing ability for larger scale information exchange [138].

The IEEE C37.118.2 standard, which represents the communication aspect of the standard, does not explicitly address the communication services. Instead, it specifies the synchrophasor message format. As described in Chapter 2, it defines the four message types of Data, Configuration, Header, and Command. Therefore, in order to be compliant with IEC 61850, the functions that are performed by these frame types need to be mapped to the existing services in IEC 61850. The control and configuration services are mapped to the conventional IEC 61850 MMS over TCP/IP, while the data need to use the proposed R-GOOSE or R-SV services. According to the IEC 61850 standard services, fast cyclic communications are typically based on SV, and additional event data can be communicated using GOOSE. Therefore, synchrophasor measurement data should map into the SV service [138].

The UDP protocol utilised in IEC 61850-90-5 does not guarantee data delivery and a lost packet cannot be recovered automatically. In the case of GOOSE messages, the reliability is achieved by repetitive sending of the same message. Therefore, the probability for data to be received by subscribers is greatly increased. SV messages do not originally make use of a repeat mechanism. As for applications with high send rates, such as Merging Units in substations, loss of a few samples is not critical. However, for synchrophasor applications where the send rates may not be as high as the previously mentioned applications and data is transmitted over wide area, it may be desirable to increase the reliability. If required, this can be provided through using the re-transmit approach of GOOSE for the SV packets. Furthermore, where the loss of samples is critical, but the response time requirement is not deterministic, the reporting mechanism of IEC 61850-7-2 and IEC 61850-8-1 can also be used. However, the TCP based services are restricted to point-to-point associations between client and server [138].

According to the details that have been laid out in the report, the main focus of IEC 61850-90-5 is to provide a more seamless interoperable system. In this regard, the communications delay may not be as low as the time-critical services of the original three-layer IEC 61850. This is because the fast services of the standard are now mapped into the Internet Protocol and transmitted over wide area network.

4.7 Concluding Remarks

SAS is widely used in order to improve the reliability of power systems. The success of a SAS relies heavily on the use of an effective communication system to link the various monitoring, control, and protection elements within a substation. In this research, for the performance analysis of substation communications networks, typical substation communication architecture has been simulated using OMNeT++, an open source DES tool. From the analysis, it can be observed that IEC 61850 based on Ethernet shows acceptable performance for substation communications. Furthermore, preliminary studies were performed to introduce and evaluate the IEC 61850 protocol for PMU applications. For future work, this simulated model of a substation communications network can be refined and improved from a number of aspects. One is to use more accurate Application Layer and message format for IEC 61850-based communications, Sampled Value and GOOSE. Also, VLAN can be configured in the Ethernet Layer in order to reduce the broadcast domain and limit it into the bay. In addition, the considered substation in this research has star architecture, which has a backbone switch that links all other switches. The advantage of star configuration is its easy maintenance, flexibility for expansion, and low delay. However, a failure of this switch will result in the entire communication system going down. Other substation communications architectures that provide higher redundancy can be investigated in future work.

Chapter 5

Performance Evaluation of WAMS Communications Infrastructure

5.1 Introduction

WAMS will be vital in the operation of future systems, where the need to instantly detect problems and react swiftly to a wide range of technical issues will become more crucial in order to deliver secure and reliable power. With regard to the WAMS deployment on the GB transmission system, operated by NG, a PDC located at the control centre is maintained by Psymetrix and is running the PhasorPoint application for stability analysis [97]. Critical to the operation of such systems is a robust and secure communications infrastructure; with the performance of communications links between PMUs and PDCs having a direct impact on the ability to meet specific monitoring and control requirements. In this chapter, performance evaluation of the WAMS communications infrastructure is presented in order to determine the characteristics of communication delays and bottlenecks that can occur in WAMS. An actual WAMS as installed on the transmission system of GB is modelled using both proprietary and open source DES tools, OPNET and OMNeT++. Comparisons will be drawn between the modelled approach and measurements from the actual WAMS as well as between the two simulation environments. In addition, different protocols, mechanisms, and topologies will be investigated for the GB WAMS future developments.

5.2 The GB WAMS Communications Infrastructure Analysis

5.2.1 Wide Area Network Model Architecture of GB

The considered WAN of the GB WAMS consists of 9 substations, which are geographically distributed. Except for Substations 8 and 9, which have been equipped with two PMUs, all other substations have only one PMU. These PMUs obtain the analog input signals corresponding to voltages and currents from the instrument transformers and measure power system parameters. The PMUs data messages are based on the IEEE C37.118 standard, which specifies a set of fundamental characteristics including time reference, rate of measurement, phase reference, accuracy metrics, and format of messages. PMUs are also connected to a Local Area Network (LAN), and the LAN is in turn connected via a substation router to the WAN. Using this network the measurement data from the PMUs are transmitted to a PDC based on TCP/IP protocol. Figure 34 presents a simplified schematic of the WAN model infrastructure [139].

Substations 6 and 7 are connected to the WAN through 2 Mbps links, and the other substations are connected by 256 kbps links. In addition, the bandwidth of the link between the IP Cloud and PDC is equal to 155 Mbps. Links are shared and used for

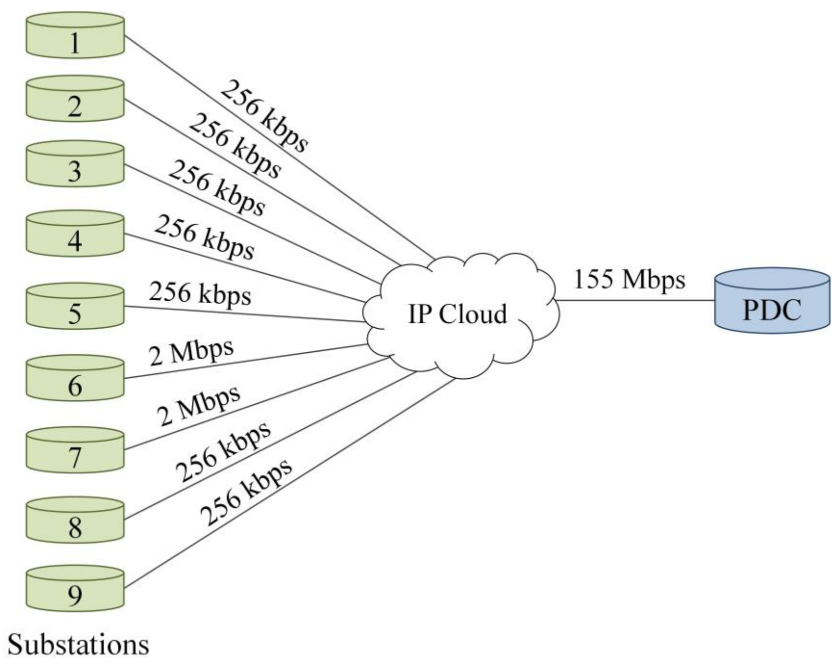


Figure 34 WAN infrastructure schematic of the real system

different communication applications. All PMUs have a sampling rate of 50 samples per second, so they generate constant traffic. However, there are other substation-based applications that generate variable traffic. The PMU in Substation 1 is Arbiter 1133A and the size of packets transmitted from it is equal to 50 bytes [140]. For the other 8 substations, AMETEK TR-2000 multi-function recorders are used as PMUs and generate packets of 42 bytes [141]. The packet sizes have been obtained by running Wireshark [27] on the Psymetrix [97] PDC server and capturing PMU packets. These are the respective IEEE C37.118 packet sizes in the Application Layer. In fact, the headers for IP and TCP are added to the IEEE C37.118 packet when packets are encapsulated through the protocol stack in the respective layers. The packet size depends on the number of synchrophasor parameters that a PMU measures. It should also be noted that the PDC uses a DELL PowerEdge workstation with 1 Gbps connection ports as a server, and as mentioned, the deployed PMUs are not all from the same manufacturer.

This section has provided relevant information about the physical structure and characteristics of the WAN model. Due to a lack of detail regarding some aspects of the model and also for simplicity, some assumptions and simplifications have been made in order to perform the simulations. The simplifications, along with the main aspects of the model implementation and configuration, will be fully described in Section 5.2.3.

5.2.2 Calculation of latency for the WAMS network

Generally, the time from when an event occurs in a power system until the corresponding data becomes available at a data receiver unit is called latency. Latency is important for real-time applications, and the acceptable level is highly dependent on the type of application [142]. Performing a tcpdump [143] capture at the PDC server allows a user to intercept and display details of synchrophasor and other application generated packets being transmitted or received over the network interface. Tcpdump is a command-line packet analyser that prints out a description of the contents of packets on a network interface. Therefore, the packet specification of all the PMUs that are communicating with the PDC can be obtained. Wireshark [27] functionality is very similar to tcpdump [143], but it also has a Graphical User Interface (GUI), plus more information-sorting and filtering options. Opening up the captured file using Wireshark and decoding packets as PMU packets, all the phasor data captured by the tcpdump function can be inspected. The packet information provided allows users to investigate the latency for the individual PMUs.

The two parameters that are required for latency calculation are the time stamp of the PMU and arrival time. Wireshark receives the time stamp recorded on the PMU during measurement, expressed as SOC (Second of Century) time. In addition, arrival time is the time the data frame arrived at the PDC. The time on the central PhasorPoint PDC server is locked to a National Grid Network Time Protocol (NTP) server. NTP is a networking protocol designed to synchronise clocks between computer systems. It is possible to observe how well it is locked to the source NTP server, but time accuracy will depend on the accuracy of the source NTP signal. Based on the information from NG, currently the PhasorPoint [97] server deviates from the NTP source by -0.000158 s. On this basis it has been deemed comparable to the GPS time of the PMU. Therefore, the packet latency can be calculated from Equation (6).

$$Latency = Arrival\ Time - PMU\ Time\ Stamp \tag{6}$$

Calculating the latency of each packet one-by-one manually is a very time-consuming process. Automating the large-scale calculation process can save time, reduce error and enables more detailed and larger scale analyses. Therefore, a novel algorithmic procedure was implemented in MATLAB to automate the large-scale latency calculations.

The algorithmic procedure consists of several sub-routines called by a main function. It is able to read the exported comma-separated values (CSV) file from Wireshark and is then able to calculate each packet's latency. As each PMU type may have different formats when defining time stamps, such as number of digits, the algorithmic procedure requires the user to specify each of the PMU types and then calculates the latency value accordingly. A new Excel file is then created and the details of each packet along with its latency are written in a separate row. By having the time stamps of all packets, the latency graphs against time for all PMUs can be synchronised.

Since the resultant latency has great variation, it is difficult to compare the graphs of different PMUs' latencies together. Therefore, it is necessary to calculate and plot the Exponentially Weighted Moving Average (EWMA) of each PMU's latency values.

Hence, after calculating latency, the algorithmic procedure also calculates EWMA values, as well as other characteristics such as maximum and minimum latency values for better statistical comparison. The EWMA model enables calculation of a value for a given time on the basis of the previous values. In fact, this method can provide a weighted average of previous latency values as determined by a specified parameter. Therefore, EWMA can weight current values more heavily than past values and places more importance on changes in recent values. This gives the advantage of being quicker to respond to value fluctuations than methods such as the Simple Moving Average (SMA). The desired EWMA smoothing factor, which is used in the algorithmic calculations, can be determined based on the level of smoothing requirements. The lower smoothing factors result in the smoother latency graphs. The user can also specify the desired EWMA smoothing constant that is used in the algorithmic calculations. The novel algorithmic procedure also provides the time stamp of the packet that has maximum or minimum latency.

In the real-world WAMS being considered here (that of GB), the communication network available to the PMUs is not dedicated to the WAMS application. In fact, it is a shared network that different types of applications use for their communications. The traffic that these non-WAMS applications generate on the network has been considered as background traffic. The background traffic is not necessarily constant over time. For example, during working hours, operational and field staff are expected to use communication applications that generate additional traffic. Therefore, it was necessary to perform investigations in order to analyse PMUs latency over different times of a day. To analyse latency over different times of a day, tcpdump data is required that has captured data over a one-day period. To reduce the file size, the traffic should be captured discretely in specified time intervals. In this case, it was every 5 minutes such that every 5 minutes tcpdump generates a separate .pcap file [143]. The algorithmic procedure is implemented in MATLAB in such a way that it is able to open each exported CSV file automatically, one-by-one, and then calculate the latency. At the end, calculated latency values for all packets are written continuously in a single Excel file, which is saved in a predefined location. The procedure also records the maximum and minimum latency in each individual file with their relevant time stamps.

Figure 35 shows the measured latency for the PMU packets sent from five of the PMUs located inside substations to the PDC over a period of one second. As other PMUs show

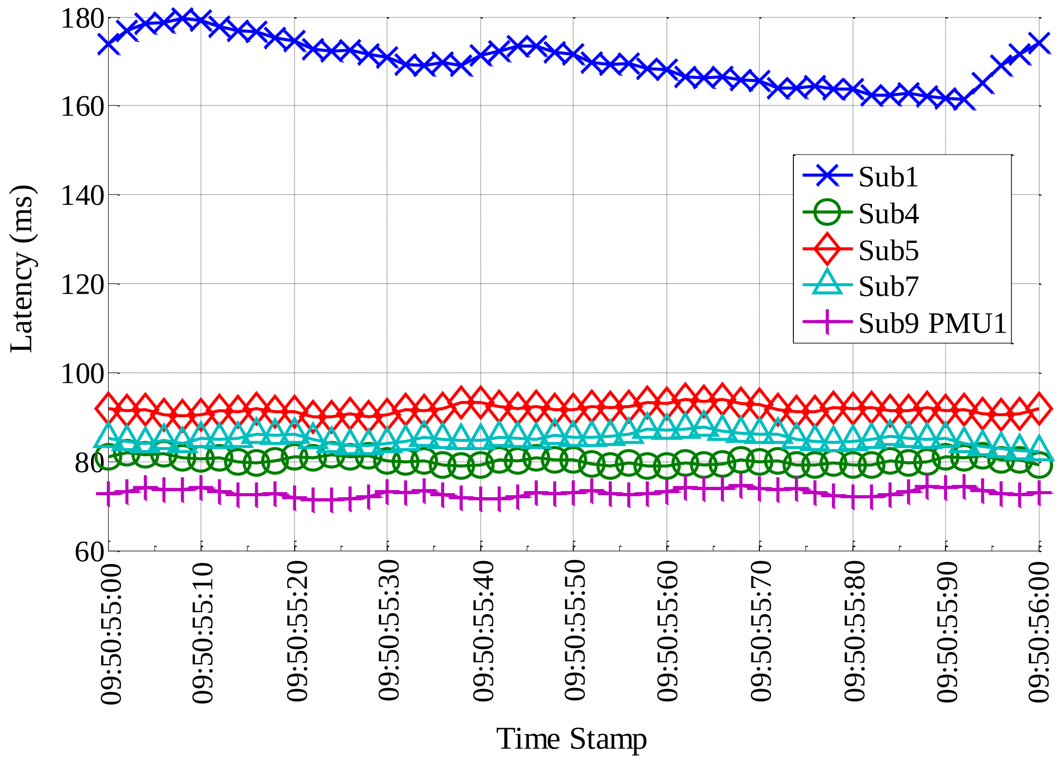


Figure 35 Latency of the PMU packets for 5 of the PMUs

similar results to these 5 PMUs, for better comparison these 5 PMUs have been selected for the analysis. In order to clearly illustrate the latency trends, the EWMA graphs were plotted based on a 0.06 smoothing constant that was chosen empirically. The sampling rates of the PMUs are 50 samples per second, so each PMU transmits one packet every 20 ms. Due to the PMUs' high sampling rates, a short period of time was adopted when plotting graphs in order to better present individual packet latency. Table 5 presents the actual statistical characteristics regarding latency, including minimum, maximum, average, and standard deviation, for a number of the PMUs over a 1 minute period. However, the calculated latency time includes any internal measurement processing delay associated with a particular type of PMU, in addition to the network latency. Hence, to obtain the actual network latency, we need to deduct the internal PMU delay, which occurs after the time stamp point, from the total latency calculated from the Wireshark information.

The internal delay of the PMU depends on different factors including measurement delay due to the data acquisition delay, signal processing time for phasor calculation, and data transfer time, which is dependent on the utilised interface [67]. PMUs from various manufacturers may have a different internal delay according to their adopted

Table 5 Actual latency characteristics (millisecond)

Substation	PMU	Minimum	Maximum	Average	Deviation
1	1	134.00	295.40	167.53	28.86
4	1	58.21	687.60	86.88	47.41
5	1	70.60	201.50	95.03	13.72
7	1	65.21	170.80	84.60	10.95
8	1	53.95	151.60	72.29	10.97
	2	53.79	214.40	73.65	13.53
9	1	55.76	139.30	75.05	11.07
	2	55.25	164.90	75.22	11.22

procedures and design specifications. In addition, PMUs from the same manufacturer, depending on their configuration settings, such as window size, can also exhibit different delays. Substation 1 in the considered WAMS has been equipped with an appropriately configured PMU from Arbiter Systems. Hence, investigations were carried out to accurately estimate the internal delay of this PMU. The results of this study are as follows.

As described in Section 3.2, a PMU rapidly samples analog power system quantities and generates discrete digital samples of the data using an analog to digital converter. Using the data samples taken from the waveform, phasor values are computed by applying the Discrete Fourier Transform (DFT). In practice, a PMU collects a window of measured samples to calculate the phasor representation of the input signals. A window length of 6 cycles or more may be needed to smooth the frequency spectrum obtained and thereby reduce error in estimation of phase and frequency. Meanwhile, the calculated phasors must also be time-stamped using GPS signals. Figure 36 shows the basic block diagram of a working PMU in principle [88].

The original IEEE 1344 synchrophasor standard recommended the end of a window for placing the time stamp, while IEEE C37.118 recommends the middle of the window [144]. However, neither of the standards requires the time stamp to be placed in a certain location relative to the data window. Regardless of the placement of the time stamp in the measurement window, a PMU must wait for a full window of the data to be sampled. The following assumptions and internal measurement delay calculations are

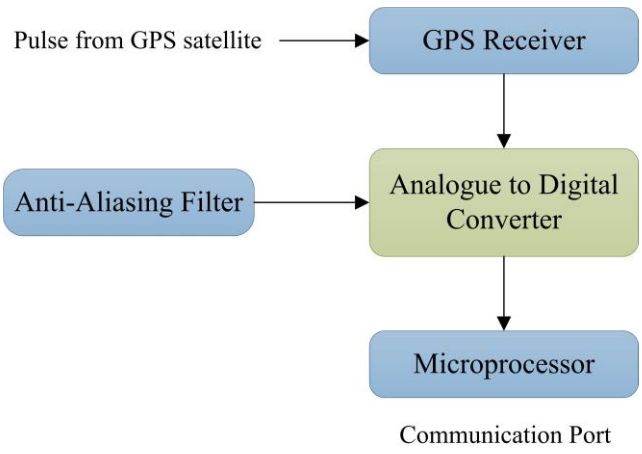


Figure 36 Basic block diagram of a typical PMU

based on information from the IEEE C37.118 standard measurement specifications [33] and the operational manual of Arbiter PMU in use [67].

It should be noted that the Arbiter 1133A does not time-tag like many PMUs, but rather it measures synchronously. There is a difference in these two concepts: i.e. "time tagging" and "synchronous measurement". The important fact to know is that the measurements are accurately timed in synchronous measurement. In other words, all measurements with this PMU start at exactly the second or multiples by 20 ms after, when the reporting rate is $50x$. This is in contrast to other PMUs which start sampling more or less "freely" and add a time-tag to the sample they take.

In the Arbiter PMU, results are calculated every 50 ms, and there is also a calculation time associated with the signal processing that is approximately 15 ms. Then there is a communication time, which is dependent on the employed interface and message format. Given the packet size from the Ethernet overhead and the message length for selected data items, we can calculate the time a message takes to go out on the wire and reach the output port of a PMU. In addition, the time reported in the data frame is used for reference; this is the time for which the estimator result is calculated at the centre of the measurement window in the implementation. Therefore, half the window length for the selected window must be also added in order to determine when the PMU will have the data available to start the calculations. The descriptions above suggest a series of steps to determine when a message will be ready for transmitting from the Arbiter PMU port. The following is a sample calculation:

- Select a nominal message time (this must be at intervals equal to one over the reporting rate, which in this case is every 20 ms)
  - The time tag of $xxx.06000$ seconds is considered
- Add half the window length (for this case the window length has been set to 6 cycles, and as the power network works on the 50 Hz frequency and by converting cycles to ms, half the window length would be 60 ms)
  - Data available at $xxx.12000$ seconds
- Round up to the next 50 ms increment if required, when calculations will begin
  - Next calculation cycle starts at $xxx.15000$ seconds
- Add calculation time of 15 ms
  - Thus, calculation is complete at $xxx.16500$ seconds
- Add data transfer time, T_t, to the output; considering a 50 octets long packet and Ethernet interface which runs at 100 Mbps:

$$T_t = \frac{50 \times 8}{100 \times 10^6} = 4\ \mu s \tag{7}$$

  - As the value is negligible it can be ignored in the calculation

Thus, the difference between the time tag and the time that data is ready on the wire for transmission, which is the PMU internal delay, would be:

$$xxx.16500\ s - xxx.06000\ s = 105\ ms$$

It should be noted that this delay would be different for various values of time tags, as it depends on when in the 50 ms calculation cycle the half window length ends. In fact, this is determined for each packet by how far in time (ms) it is from the next 50 ms calculation cycle. In the above example, the PMU starts calculating 30 ms after the sampling ends. Thus, depending on the sample time, the delay could be anywhere between 75 ms (finished sampling and start calculating directly) and 115 ms (finish sampling and wait the maximum of 40 ms), as depicted in Figure 37.

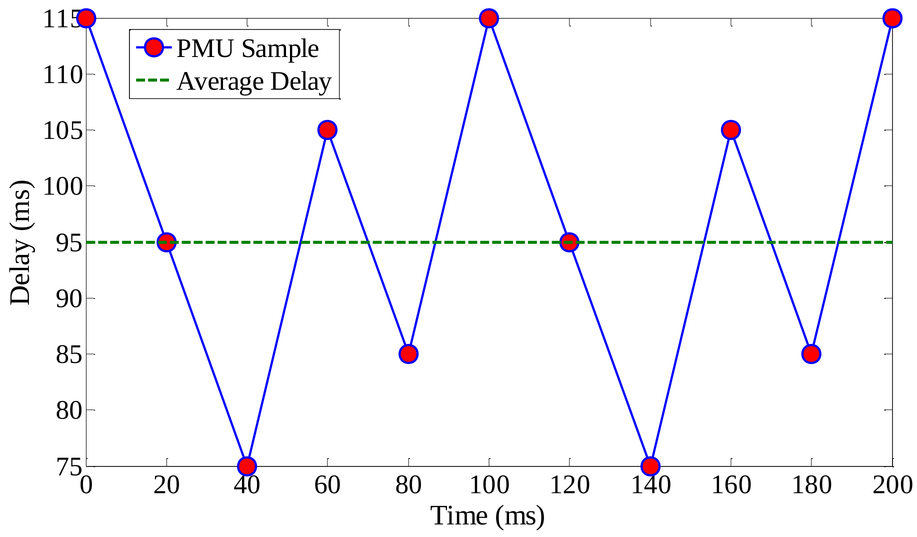


Figure 37 Arbiter PMU internal delay

PMU standards recommend a maximum allowable time for synchrophasor calculation [32]. The proceeding sample calculation gives a credible value falling within the allowable range. As described, a phasor is calculated based on a user-definable number of cycles of the 50 Hz waveform. In this case the measurements were taken over 6 cycles. As the reporting rate is 50 samples per second, we get 6 samples within 6 cycles. However, it does not take 6 cycles, calculate 6 samples, report and then again take 6 cycles. It will start sampling 6 cycles to calculate 1 report (with time in the middle of the sampling window), but after 1 cycle it will start another 6 cycles and after another cycle it will start another 6 cycles. Figure 38 illustrates this concept; the blocks are the cycles and the numbers are the reports (6 reports have been shown in this figure, but it goes on).

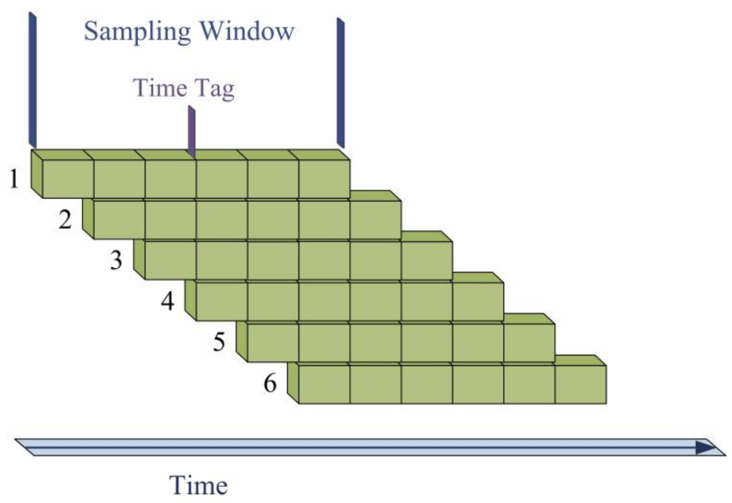


Figure 38 Sampling window for phasor calculation

In the case of other substations, where other types of PMUs are installed, the internal delay will be different. The AMETEK TR-2000 is a multi-function recorder that can simultaneously perform a number of tasks, including disturbance recording, power quality analysis, and phasor measurements. According to the operation manual and information provided by the manufacturer, it uses a 1 cycle window to calculate synchrophasor data from the DFT technique. The time stamp point is at the beginning of the window so the whole window length must be considered, which is 1 cycle or 20ms. A 10 ms calculation time has also been assumed for each sample. Therefore, on average we assumed 30 ms internal delay for the AMETEK PMUs. As AMETEK TR-2000 is a fault recorder, it is reasonable for it to have a lower internal latency.

By applying these details, the algorithmic procedure as implemented in MATLAB in this research also calculates the network communication latency by subtracting the internal delay corresponding to the time tag of each sample from the total latency and appends accordingly updated values. Figure 39 illustrates the network communication latency for the same PMUs and period of time as Figure 35. The PMU in Substation 1 still has a higher latency than other PMUs. This might be due to the existence of higher

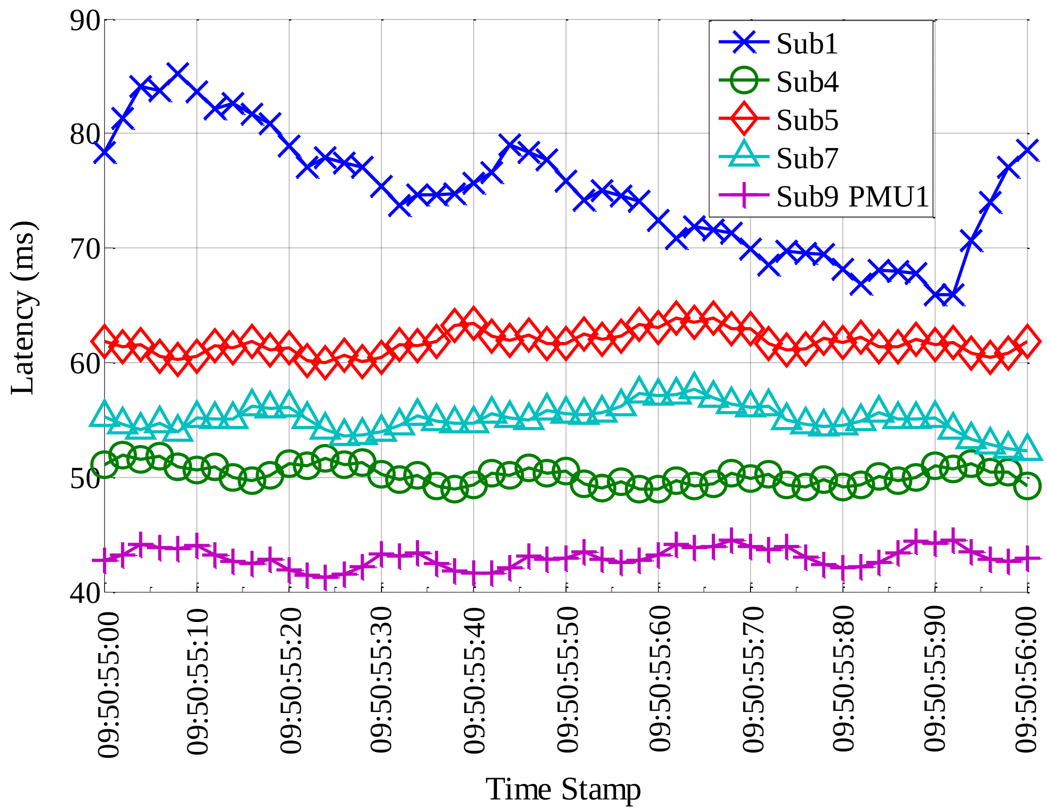


Figure 39 Smoothed network latency for 5 of the PMUs

traffic levels in this substation, or other sources of delay inside the PMU such as TCP buffer or the algorithm it uses. Overestimating PMU calculation times on other substations may be another reason.

Using TCP/IP, the TCP stack can buffer multiple messages and send them out in one packet over the network delaying the first messages in the packet. There is no way of predicting if the stack will or will not do this. This can be prevented by using UDP which does not buffer multiple messages in one packet.

In this section, the actual latency measurements for the considered GB WAMS were analysed and in the next section the model and simulation process will be discussed. The results presented in this section along with the results obtained in the next section from network simulations will be compared and discussed in detail in Section 5.2.4.

5.2.3 The GB WAMS Simulation Model

5.2.3.1 Simulation Model Configuration in OPNET Modeler

As described in Section 5.2.1, there are 9 substations in the WAN model that are located at different distances from the PDC. According to the information provided by National Grid, Substations 6 and 7 are connected to the WAN by 2 Mbps links that have more communications network activity in terms of staff presence and data transferred. Whereas Substations 8 and 9, which have been equipped with two PMUs, have a lower level of background traffic. Based on this information, some substations should be modelled differently from others. All substations have one local server and several workstations. Substations 1 to 5 are assumed to have a similar structure and each of them has five workstations such that one of them is defined to operate as a PMU. Substations 6 and 7 are assumed to have 13 workstations each, such that one of the workstations works as a PMU. Finally, Substations 8 and 9 have 3 workstations each, such that two of them work as a PMU. Figure 40 illustrates the simulation model as implemented using OPNET Modeler [23]. The 9 octagons on the left-hand side of the IP

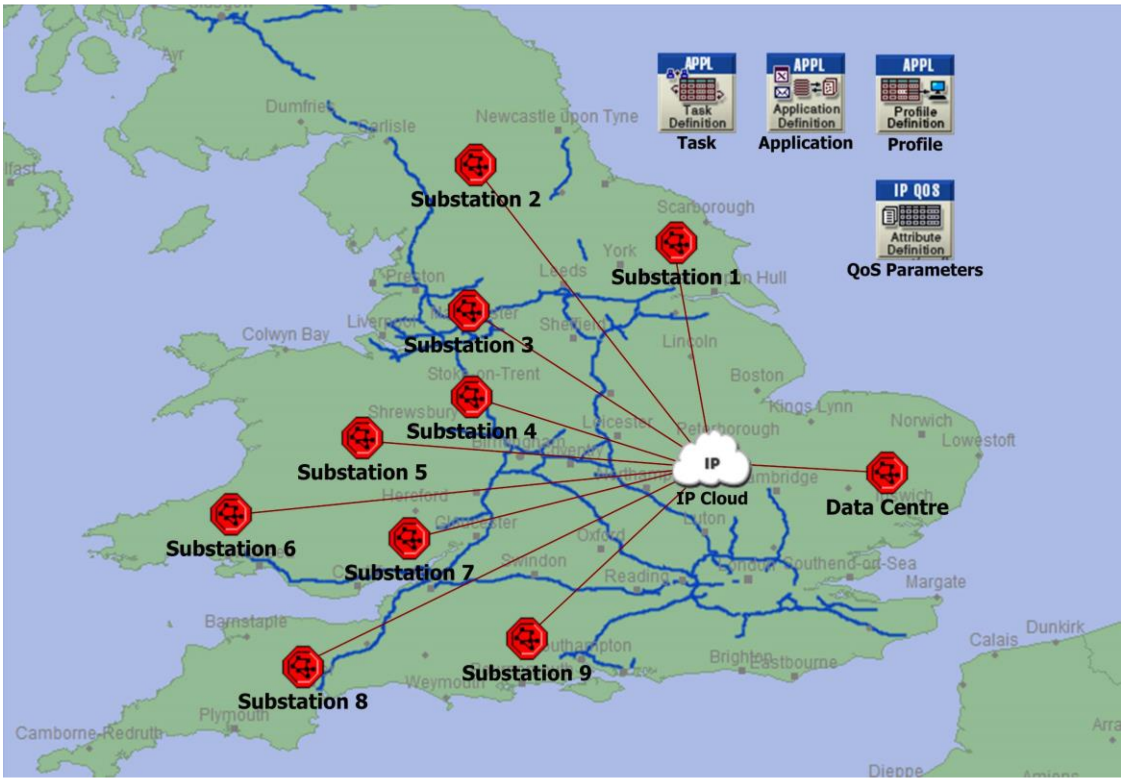


Figure 40 The infrastructure of the GB simulated network in OPNET

cloud represent the 9 substations and the one on the right-hand side is the data centre. The data centre was configured in a way to have 2 workstations and 3 servers, as shown in Figure 41; one of the servers is the DELL PowerEdge that works as a PDC.

It should be pointed out that in Chapter 4, the simulation and modelling of a typical power system substation communication infrastructure have been presented; nevertheless in this chapter the architecture of substations are modelled based on the workstations that transmit data outside the substations scopes and over WAN. It is also important to note that the geographical locations of substations and data centre in the simulation model are not their actual locations in the real system due to the confidential nature of information.

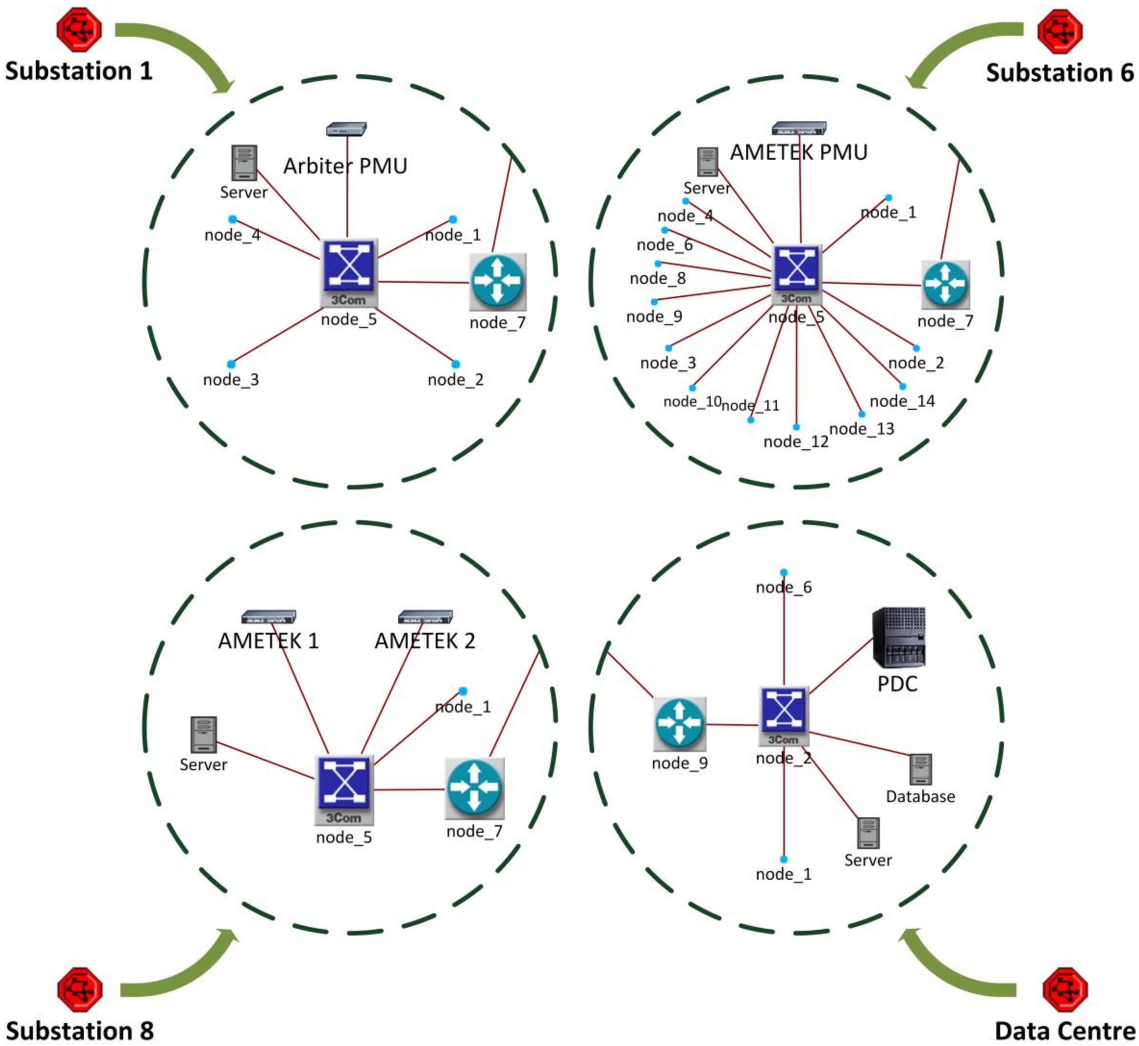


Figure 41 Subnets configurations of the WAMS model in OPNET

The workstation nodes are "Ethernet_wkstn_adv" models running over TCP/IP as defined in the OPNET model library [23]. It is important to note that different methods are available in OPNET for introducing communications network traffic. Since the EtE delays of PMU packets from the source Application Layer to destination Application Layer are required to accurately model PMU traffic, custom applications were defined. In OPNET, all custom applications are defined through a series of tasks. Each task is further divided into individual phases [23], [145]. Therefore, two tasks were configured by using the Task Config utility object in OPNET that represents traffic associated with the two types of PMUs that exist in the model. The main difference between these two tasks is the packet size, such that for Arbiter PMU is 50 bytes and for AMETEK PMU is 42 bytes. Both tasks were configured to generate packets every 20 ms, which means they create 50 samples per second. The final destination of all PMUs packets is the DELL PowerEdge server in the data centre node, which represents the PDC. After defining the single phase task of custom application for both types of PMUs, the custom application itself can be configured using the Application Config utility object in OPNET. Finally, by using the Profile Config utility, the profile that employs the configured custom applications can be specified. A user profile is a mechanism for specifying how applications are used by an end user during a simulation. In order to separate the latency results for each PMU, a distinct profile was created for each individual PMU in the network. Otherwise, the latency results for all PMUs are shown together in the same profile at the PDC node in OPNET, which makes the individual analysis of latency for each PMU impossible.

Apart from PMUs, for other workstations inside the substations, standard application models in OPNET were used to configure traffic. Standard application models provide an adequate level of detail for modelling the commonly used applications. For these workstations, one profile consisting of Database Access, File Transfer, and Email applications were specified that may send data to the substations' local server or the servers at the data centre. Once all applications and user profiles have been defined, they can be deployed by corresponding nodes. This can be done by configuring each node through the Edit Attributes window to support desired profiles and applications.

The traffic is generated in the Application module and then is passed to the Transport Layer module and thereafter to the Network Layer and so on. The PMU generated data will be first transmitted to the substation switch, and then to the substation router. Switches and routers were given default configurations and the 100Base-T link was used for all substation LAN communications. A standard IP/Ethernet cloud was employed as opposed to an IP/Multi-Protocol Label Switching (MPLS). This approach has been adopted as insufficient information was available on the exact implementation of the MPLS deployed in National Grid. The modelling of the system as an IP/Ethernet cloud was configured in a way to show a comparable performance with the MPLS behaviour and, in turn, with the results obtained from live Wireshark data. In 5.4, the performance of a MPLS-enabled communications infrastructure is evaluated on the same considered GB WAMS model and results are compared with the conventional IP network. The IP/Ethernet cloud was specified with normal distribution packet latency with the mean outcome of 0.03 s. Substations have been connected to an IP/Ethernet cloud using PPP point-to-point links and the same type of link was used for connecting the IP/Ethernet cloud to the router in the data centre. The links' data rates have been selected according to the specified architecture in 5.2.1. From the router in the data centre, the data finally will be transmitted through the LAN to the PDC server.

Furthermore, background traffic was defined for the links between substations and data centre in the WAN to make the simulation model and results more realistic. The determined background traffic of each link is proportional to the number of workstations in different substations and the traffic they generate. It was not possible to

Table 6 WAN links background traffic

From	To	Background Traffic (% of link bandwidth)
Substation 1	IP Cloud	50%
Substation 2	IP Cloud	50%
Substation 3	IP Cloud	50%
Substation 4	IP Cloud	50%
Substation 5	IP Cloud	50%
Substation 6	IP Cloud	70%
Substation 7	IP Cloud	70%
Substation 8	IP Cloud	0%
Substation 9	IP Cloud	0%
IP Cloud	Data Centre	60%

simulate the exact data traffic of the real network due to its stochastic nature. However, reasonably accurate traffic profiles were determined and adopted for implementation. Table 6 shows the applied background traffic for WAN links in terms of percentage of link bandwidth.

The overall communication delay consists of four components: ***Transmission delay***, which occurs during transmission and depends on the data size and link data rate; ***Propagation delay***, which is related to the transmission distance and speed of the employed media; ***Processing delay***, which is the time taken to process the packets, for instance in routers; and ***queuing delay*** that is caused by the network congestion and is the time packets need to wait in a queue until they can be processed [18], [146]. However, it is also necessary to include the internal processing delay of the PMUs in the modelled network. Therefore, in the case of an Arbiter PMU the average delay of 95 ms and for AMETEK PMUs the average delay of 30 ms was introduced in both their node models in OPNET, respectively, through the packet stream connected to the Application Layer.

5.2.3.2 Simulation Results and Analysis

After the completion of network configuration, the statistics to be collected can be specified in OPNET [23]. In this WAMS network research, the EtE delay from the PMU to PDC is a key statistic that reflects the WAMS performance. Therefore from the node statistics section in OPNET, the responding or requesting custom application statistics can be selected. Figure 42 illustrates the latency results in OPNET over 1 minute of simulation time.

It should be noted that in OPNET the default collection mode for network delay statistics is bucket mode. In this mode, OPNET groups data points that occur within a period, referred to as a bucket, and then applies a statistical function to each group of values. The resulting output vector contains one value for each bucket. This value can be the maximum, minimum, mean, etc. of the results for samples available in a bucket. The default bucket mode in OPNET for the provided result in Figure 42 is sample mean. The collection mode was also changed to All Values mode so that it was possible to obtain all samples latency in order to compare the characteristics of OPNET results with the Wireshark results as presented in Table 5. After exporting the latency results

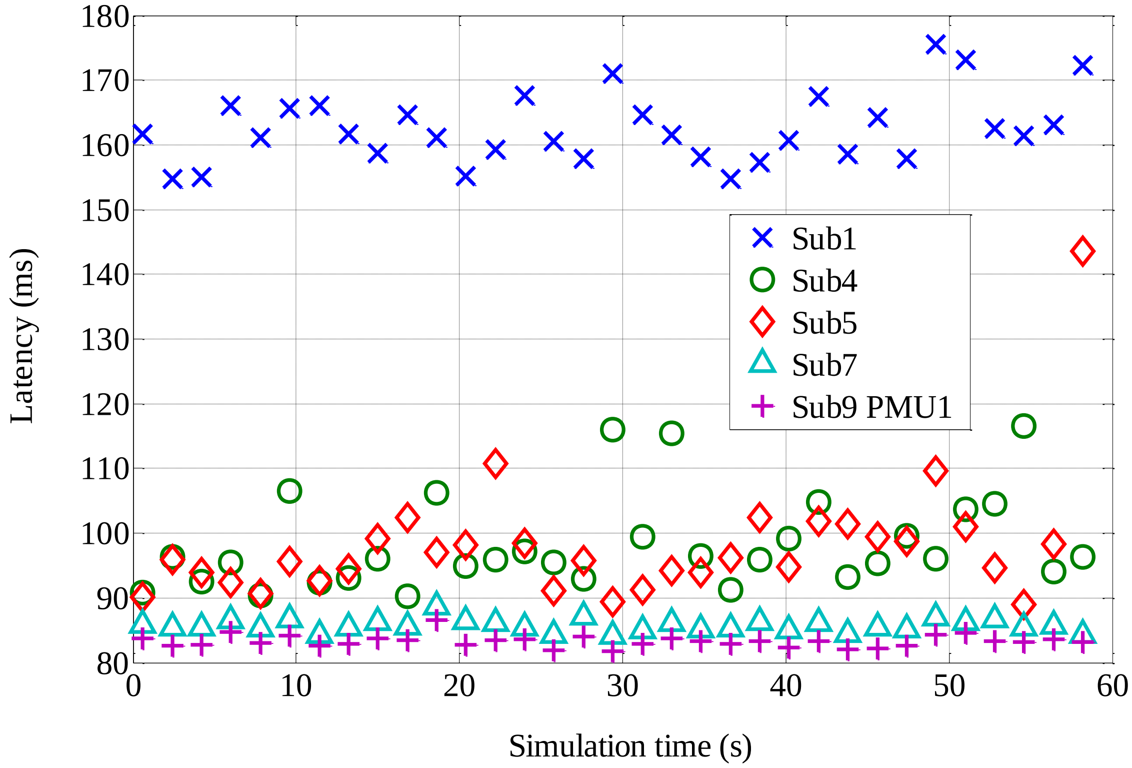


Figure 42 Simulated latency of the PMU packets in OPNET

Table 7 Latency characteristics of OPNET modelling (millisecond)

Substation	PMU	Minimum	Maximum	Average	Deviation
1	1	127.8	403.3	165.104	28.73
4	1	64.85	354.9	100.67	29.06
5	1	65.12	525.7	104.94	50.38
7	1	62.15	120.9	86.04	8.39
8	1	60.49	204.2	82.82	9.39
	2	56.03	201.2	81.73	9.42
9	1	61.53	218.4	84.49	9.5
	2	60.67	202.2	83.76	9.35

from OPNET to Excel, the required characteristics were calculated and have been presented in Table 7.

From the obtained simulation results, we can see that the latencies of the PMUs are very similar to the real system results provided in Section 5.2.2.

5.2.4 Results Discussion

Both Wireshark and OPNET results show that although Substations 8 and 9 have two operating PMUs and are connected to the WAN through 256 Kbps links, the latency of the PMUs packets are less than other substations, including the 2Mbps connected substations. This is due to the lower overall traffic levels in these two substations. According to the investigation performed PMUs latencies are very sensitive to the level of introduced background traffic.

We can see that in some cases PMU packets may experience greater latency than their expected average latency. For example, consider PMU 4 in Table 5, which had a maximum latency value that was about 8 times higher than its average. This variation in latency can be due to congestion in the network. When a connection is in use, no other data can be transmitted between other points concurrently. Therefore, sometimes devices have to wait until the network becomes idle and then initiate a connection to undertake a task. For further analysis, the probability distribution of latency values for each substation has been investigated. The analysis has shown that the Generalized Extreme Value (GEV) probability distribution type is the closest distribution to the obtained PMUs latency results among more than 15 considered distribution types. Table 8 shows the three closest probability distribution types to the latency results of a number of substations. In addition, Figure 43 and Figure 44 show the Cumulative Distribution Function (CDF) and CDF error for the three closest probability distribution types to the latency results of Substation 1, respectively. As can be seen from the figures, the GEV probability distribution has the lowest error. The probability distributions of latency values for the PMU in Substation 1 and the first PMU in Substation 9 are presented in Figure 45.

Table 8 Probability distribution types for the latency results

Substation	Probability Distribution Types
1	**generalized extreme value**, tlocationscale, loglogistic
4	**generalized extreme value**, tlocationscale, loglogistic
5	**generalized extreme value**, loglogistic, lognormal
7	**generalized extreme value**, loglogistic, lognormal
9 – PMU1	**generalized extreme value**, lognormal, inverse guassian

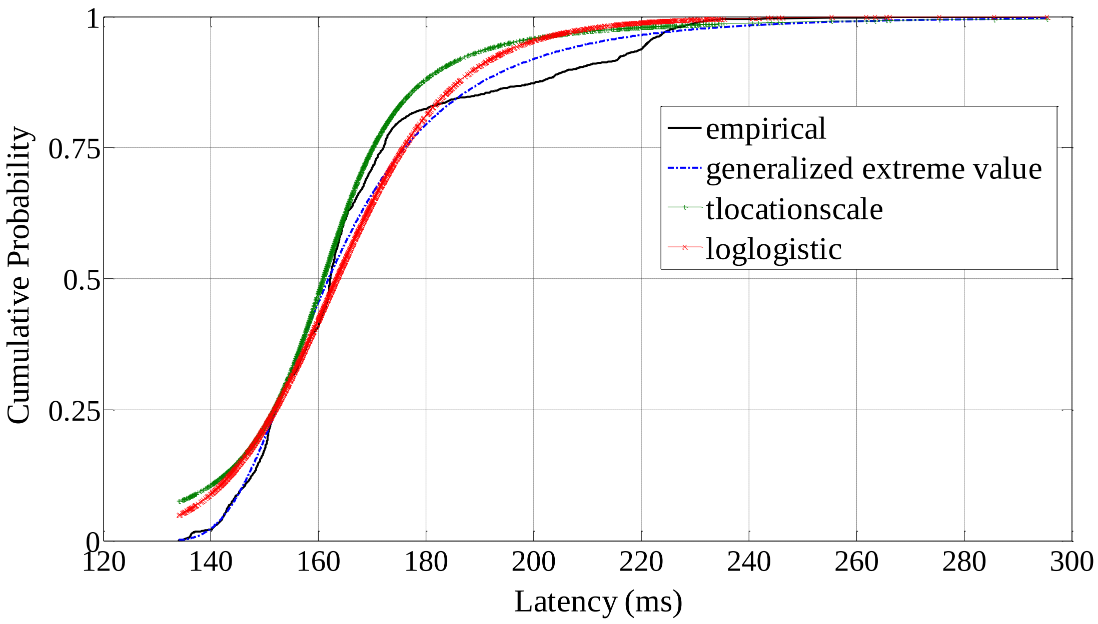


Figure 43 CDF for the latency results of Substation 1

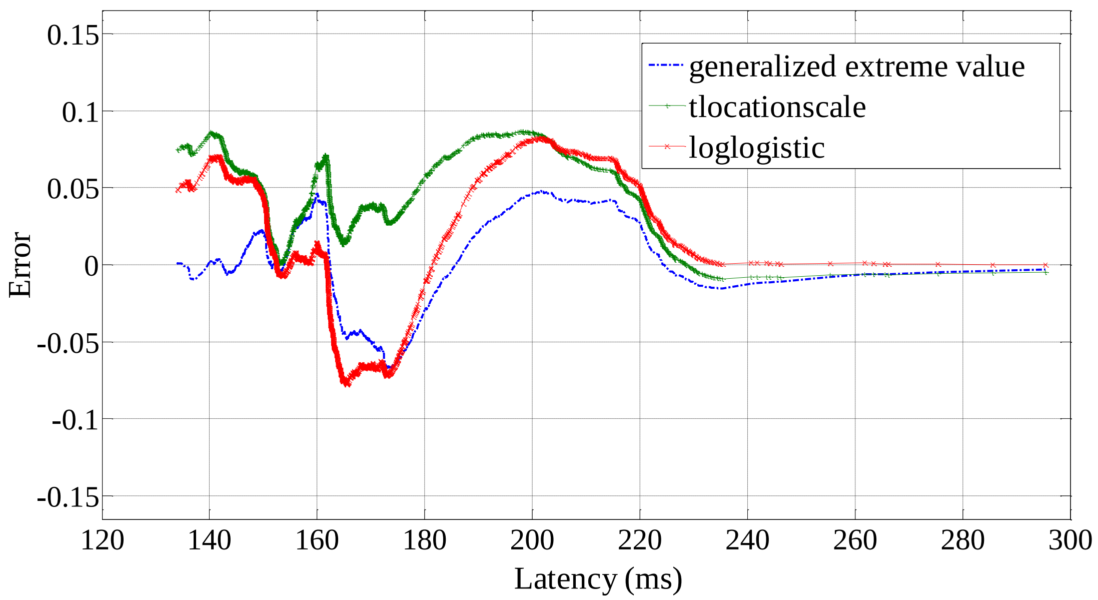
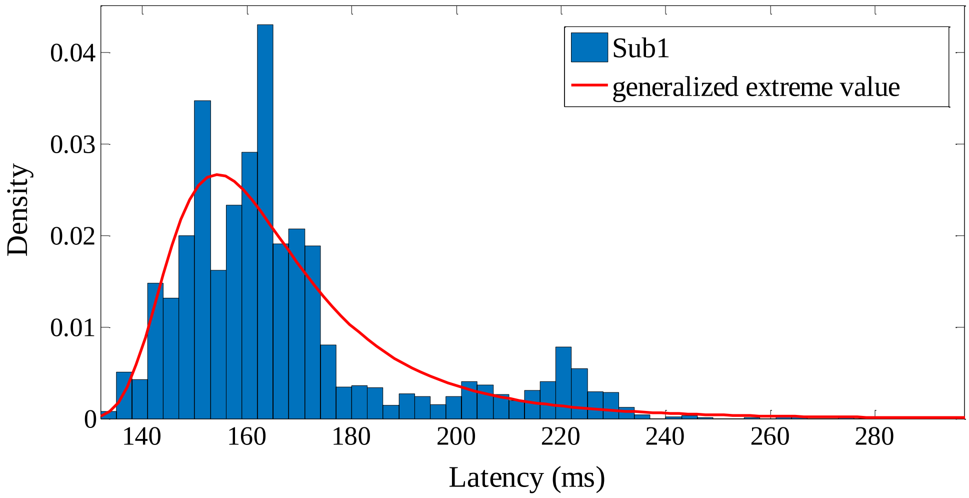
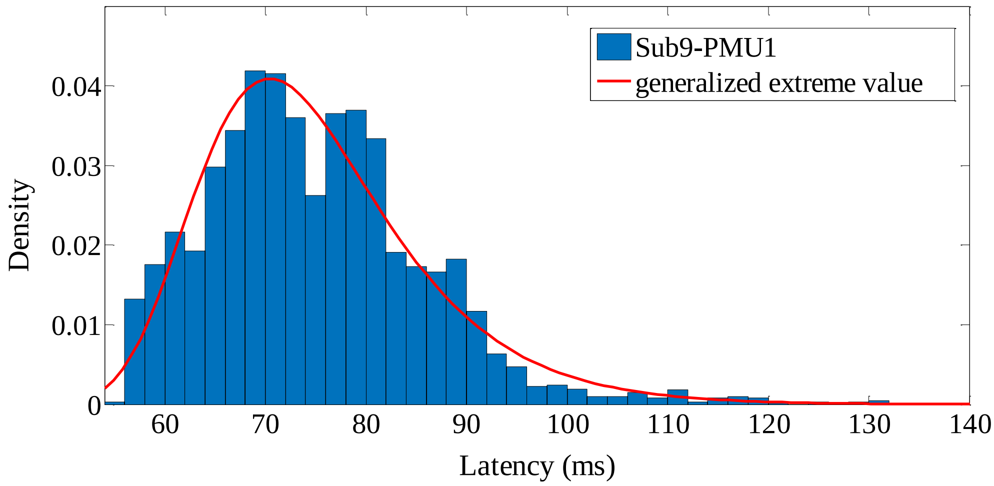


Figure 44 CDF error for the latency results of Substation 1

Substations that have similar configuration and PMU type might have different latency averages. This is more likely to happen in the actual system rather than OPNET simulation. This is because in OPNET we defined the same traffic profile for all workstations. Apart from the different traffic levels, the communication path that they use can be another reason. The number of hops or routers that packets pass through to reach the data centre may be different. A high hop or router load will add delay to the



(a) Substation 1



(b) Substation 9 – PMU 1

Figure 45 Probability distribution of the latency values

connection. Furthermore, the internal delays of PMUs have been investigated, determined and analysed in detail. As can be seen from the latency results of Substation 1, the internal delays of PMUs can introduce considerable delay and, in turn, have significant impact on the performance of WAMS applications.

One of the important factors that should be noticed with regard to delay in a WAMS is the window size of the PMUs and the algorithm they use. By having longer window size measurements are provided with higher accuracy, but it imposes extra delay on the measurement process. Therefore, window size and the algorithm adopted by PMUs should be proportional to the PMUs application. For PMUs that are used for monitoring or off-line analysis accuracy is desirable, while for PMUs deployed in control and protection systems the fast provision of measurements is more important. Transmitted packets from other workstations inside the substations that have a different traffic profile experience higher latency than PMU packets. This can be due to the larger packet size that they generate. Although PMUs generate large volumes of data in the long-term, the stream of data per second is modest.

Further latency results and evaluation are available in Appendix B.

5.3 The GB WAMS Future Development Analysis

Apart from the analysis presented in Section 5.2 for the existing WAMS, further scenarios have been proposed to evaluate the WAN performance for the future GB WAMS developments [147]. In fact, this is the stage that the developed simulation model can be employed for analysing possible future architectures as well as methods to improve the performance, such as new communication protocols, mechanisms etc. In this regard, four main scenarios have been specified, of which the first two scenarios investigate the future possible architectures and the last two scenarios investigate a different communication protocol and mechanism. The first scenario examines the effect on PMUs latencies, by increasing the number of PMUs installed in each substation. In the second scenario, the number of PMUs in substations is kept unchanged, but it is assumed that more substations in the power system are equipped with PMU and join the WAMS. Hence, the overall number of PMUs increases and investigations will be carried out to find the upper limit for the number of additional substations in order to achieve an acceptable level of latency for the WAMS operation. The third scenario evaluates the effectiveness of using UDP Transport Layer protocol instead of TCP for PMUs communications. Finally, the fourth scenario considers the QoS mechanism for improving the WAN performance.

5.3.1 Increasing the Number of PMUs in Substations

The number of installed PMUs in a substation depends on various factors, such as number of the substation’s feeders from which measurements are required, applications, redundancy, etc. For example, when the operating application only considers the frequency of different locations, by installing multiple PMUs in the same substation, they just provide the same information. On the other hand if the power calculations are required on various feeders, we have to install multiple PMUs in one substation. In this scenario the latencies of the PMUs packets have been compared when different numbers of PMUs are deployed in substations and for different levels of WAN links background traffic. As the WAN shares links for different applications, the ICT infrastructure of the WAMS has been tested for various background traffic conditions. Table 9 shows the obtained simulation results. It can be seen that in higher links background traffic and number of PMUs the performance of communications network is degraded significantly. In this case, phasor data have to be queued in the router buffer and wait for processing due to the network congestion. Substations 1 and 5, which have been connected to the WAN through 256 kbps links, for the 60% background traffic and 4-PMU case study could not send PMU packets to the PDC successfully in the determined simulation time. While Substation 7, which has been connected through a 2 Mbps link, shows acceptable performance. Overall, substations connected via 2 Mbps links shows a modest increase in latency compared to other substations.

Table 9 Average latency for different numbers of PMUs in substations (millisecond)

Background Traffic (% of link bandwidth)	Number Of PMUs	Substation 1 (256 kbps)	Substation 5 (256 kbps)	Substation 7 (2 Mbps)
0	1	148.6	82.3	80
	2	150.6	83.8	80.7
	3	152.9	84.8	82.1
	4	153.9	86.3	82.3
20	1	150.6	87.3	80.3
	2	153.7	88.8	81.3
	3	158.3	91.3	82.3
	4	174	101.1	82.7
40	1	157.5	92.4	81.6
	2	165.1	97.4	82.2
	3	207.4	133.6	82.7
	4	2993.9	3512.9	84
60	1	176.5	107.4	83.7
	2	363.2	176.3	84.1
	3	3776.5	3603.8	84.9
	4	-	-	85

5.3.2 Increasing the Number of Substations

WAMS cannot benefit from the main provided parameters of the power system efficiently unless PMUs have been installed to the appropriate number of substations over the transmission system. Although WAMS can completely replace the SCADA in theory, it is not practical with the present level of technology, and PMUs cannot be installed as widely as RTUs. There is a number of problems with respect to achieving this aim including: ***communication problems***, the large amount of real time data, which is produced by WAMS in the time scale of millisecond, would bring much pressure to the present communication infrastructure of the power system; ***storage problems***, the control centre needs to store a huge amount of real-time data that could reach the level of TB or even PB every year; ***management problems***, processing and utilizing a massive volume of data will be a big challenge [148, 149].

In this scenario, the number of substations has been increased in order to investigate the performance of WAN communication infrastructure, when more substations are equipped with PMUs and join the WAMS. It has been assumed that the new connected substations have the same structure as Substations 1 to 5 in the considered WAMS. Hence, they have been equipped with one PMU and connected to the WAN through 256 kbps links. Table 10 shows the average latency of the PMUs for three of the substations when extra substations are added to the WAMS. After connecting more than 20 extra substations, the latency will be very high and from the point we add the 25th substation (total of 34 substations), the communication network will become unstable and latency values are not converged. Therefore, in order to add more PMUs into the WAMS in future the existing communications infrastructure need to be upgraded.

It should be also noted that to have a completely observable power system, it is not economical to equip all buses with PMUs as a PMU and its associated facilities are

Table 10 Average latency for different numbers of substations (milliseconds)

Number of Additional Substations	Substation 1	Substation 5	Substation 7
10	172.7	106.2	90.3
15	178.5	108.6	93.4
20	188.8	118.8	105

costly. Furthermore, it is not necessary to equip all buses as the voltage phasor of the buses adjacent to the bus with installed PMU can be computed using current phasor and the line parameters. Accordingly, the first step in placing the PMUs is to determine the appropriate locations. In an actual power system, there may be certain buses that are strategically important, such as buses that are connected to a heavily loaded or economically important area, or a bus anticipated to be a future expansion point. In these cases, PMUs should be placed at the preferred buses, and the rest of buses should be made observable by placing a minimum number of additional PMUs. There has been a significant research activity in recent years to find the optimal number and placement for PMUs [150, 151].

5.3.3 UDP/IP Protocol

UDP, User Datagram Protocol, is a transport mechanism over IP that offers a connection-less communication. It does not provide mechanisms for flow control and rate adaptation that otherwise are associated with TCP. In the case of UDP, there is no built-in ordering and recovery of data and therefore the transmission speed can be higher than TCP and can offer a more stable delay. Accordingly, time-sensitive applications, such as voice over IP and video streaming, often use UDP since a small amount of lost data is preferable over delayed data in these types of applications.

In this scenario, all the PMUs have been configured to use UDP/IP protocol in their communications with PDC. Table 11 presents the obtained simulation results. The results show a lower average latency compared to the currently employed TCP/IP protocol. Based on the obtained results, as for time-sensitive PMU applications like

Table 11 Latency characteristics using UDP/IP (millisecond)

Substation	PMU	Minimum	Maximum	Average	Deviation
1	1	124.6	355	160.3	26.34
4	1	59.78	369.8	95.38	27.48
5	1	59.9	285.4	95.82	25.18
7	1	57.55	124.7	82.74	8.86
8	1	57.9	218.9	80.76	9.43
	2	60.23	210.1	80.78	9.46
9	1	57.72	189.8	80.19	9.33
	2	59.97	196.9	81.38	9.22

control and protection it is recommended to use UDP protocol. However, if the PMU data are used for monitoring and off-line analysis, the TCP protocol can guarantee the delivery of all generated PMU packets.

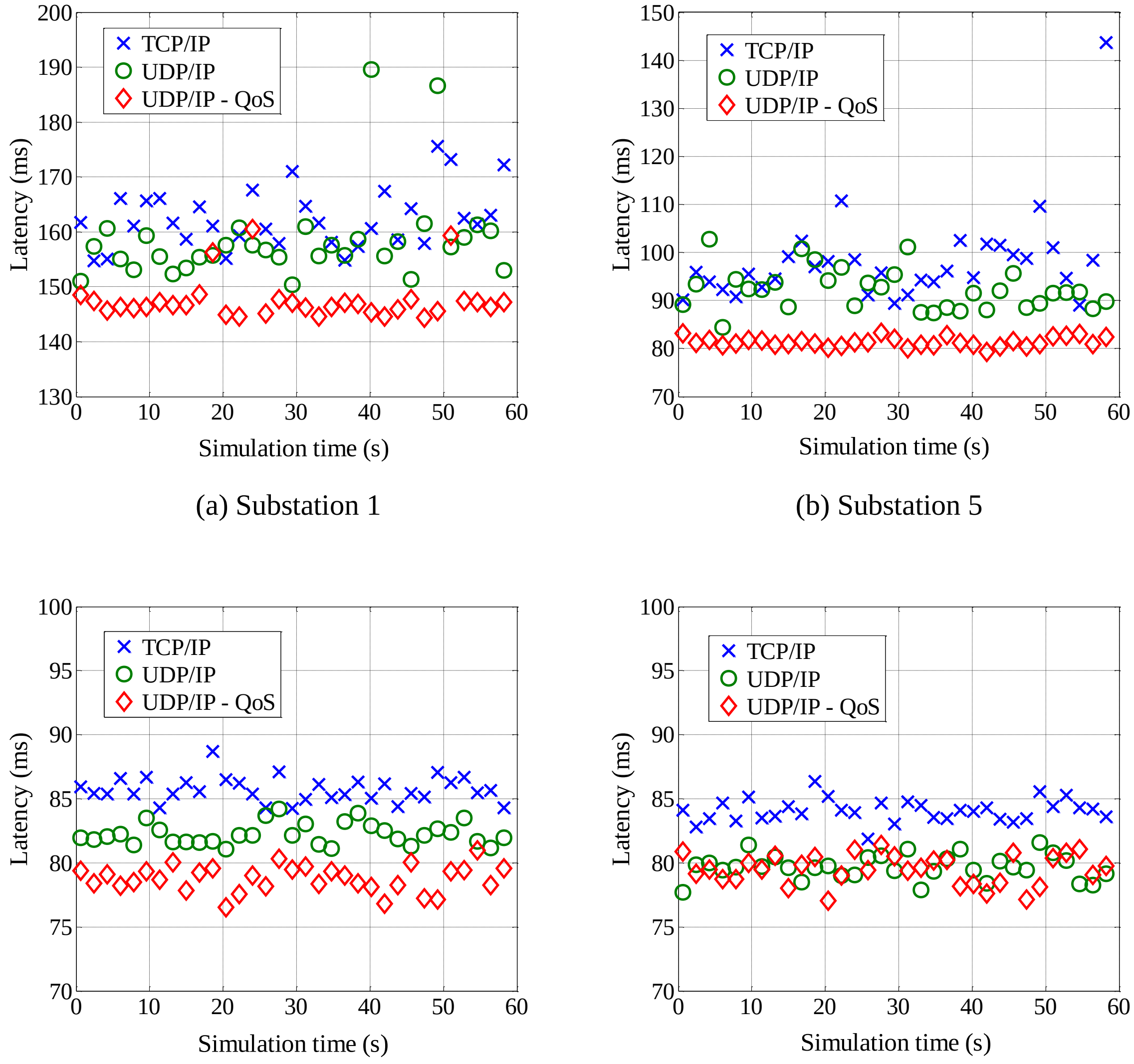
5.3.4 UDP/IP protocol with QoS

Quality of Service (QoS) policy can be used to ensure the excessive delay does not occur for the time-critical applications packets in a shared network. In fact, QoS is a request from an application to the network to provide a guarantee on the quality of a connection. By marking the packet for different levels of priority, the queue with higher priority is first checked for the sending packet. For further improvement of the WAN performance for PMUs communications, in this scenario the deployment of QoS mechanism has been investigated.

The Weighted Fair Queuing (WFQ) scheduling schemes alongside the Type of Service (ToS) profile have been used in OPNET to carry out the relevant analysis. The QoS profiles in OPNET contain detailed information about their mechanism settings, such as the number of queues used, their respective weights, and queue size limits. Table 12 shows the simulation results. According to the obtained results, the QoS mechanism improved the WAN performance significantly, especially regarding maximum latency and deviation. However, a slight increase in the average latency for PMU2 in Substation 9 can be seen. This happens because of the effect that the traffic in the same priority class has on themselves. For better comparison, Figure 46 shows the graphs of relevant results in the same plot for the three scenarios: TCP/IP, UDP/IP, and UDP/IP with QoS.

Table 12 Latency characteristics using UDP/IP with QoS (millisecond)

Substation	PMU	Minimum	Maximum	Average	Deviation
1	1	125.9	212.6	147.57	9.44
4	1	62.02	153.6	82.23	9.68
5	1	61.5	142.8	82.44	9.46
7	1	59.08	117.7	79.37	8.11
8	1	60.8	142.3	79.6	8.3
	2	57.84	143.6	80.07	8.65
9	1	56.57	141.3	80.2	8.72
	2	62.9	144.3	84.5	8.5



(a) Substation 1

(b) Substation 5

(c) Substation 7

(d) Substation 9 – PMU 1

Figure 46 Comparison of results for the three scenarios

5.4 Evaluation of MPLS-Enabled Communications Infrastructure

5.4.1 Multi-Protocol Label Switching (MPLS)

MPLS is an advanced technology for high performance packet control and forwarding mechanism [152]. In fact, MPLS adds new capabilities to the IP architecture, which enables support of new features and applications. It increases the network performance, improves the scalability of Network Layer routing, and provides routing flexibility and Traffic Engineering (TE) [153]. The MPLS domain can be divided into two parts of MPLS core and MPLS edge [24]. The core consists of routers that are only connected to MPLS capable routers. MPLS edge is the boundary of the MPLS network and consists of routers that are connected to both MPLS-capable and incapable routers. The routers which are in the MPLS domain and forward the packets based on label switching are called Label Switch Routers (LSR). Routers that operate at the edge of the MPLS network are specifically called Label Edge Routers (LER). Packets enter into the MPLS domain through Ingress LERs and leave the MPLS domain through Egress LERs. The Ingress LER attaches a short fixed-length label to every incoming packet and then forwards it into the MPLS core. This label is used, rather than the IP header, by LSRs to forward the packet through the MPLS network. The route by which the packet is forwarded through the MPLS domain is assigned when the packet enters the domain. This route that is established between Ingress and Egress LERs is called Label Switched Path (LSP). On the other edge of the network, the Egress router removes the attached label of the outgoing packet and sends the packet further to the destination according to the IP routing [25, 93].

The MPLS header has 32 bits, as shown in Figure 47 [26]. The header consists of a 20-bit Label value, which represents the LSP assigned to the packet; LSRs use this value to

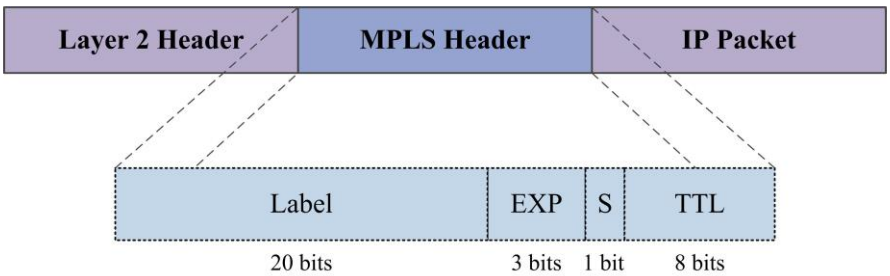


Figure 47 MPLS header

make forwarding decisions. Following the Label field is the 3-bit Experimental (EXP) field, which is also known as the Traffic Class (TC) field; it is used for Quality of Service (QoS) related functions and drop precedence. The next field is the 1-bit Stack field, which is used to indicate the bottom of the label stack. Finally, there is the 8-bit Time to Live (TTL) field, which has the same function as the TTL field in the IP header. The Ingress LER sets the TTL, a counter that is decremented by each LSR along the path. If the TTL expires, the LSR discards the packet. The MPLS header is placed between the Link Layer and Network Layer headers. Since MPLS operates between layers 2 and 3, the routing process is much faster than conventional IP. In fact, it forms layer 2.5 label switched network on the layer 2 switching functionality without the layer 3 IP routing [153].

The packet is assigned a label and mapped on to the LSP in accordance with the Forwarding Equivalence Class (FEC) [154]. FEC is a set of packets that have related characteristics and are forwarded over the same path through a network. FECs can be created from any combination of attributes including source and destination IP address, transport protocol, and port number. MPLS uses Label Distribution Protocol (LDP) to exchange label mapping information between LSRs and set up LSPs. LSPs can be manually specified or dynamically computed. Multiple parallel LSPs can be configured between an Ingress-Egress pair. These LSPs can be set up on different physical paths in order to distribute the traffic load and provide more flexibility [155].

5.4.2 Simulation Model Configuration

For the performance evaluation of MPLS technology for WAMS, the same WAMS model of GB as in Section 5.2 has been considered. However, the IP cloud has been replaced by the MPLS subnet in the simulation model. The process of configuring MPLS in the network has three main steps of configuring LSPs, creating FECs, and configuring LSRs. Due to insufficient information on the exact implementation of the MPLS deployed in National Grid, the architecture shown in Figure 48 was considered for the MPLS subnet in the model. It consists of two LERs, one as Ingress and the other as Egress router, and several LSRs at the core of the MPLS network. These routers are connected through the DS1 links. OPNET supports both static and dynamic LSPs. With static LSPs, the exact route used by the LSP can be specified. Therefore, we have used static LSP, as it allows more routing control and makes the analysis straightforward.

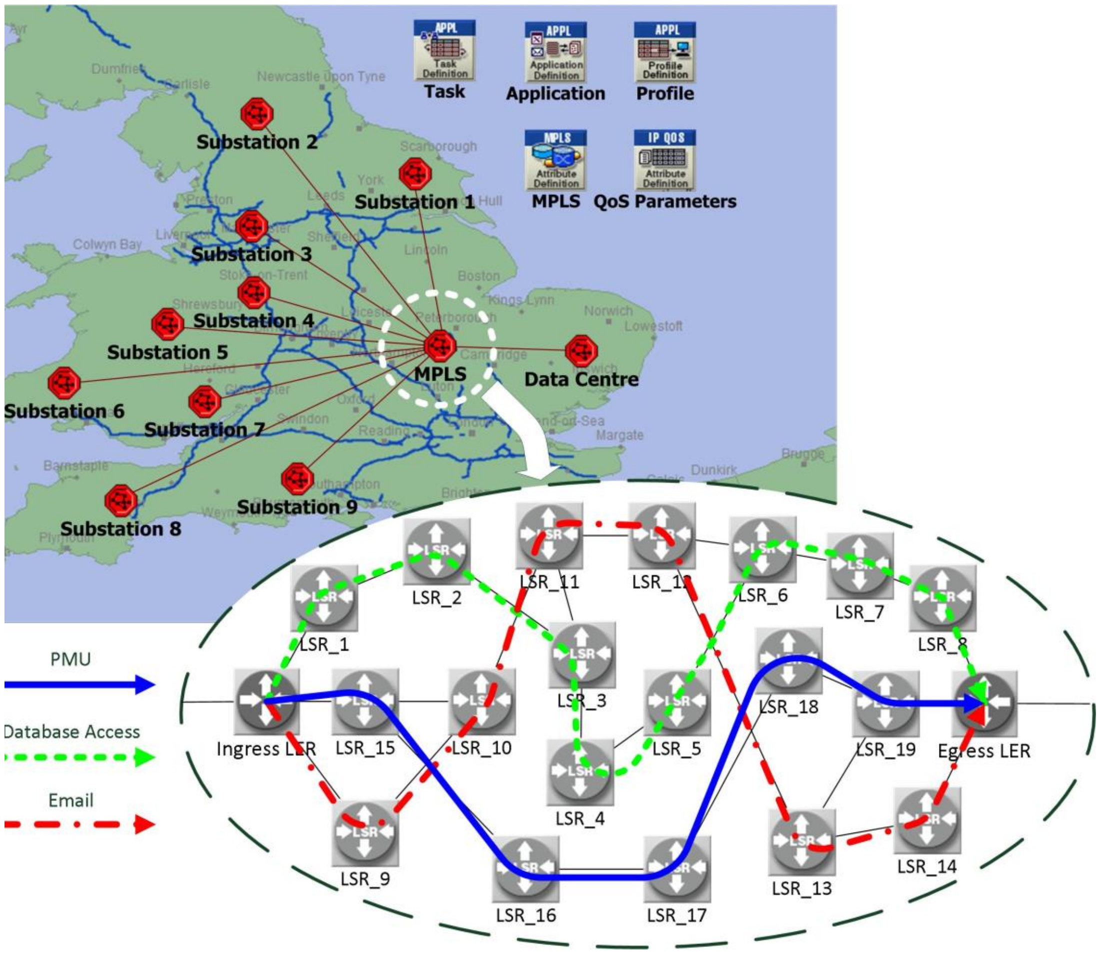


Figure 48 The architecture of MPLS subnet

Three LSPs were configured as shown in Figure 48 in green, red and blue colours. MPLS attributes, which are used to configure network-wide MPLS parameters, are grouped in the MPLS Config object. FEC specifications attribute can be used to specify the FEC parameters employed by MPLS. In this model, three types of FECs have been defined for PMU, Database Access and Email packets. Routers' MPLS attributes are grouped in the MPLS Parameters attribute on each router. Using this attribute of LERs, TE bindings between FECs and LSPs can be determined. In our simulation, the blue LSP, which is the shortest path, has been assigned for PMU packets. In addition, Database Access and Email packets are transmitted through the green and red LSPs, respectively.

5.4.3 Simulation Results and Analysis

After the completion of network configuration, the statistics to be collected can be specified in OPNET [23]. The main concern of this research is to evaluate the effect of using MPLS technology on delay characteristics of the communications network from the PMUs to PDC. Therefore, to have better comparison between different scenarios, only the communications network delay has been considered in the results, without internal delay of PMUs. Figure 49 illustrates the latency results for the generated packets of PMU in Substation 5 in three different scenarios. In the first scenario, PMUs packets are transmitted over a conventional IP network based on TCP protocol. In the second and third scenarios, the MPLS feature has been added and PMUs packets are transmitted based on TCP and UDP protocols, respectively. Furthermore, for better presentation of results and in order to have better insight into comparison of the three scenarios, Figure 50 shows the three-dimensional (3D) plot for the PMU 1 in Substation 9. The additional dimension, in which graphs can be separated, mitigates the problem of over-plotting. As can be seen from the graphs, the MPLS/UDP scenario shows better performance, especially in preventing dramatic increase of delay.

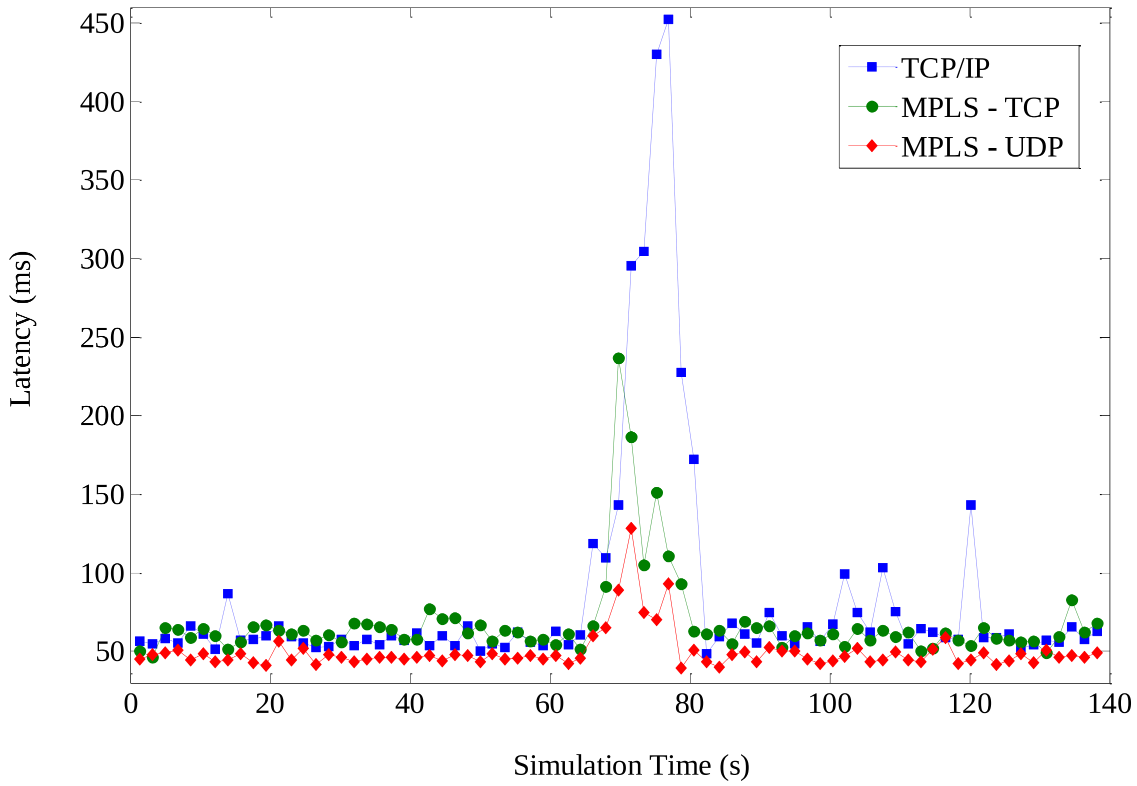


Figure 49 Latency of PMU packets in Substation 5 for the three scenarios

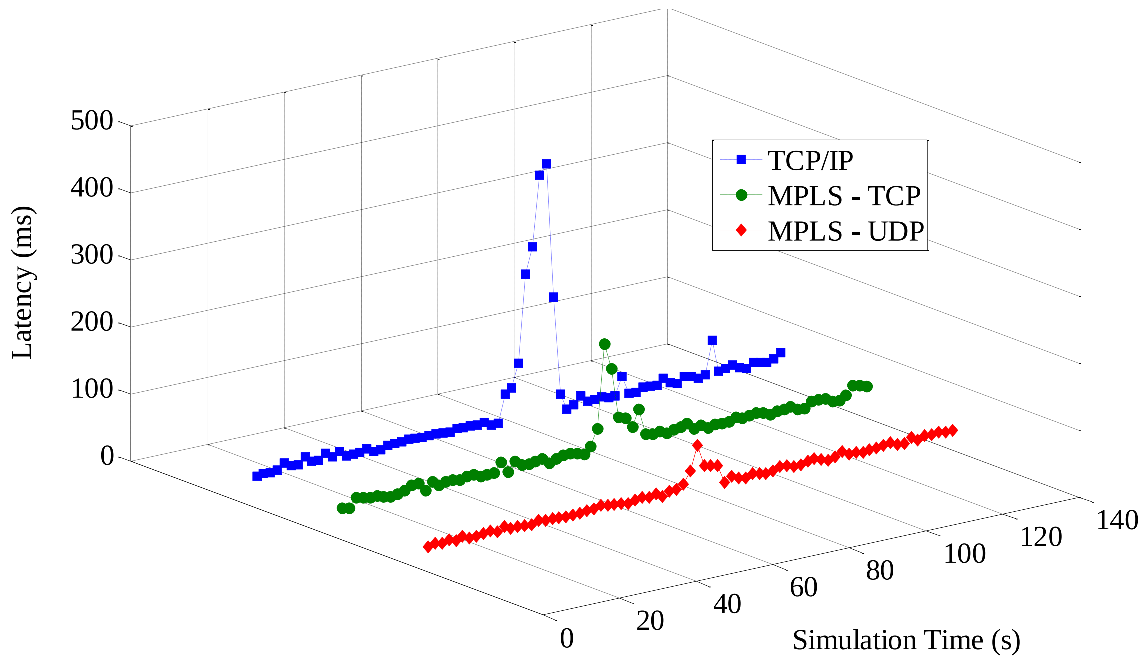


Figure 50 Latency of PMU 1 packets in Substation 9 for the three scenarios

Furthermore, after exporting the EtE delay results from OPNET Modeler, the required delay characteristics for four of the PMUs have been presented for each scenario in a separate table. Table 13 shows the latency characteristics of the conventional TCP/IP scenario. In addition, Table 14 and Table 15 show the results for the two MPLS-enabled scenarios using TCP and UDP protocol, respectively. These characteristics are minimum, maximum, average, and standard deviation of the packets delays. It should be noted that Substation 9 has two PMUs, and the results for one of them has been presented as they show similar behaviour. For the conventional IP scenario, all routers in the MPLS subnet are MPLS disabled, and the packets are routed using OSPF protocol without TE. However, simulations are based on the common topology. All the defined applications in the IP scenario use the shortest path to forward traffic, and this causes congestion on the links forming this path. The traffic exceeds the capacity of the shortest path, while there are under-utilised longer paths available. Therefore, as can be seen from the IP scenario results, PMUs packets may experience much greater delay than their expected average delay. For example, the PMU in Substation 1 has average EtE delay of 83.18 ms; however, according to Table 13 and for the considered simulation time period, it experienced the maximum delay of 616.84 ms. For the MPLS scenario, the MPLS features of the network are enabled, which allows results to be

Table 13 Latency characteristics for conventional TCP/IP scenario (millisecond)

Substation	Minimum	Maximum	Average	Deviation
1	47.11	616.84	83.18	85.04
5	40.67	452.05	82.58	73.98
7	40.46	419.60	67.96	68.46
9-PMU 1	30.98	414.20	66.91	68.76

Table 14 Latency characteristics for MPLS-enabled scenario using TCP (millisecond)

Substation	Minimum	Maximum	Average	Deviation
1	46.42	216.76	68.78	30.84
5	46.09	237.01	67.19	27.90
7	38.28	204.14	55.00	23.13
9-PMU 1	34.74	202.05	53.99	23.14

Table 15 Latency characteristics for MPLS-enabled scenario using UDP (millisecond)

Substation	Minimum	Maximum	Average	Deviation
1	40.66	158.58	52.36	15.03
5	39.23	128.11	49.59	12.63
7	33.90	99.35	39.82	9.09
9-PMU 1	30.90	96.74	37.10	9.14

obtained for MPLS TE simulation. Database Access traffic is routed to the green LSP and Email traffic is routed to the red LSP. Hence, these traffic types avoid the bottleneck of the shortest path, and the network can offer better service to the WAMS time-critical application. Finally, as can be seen from the results, WAMS communication over UDP through MPLS has shown the lowest EtE delay among the three scenarios.

5.5 Simulation Model using OMNeT++

The open source DES tool OMNeT++ [21] has also been used to simulate the considered WAN. The INET framework, an open-source communication network simulation package for the OMNeT++, contains the common node models and protocols [127]. However, a number of modifications have been made to simulate the WAN that will be discussed in this section.

Using NED Editor in OMNeT++, the communication network's topology is created. To simulate the considered WAN, the StandardHost node model in INET framework has been used for workstations. In order to model the two types of PMUs, the internal delays of them have been added by modifying the StandardHost node model. Furthermore, the required communication links according to their data rates have been defined. Using these workstations and communication links, different compound modules to represent different substations and data centre have been designed. By connecting these compound modules, the entire network can be created as shown in Figure 51. For IP cloud, the InternetCloud node model in INET framework has been

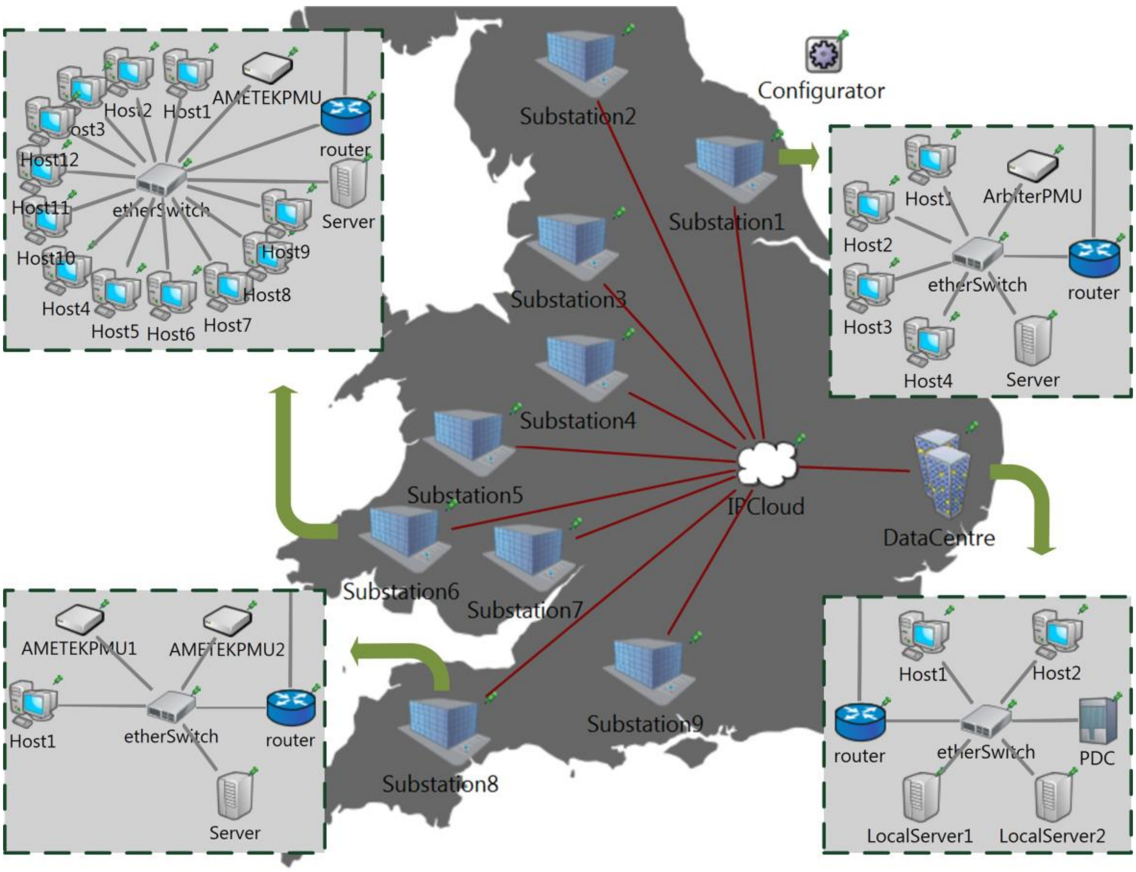


Figure 51 The GB WAMS simulated network in OMNeT++

used. It has been configured based on the specified parameters in 5.2.3.1 for OPNET and by writing a separate XML file.

In OMNeT++, introducing communications network traffic for each workstation takes place in .ini files that also carry configuration options for the simulator. In this section, it is assumed that PMUs are communicating with PDC over UDP/IP protocol. Therefore, from the application sources available in INET framework, the UDPBasicApp has been used to configure the two types of PMUs traffic. In order to have the EtE delay of each PMU separately in the simulation result, the PMUs have been configured to send their data to the different ports of the PDC node. On the other hand, the UDPSink application has been defined for PDC to handle and discard the transmitted PMUs packets, as well as calculating the EtE delays.

Apart from the PMUs, for other workstations inside the substations and data centre, traffic similar to OPNET model has been specified using TCPBasicClientApp. After assigning traffic and configuration options for a simulation in the .ini file, the simulation can be run. Simulation results are saved in the results folder of the project. The OMNeT++ Analysis Tool enables users to select, process, and plot the results. It will save the analysis into a .anf file in the parent folder. Table 16 shows the latency characteristics obtained from the OMNeT++ results. It shows a similar behaviour with OPNET results, especially in the case of average values. However, there are some differences that can be due to the model components library and the way that communication links background traffic has been introduced in OMNeT++, by reducing data rates of the communication links. As can be seen from the results, although

Table 16 Latency characteristics for UDP/IP scenario using OMNeT++ (millisecond)

Substation	PMU	Minimum	Maximum	Average	OPNET Comparison	Deviation	OPNET Comparison
1	1	128.04	303.09	156.3	-4	30.5	+4.16
4	1	62.72	234.27	99.4	+4.02	34.5	+7.02
5	1	62.46	240.8	96.3	+0.48	36.9	+11.72
7	1	60.65	258.6	83.83	+1.09	24.2	+15.34
8	1	64.20	136.65	76.52	-4.24	18.1	+8.67
	2	68.8	140.8	81.25	+0.47	18.1	+8.64
9	1	64.14	136.3	77.44	-2.75	18.59	+9.26
	2	68.9	141.3	82.15	+0.77	18.57	+9.35

OMNeT++ does not provide models' library as specific as OPNET, the results are acceptable.

5.6 Concluding Remarks

The main concern of this chapter is the delay characteristics from the PMUs to PDC, due to their critical role in providing satisfactory performance levels in real-time WAMS applications. This chapter demonstrated a novel framework of the WAMS modelling and analysis tools. An actual WAMS for the GB transmission system has been simulated using both proprietary and open source DES tools, OPNET and OMNeT++. The calculated delay of PMU packets, using Wireshark and MATLAB, verified the obtained simulation results. In this research, the internal delays of PMUs were taken into consideration and it was shown that they can introduce considerable delay and have significant impact on the performance of WAMS applications. In the existing GB WAMS, the packets generated by PMUs are transmitted based on TCP/IP protocol to the PDC server. However, other communication protocols, mechanisms, and topologies have been investigated for future developments. In this chapter, the obtained results were presented in different scenarios. The analysis showed improvement on PMUs data transmission when using UDP transport protocol as compared to when employing TCP. The effect of the QoS mechanism on WAMS network delay was also evaluated. It was demonstrated that how QoS policy can be used to ensure the excessive delay does not occur for the PMU packets. Moreover, the WAMS as installed on the GB transmission system was used to illustrate the benefits of employing MPLS TE to enhance the real-time communication of PMUs. Performance of WAMS communications infrastructure was evaluated and compared with regard to conventional IP and MPLS networks. MPLS-enabled communications infrastructure utilises the network resources efficiently compared to IP network and provides better performance.

Chapter 6

Conclusions and Further Research

6.1 Conclusions

This final chapter provides a summary of the work presented in this thesis and highlights the main achievements and contributions.

As discussed in Chapter 1, the benefits of reducing carbon emissions and the need to reduce reliance on fossil fuels have caused a higher penetration of renewable and variable sources in power generation. Furthermore, the real-time operation of power systems is largely dependent on the type and amount of generation as well as the nature of the loads. In such a condition with high penetrations of renewables, power systems face more challenging network-wide issues with regard to ensuring secure and reliable operation. The changes expected to occur in the energy industry in the next 20 to 30 years will have a much faster pace than the changes of the previous decades. In the case of the UK, wind energy plays a key part of decarbonisation. The installed capacity of wind generation and HVDC interconnectors connected at the transmission level may exceed the minimum demand in a few years. As a result, during periods of low demand and high non-synchronous generation, the challenges are likely to be intensified. If one part of a power grid becomes significantly out of synchronism with the rest, the whole network can become unstable, and blackout may occur. The concept of collecting real-time measurements extensively throughout transmission networks provides the possibility to operate and manage such systems more efficiently and securely [7].

Driven by the growing smart grid applications, ICT infrastructures are becoming more important for the communication of monitoring, control and protection information at both the local and wide area levels. The excess delay in the communications network is a challenging factor that affects the data transmission and could make the applications at best inefficient and at worse ineffective. The main area of investigation reported in this thesis is the performance evaluation of communication infrastructures in the smart grid. This evaluation began from inside substations based on the IEC 61850 standard. IEC 61850 is a standard released by the IEC for power utilities that can provide integrated and interoperable data communications. It defines communication between IEDs in substations and related system requirements. Chapter 2 presented the relevant background information on IEC 61850 alongside the other common open standards for ICTs in the scope of the smart grid.

In the IEC 61850 standard, protection and control functions of substations can be represented with LNs. This is one of the outstanding advantages of the standard over legacy protocols [45, 69]. In addition, the dominant architectural construct that IEC 61850 adopts is the abstracting technique. This feature provides the definition of objects that are independent of any underlying communication protocols. In fact, the abstract model can be mapped to any protocol stacks that can meet the data and service requirements. Therefore, the system will be compatible with future developments in the field of communication technologies. IEC 61850 provides five types of communication services. Among them, this thesis focused on SV and GOOSE messages as they are more suitable for time-critical applications. These two services are directly mapped to the Ethernet Link Layer and eliminate the layers in between [53].

An important component when providing monitoring and control for transmission networks is the SCADA system, which connects the substations to the control centre by polling data from RTUs. However, due to data rate limitations, this monitoring is relatively static and therefore not suitable for real-time applications. Moreover, because of the extension of the power networks, suitable devices are required to enable synchronization between the remote instruments. The state-of-the-art synchronised phasor measurement technique offers a complementary way to monitor the power systems. Wide area monitoring is one of the vital requirements in developing the smart grid concept in power systems. In this regard, PMUs are considered to be the key component of WAMS [35]. They can improve monitoring by providing precise synchronised measurements in near real-time, with high rates and high accuracy. In Chapter 3, the WAMS deployment on the GB system was described, both at transmission system and laboratory levels. Moreover, future aims and challenges for the development of WAMS were discussed. Efficiently storing, processing and analysing a huge volume of PMU measurements are the crucial challenges in developing such a system. In this regard, frameworks such as Hadoop can provide a scalable fault-tolerant distributed system for data storage and processing. Hadoop splits data into chunks and distributes them across the nodes in clusters and enables parallel processing.

Brunel University has deployed PMUs as well as commercial and open source PDCs to visualise, process and archive measured grid data at a lower voltage level, locally in the laboratory. In this thesis, an investigation on openPDC features has been performed, and samples of events captured using this laboratory-based deployment of PMUs have been presented. OpenPDC was released to provide open source PDC, and its modular design enables processing of time-series measurement data in a protocol independent manner. Its Input, Action and Output Layers deal with measurement acquisition, measurement processing and measurement forwarding, respectively.

PMUs offer state-of-the-art technology for improving wide area monitoring, control and protection. However, a high-speed and appropriate communication infrastructure is the key to transfer phasor measurement data to the remote control centres and make time-critical wide area measurement applications feasible. WAMS applications inherently depend on the underlying ICT infrastructures. A low latency communications infrastructure is required for transmitting time-critical PMU data across a geographically-dispersed network. Even if all phasors are successfully delivered to the PDC, the time delay associated with each phasor measurement causes the derived system state to be different from the actual system state by that time. In addition, for WAMS applications such as control and protection, the delay must be sufficiently low to act in a timely manner. Therefore, along with the continual deployment of PMUs in Great Britain's transmission system substations, a high-performance communications infrastructure is becoming essential with regard to the establishment of reliable WAMS.

Chapter 4 described an example of a SAS and presented simulations of a typical substation communications architecture based on IEC 61850 using OMNeT++. Two scenarios were considered for the simulation based on the LAN link data rates. The second scenario, which had higher LAN data rates, showed a great improvement from the latency perspective. Overall, it could be observed that IEC 61850 based on Ethernet provided acceptable performance for substation communications. In addition, the integration of IEC 61850 standard for PMU communications was simulated within the scope of substations and investigated for transmission over wide areas. According to the obtained simulation results, the Ethernet-based IEC 61850 could reduce the average delays of PMU packets by 27% compared to the conventional UDP/IP protocol within the substation.

It is necessary to fully investigate the EtE delay in WAMS, and the research presented in Chapter 5 concerns this issue. In that chapter, the existing WAMS as installed on the GB transmission system has been considered for novel modelling and analysis.

First, the actual PMU packets as received at the Psymetrix PDC server were captured using Wireshark. The obtained information provided real insight into the WAMS communications traffic and PMU packets and enabled the determination of EtE delays. A novel algorithmic procedure was implemented in MATLAB to automate the large-scale PMU packet latency calculations. This algorithmic procedure could save time, reduce error and enabled to perform more detailed and larger scale analyses. Furthermore, investigations were carried out to accurately estimate the internal delay of the two types of PMUs according to their configuration settings, operation manuals, and information provided from the manufacturers. The Arbiter PMU installed in Substation 1 was configured in a way to provide more accurate measurements, whereas AMETEK PMUs installed in other substations configured to provide measurements quickly. The obtained internal delay for each PMU type was considered in the simulated model of PMUs for DES.

Numerous DES tools are available for the analysis of the performance and behaviour of communication networks. In this thesis, both proprietary and open source DES tools have been used to evaluate the performance of ICT infrastructure in the existing WAMS installed on the transmission system of GB. Based on the obtained results, a PMU itself may not require high channel capacity, and the bottleneck for WAMS communication is the overall network latency. Low latency is essential for control and protection applications with short response time requirements. The latency measured and modelled for the existing communication infrastructure of GB WAMS is approximately 10 times higher than that required for power system protection. Therefore, when exploiting PMUs for protection schemes, a higher-speed communications infrastructure is necessary. It has been seen that in some cases, PMU packets experienced much higher latency than their expected average. It should be noted that jitter or variation in delay will cause a variation in action time of any applications that use the PMU data. In fact, data concentration will be delayed by jitter because PDC must wait for all PMU data with the same time-stamp to arrive before assembling a complete packet and forwarding it to the relevant smart grid applications. As long as the jitter is considerably lower than the data rate interval of PMUs, it should not have much effect on the application [138]. Accordingly, it is also recommended that all PMUs in the WAMS experience roughly the same level of delay because a PMU with high latency can have an undesirable influence on the whole WAMS delay.

The delays of PMU packets, calculated using Wireshark and MATLAB, verified the obtained simulation results. Therefore, the novel WAMS model can be confidently used for analysing possible future developments as well as testing the newly proposed mechanisms, protocols, etc., in order to improve the performance. To analyse the possible future developments, the number of PMUs in each substation and the number of substations equipped with PMUs have been increased to investigate the performance of the WAN communication infrastructure. The provided results showed the level of degradation of latency against increasing the number of PMUs and the point at which the communication network becomes unstable.

Furthermore, PMU communications from geographically distributed substations to PDC has been investigated over different Transport Protocols. In the existing GB WAMS, the generated PMU packets are transmitted based on the TCP/IP protocol to the PDC server. TCP rearranges data packets in the specified order and retransmits lost or corrupted data. Although TCP provides a reliable communication, it is unsuitable for real-time communications because the acknowledgment/retransmission feature leads to excessive delays [25, 152]. Therefore, the other Transport Layer protocol in the IP suite, UDP, was investigated for PMU communications in the simulation model. In the case of UDP, there is no built-in ordering and recovery of data, but the simulation results showed lower latency than the currently employed TCP protocol. For time-sensitive PMU applications such as control and protection a small amount of lost data is preferable over delayed data; thus, it is recommended to use UDP protocol. However, if the PMU data are used for monitoring and off-line analysis, the TCP protocol can guarantee the delivery of all generated PMU packets. In another scenario, the Quality of

Service (QoS) policy was also used with UDP protocol to further reduce the possibility of excessive delay occurrence for the PMU packets in the considered shared network.

The conventional IP routing has a number of drawbacks. It does not consider the capacity constraints and traffic characteristics when routing decisions are made. Hence, some links in a network can become congested while other under-utilised links exist. Furthermore, IP networks are not scalable, and TE is difficult to implement. TE is the process of controlling how traffic flows through the network to make the best use of resources and optimise the network performance. Moreover, IP routing takes place in the Network Layer, which is slower than the switching. Overall, with these limitations, it is very challenging to implement a real-time application such as WAMS in the conventional IP network. In order to overcome these limitations, Internet Engineering Task Force (IETF) has introduced Multi-Protocol Label Switching (MPLS) technology. The performance of the real-time WAMS communications infrastructure when MPLS capability is added to a conventional IP network was also evaluated in this thesis. The obtained simulation results showed that the MPLS-enabled communications infrastructure utilises the network resources efficiently compared to the conventional IP network and provides better EtE performance [152].

Using standards developed for time critical applications, such as IEC 61850, in wide area communication can provide a higher level of interoperability for power systems. However, with regard to delay, it should be noted that GOOSE and SV services of the IEC 61850 protocol are not originally IP-based. As discussed in Appendix A, the Network Layer is mainly responsible for the routing of messages from node to node. Therefore, to transmit GOOSE and SV messages in a wide area, they need to be encapsulated in an IP-based packet. In this condition, we cannot expect a delay level as low as what the original GOOSE and SV were experiencing inside substation communications. Nevertheless, in the core of the network, the MPLS technology can be used to mitigate the additional delay. Because MPLS operates between layers 2 and 3, the routing process is much faster than conventional IP. In fact, it forms a layer 2.5 label switched network on the layer 2 switching functionality without the layer 3 (IP) routing.

6.2 Further Research

In this section, further research is proposed as a continuation of the research presented in this thesis. The issues that have been addressed within this thesis can be extended, demonstrated, and developed from different aspects.

- A laboratory-based Substation Automation System (SAS) based on the IEC 61850 standard should be designed and implemented. The design can be based on the available IEDs in Brunel University. Figure 52 shows a proposed design for this SAS. Both the SEL 487E transformer protection relay [156] and SEL 351S protection system [157] IEDs support IEC 61850 communication standard. The SEL 487 operates as a bay controller to perform transformer protection, bus breaker control, bus protection, etc. The two SEL 351S provide feeder protection, feeder breaker control, etc. The test injection set, OMICRON-CMC 256 [158], can be used to generate a fault condition such as overcurrent. The laboratory-based SAS provides a platform for better understanding of the evolving IEC 61850 protocol and contributes to the research regarding the deployment of this protocol in different

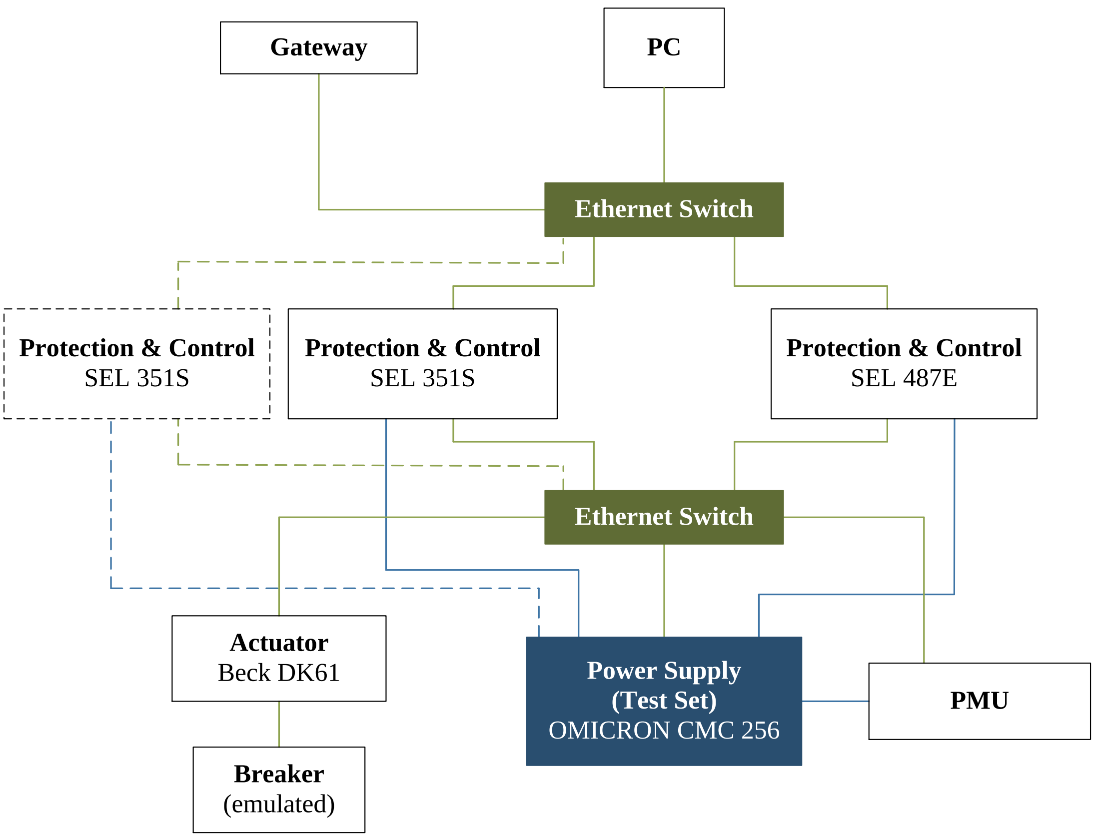


Figure 52 A proposed design for the laboratory-based SAS

levels of power automation. It can be also used for testing and validation of new IEDs and substation automation applications.

- The algorithmic procedure as implemented with Wireshark should be used to develop a toolkit for the online monitoring of WAMS communication networks in the future. It can also be used to indicate the latency characteristics at specified time intervals. For example, the maximum latency can be monitored, and when the calculated values exceed the predefined limits, an event can be triggered to inform the operator.
- Wide area controllers need measured signals in remote areas to be transmitted through communication networks. The communication networks introduce time delays to the control loops, which can reduce the controllers' performance. Therefore, in the design of such controllers, the delays must be considered and compensated. These delays are not constant and can vary from tens of milliseconds to several hundred milliseconds. The results provided in this thesis yield accurate delay values and can be used for the efficient design of wide area controllers for the GB system. In this way, controllers can actively compensate time delays in the wide area feedback signals [159-161].

Appendix A

Network Architecture and Protocol Layers

A communication network provides data transfer services between two or more endpoints to support their respective applications. In communications between nodes, the Application Layer and Physical Layer are always present. An Application Layer is necessary for meaningful communication and must be defined for executing a function. On the other hand, a medium is required as a Physical Layer to make the transfer of bits of data possible. However, in order to have a reliable and efficient communication network, more layers can be added between these two layers to provide additional services [95].

In this case, each layer provides its services to the above layer by performing specific actions within the layer as well as using the services of the layer directly below it. The network protocols are organised in these layers, and each protocol belongs to one of the layers [162]. A protocol is basically a set of rules specified for orderly communication through a network [163]. It should be noted that a layer N protocol is distributed among the end systems, and if required, among packet switches and other components that build up the whole network [162]. These layers determine how data should flow from one end to another over a communication network. The devices can communicate only when each of their corresponding layers conforms to each other [163].

In fact, each protocol in layers defines two types of interface. First, there is a service interface to the objects on the same device for using services. Second, there is a peer interface to its counterpart on another device, which defines the form and meaning of exchanged messages between protocol peers for communication. Apart from the Physical Layer that peers can directly communicate with each other through a communication link, peer-to-peer communication is performed indirectly. The protocol messages are transmitted to their corresponding peers through lower layers. The message transmitted from the application through layers is not an interpreted string of bytes for the layers. Layers do not need to know the information in the message. They just need to provide the message to their peers alongside the additional control information to help peer layers communicate with each other and deal with the message. The additional control information for each layer is attached as a small data block to the original message and used for implementing the lower layers' communication services. Headers are generally attached at the beginning of the message. However, there are cases in which the control information is placed at the end of the original message, which is called trailer. The format of the header or trailer depends on the applied protocol specification. On the other hand, when the transmitted data arrive at the destination host, they will pass up the layers up to the Application Layer, and each peer layer will remove its corresponding header. Finally, the destination host application will receive the exact message sent by the source host application without any headers [164].

The protocols of the different layers altogether are called the protocol stack. The protocol stack for communication network interconnection can have any combination of layers between the Application and Physical Layers [95]. In addition, many different protocols that satisfy the requirements for application communications can be utilised. There are standardization bodies, such as the International Standards Organization (ISO) and Internet Engineering Task Force (IETF) [165] that proposed specific network architectures. Open Systems Interconnection (OSI) and Internet are two of the most widely referenced architectures provided by ISO and IETF, respectively [164].

The International Standards Organisation (ISO) was one of the first organizations that defined a common way for communication process. It has divided the communication architecture into seven layers, which compose the so-called 7-layer model, also referred to as the OSI. The seven layers are: Application, Presentation, Session, Transport, Network, Data Link, and Physical Layers [164]. Figure 53 illustrates the concept of protocol layers and the OSI 7-layer reference model. Each layer performs specific functions and operates independently of the other layers. However, the successful operation of one layer depends on the successful operation of previous layer. The

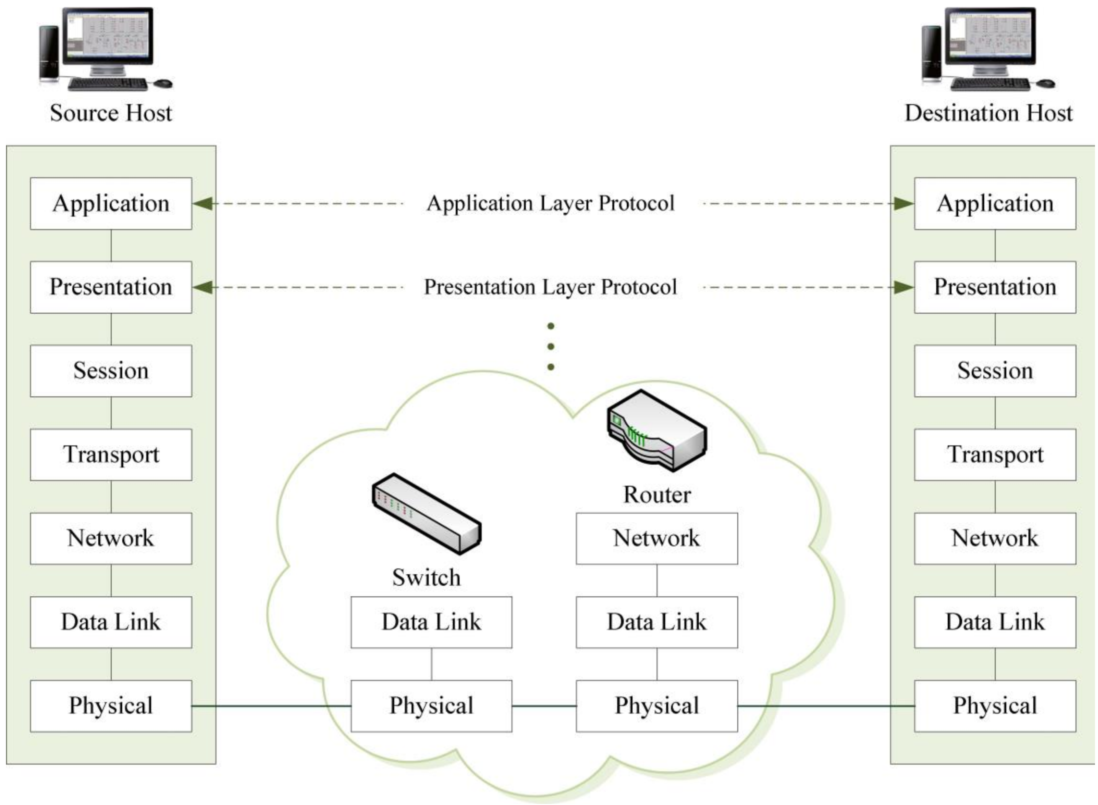


Figure 53 OSI reference model protocol layers

assigned functionality to a given layer is implemented by one or more protocols [163, 164]. The OSI reference model is only a framework for network architecture and protocol specifications. Networking standards and communication processes do not necessarily need to follow the specifications defined in the OSI model. In fact, in many practical communication networks, including the smart grid communication applications, not all seven layers are used in the proposed standards [95].

The Internet Protocol stack was developed independently of the OSI reference model and consists of five layers: the Application, Transport, Network, Data Link, and Physical Layers. The functionalities of these layers are similar to their corresponding OSI counterparts. The Internet lacks the Presentation and Session Layers available in the OSI reference model. In fact, the application developer should decide whether a specific service is required and build that functionality into the application [162].

A brief summary of the seven layers on the OSI reference model is as follows [37, 162, 164, 166]:

- The Application Layer is the topmost layer. It consists of the network applications and end-user processes and is responsible for giving them access to the network. The Application Layer has a higher variety of services that are commonly needed by users compared to the lower layers.

- The role of the Presentation Layer is to provide services that allow communicating applications to interpret the meaning of data exchanged. Unlike the lower layers, which are mostly concerned with transmitting bits, the Presentation Layer is concerned with presenting information in a manner suitable for the applications and users.

- The Session Layer allows users on different devices to establish sessions between them. It establishes, manages and terminates connections between applications. It is responsible for synchronizing and sequencing the packets in a network connection as well as ensuring that appropriate security measures are taken during a session.

- The Transport Layer transports Application Layer messages between application endpoints. It is responsible for providing data transfer at a specified level of quality, such as transmission speeds and error rates. The Transport Layer has a key role as it is located between the upper layers (which are mainly application-dependant) and the lower layers, which are network-based.

- The Network Layer is mainly responsible for the routing of messages. It provides routing technologies and creates logical paths (known as virtual circuits) for transmitting data from node to node. Routes can be based on static tables or can be highly dynamic to consider the current network load.

- To move a packet from one node to the next node in the route, the Network Layer relies on the services of the Link Layer. The Data Link Layer generates packets based on the network architecture being used. The network adaptors and drivers running in the operating system of devices typically implement the data link level.

- The Physical Layer is the lowest layer. It is concerned with transmitting raw bits over a communications link. It converts the contents of the packets into a series of electrical signals that represent 0 and 1 values in a digital transmission. The protocols in this layer depend on the actual transmission medium of the link.

It is also possible that a layer in a protocol stack provides services to more than one entity at the above layer. For example, the Network Layer at a device can use different Link Layers to communicate with other devices [95].

The layered architecture is an effective way to organise complex communication network architectures. It has conceptual and structural advantages. Layering breaks the communication networks down into more manageable components and makes the implementation changes easier for the services provided by layers. As long as a layer provides the same services to the layer above and uses the same services from the layer below, the layer implementation can be revised without affecting the whole communication system. If a new service is required, only the functionality at one layer needs to be modified, and the functions provided at all the other layers can be used without any changes. For large and complex systems such as communication networks that are constantly being updated, this ability is vital and is an important advantage of layering [162].

Apart from the advantages, protocol layering may have a few drawbacks. One of them is the possible duplication of lower-layer functionality (for example, error recovery on both a per-link basis and an end-to-end basis). Another one is that functionality at a layer may require information (for example, a timestamp value) from a different layer, which violates the purpose of the separation of layers [162].

Appendix B

Further Latency Evaluation

In this appendix, more detailed results obtained from the latency evaluation of the WAMS as installed on the GB transmission system are provided.

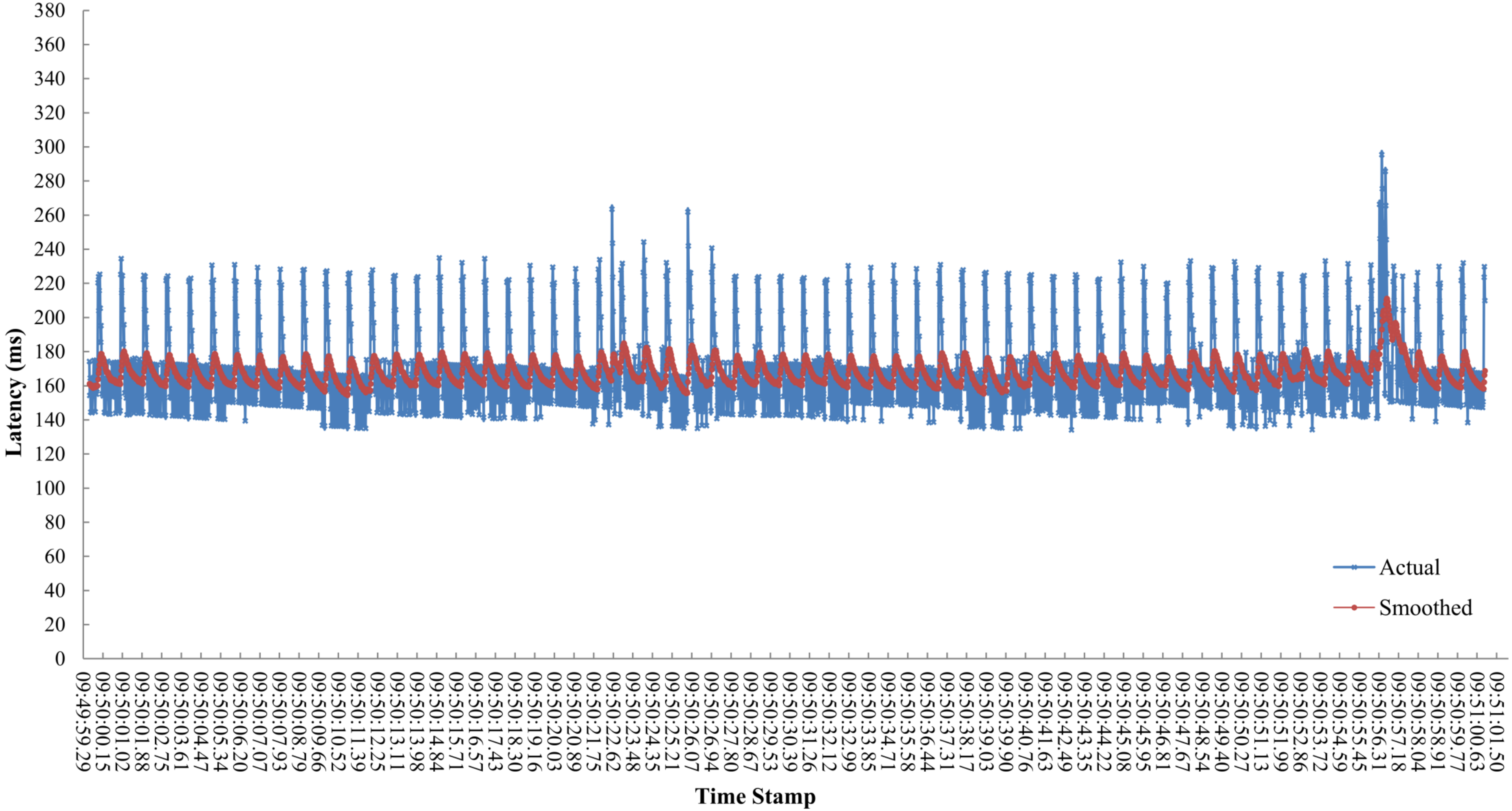


Figure 54 Latency of PMU1 for 13.03.2012 9:49:59 – 9:51:01 AM

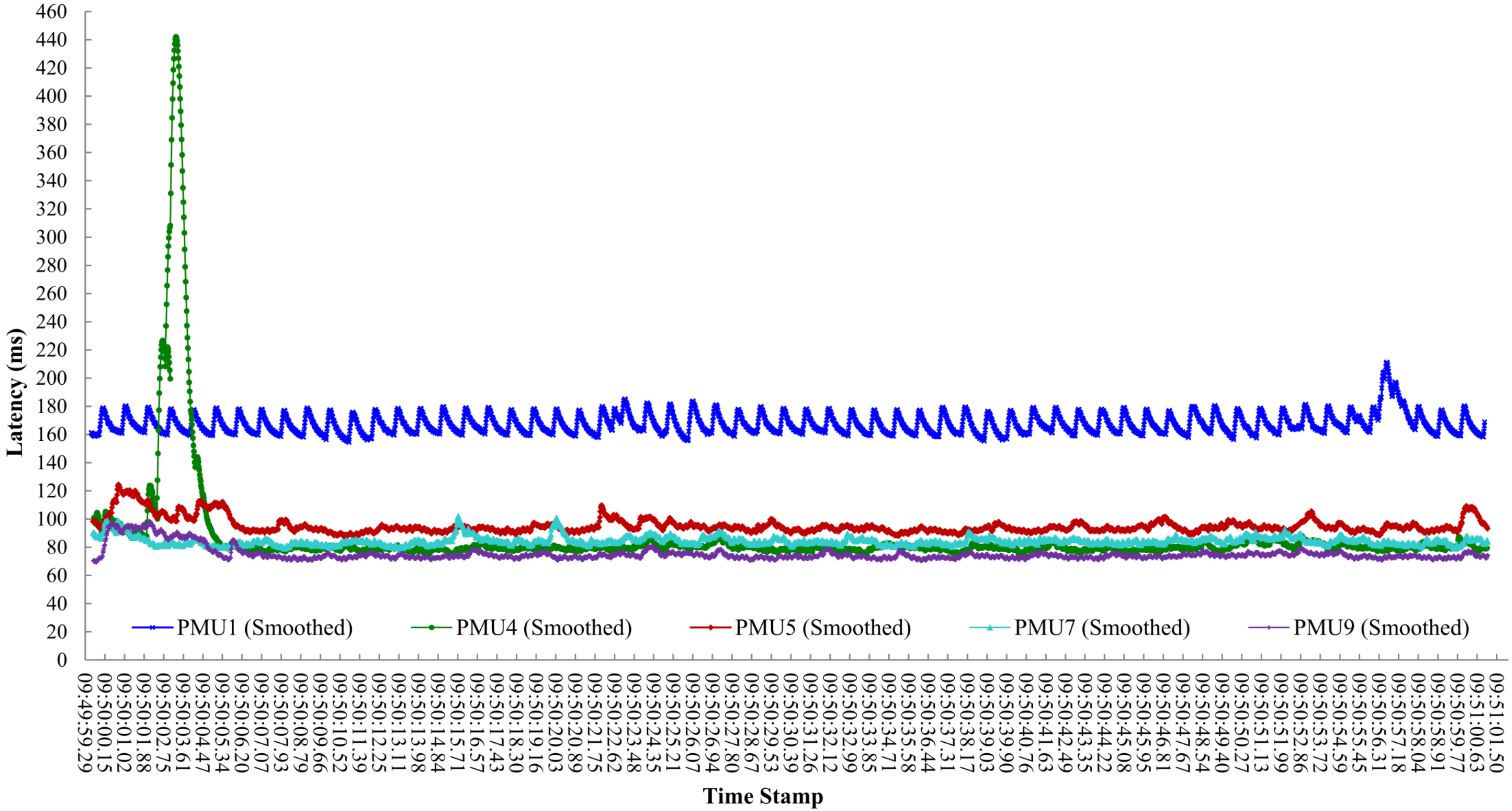


Figure 55 Latency of PMUs for 13.03.2012 9:49:59 – 9:51:01 AM

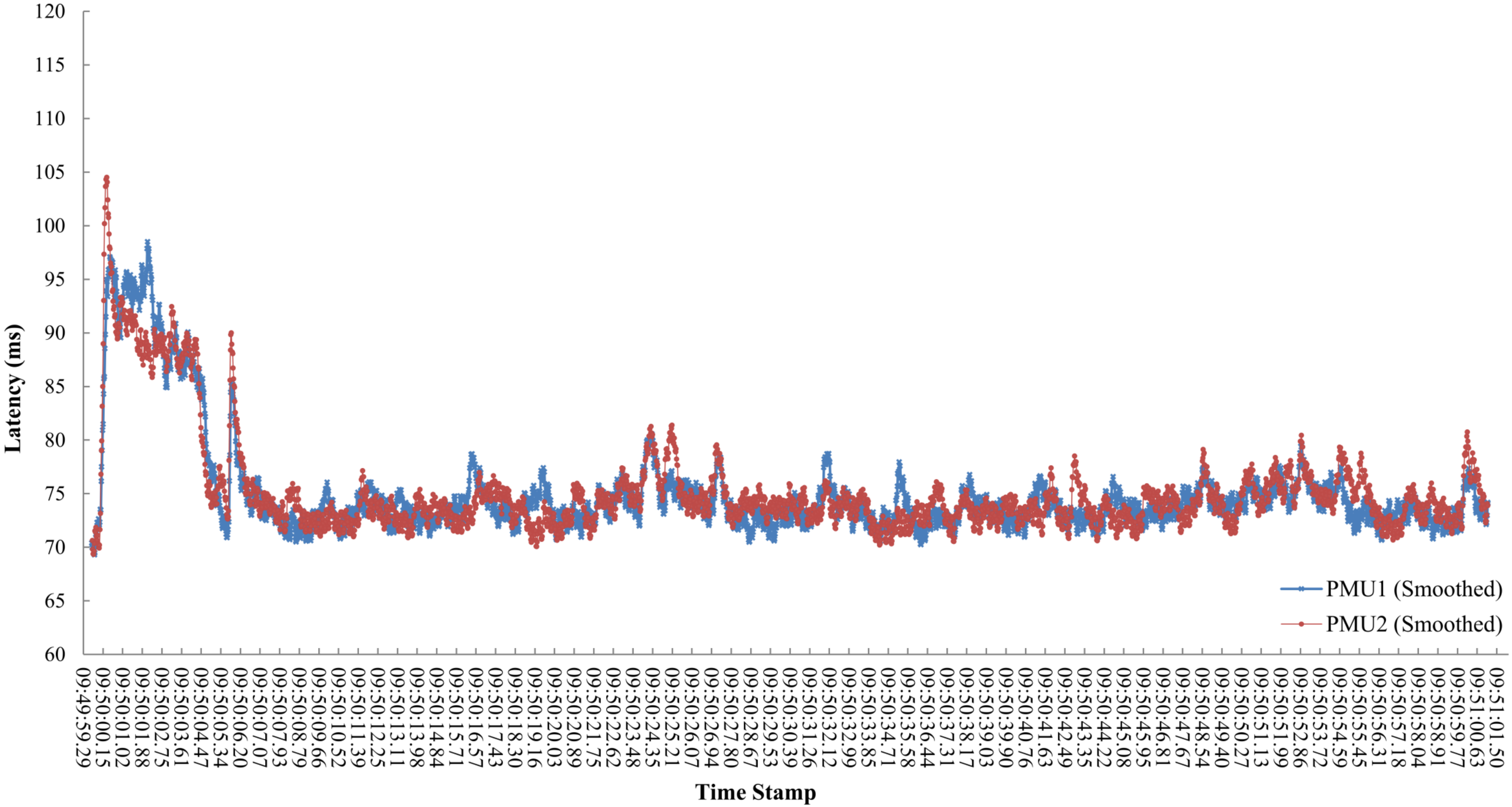


Figure 56 Latency of PMUs in Sub9 for 13.03.2012 9:49:59 – 9:51:01 AM

Table 17 Actual latency characteristics of PMUs for 13.03.2012 9:49:59 – 9:51:01 AM (millisecond)

Substation	Link Bandwidth	PMU	Min	Max	Range	Average	STDEV
1	256 kbps	PMU1	134.067	295.406	161.33	167.52	28.86
4	256 kbps	PMU1	58.218	687.6	629.382	86.88	47.41
5	256 kbps	PMU1	70.599	201.509	130.91	95.026	13.72
7	2 Mbps	PMU1	65.21	170.843	105.633	84.607	10.952
8	256 kbps	PMU1	53.955	151.624	97.669	72.29	10.972
		PMU2	53.78	214.483	160.69	73.64	13.52
9	256 kbps	PMU1	55.758	139.33	83.571	75.05	11.06
		PMU2	55.253	164.922	109.669	75.22	11.221

Table 18 Smoothed latency characteristics of PMUs for 13.03.2012 9:49:59 – 9:51:01 AM (millisecond)

Substation	Link Bandwidth	PMU	Min	Max	Range	Average	STDEV
1	256 kbps	PMU1	154.344	211.12	56.77	167.48	7.25
4	256 kbps	PMU1	74.7596	442.115	367.35	86.99	37.77
5	256 kbps	PMU1	87.41	124.42	37.011	95.052	5.55
7	2 Mbps	PMU1	79.09	102.17	23.07	84.63	3.13
8	256 kbps	PMU1	67.183	99.39	32.21	72.31	5.205
		PMU2	66.72	123.66	56.94	73.61	7.62
9	256 kbps	PMU1	69.28	98.48	29.20	75.03	4.86
		PMU2	69.340	104.52	35.183	75.20	4.695

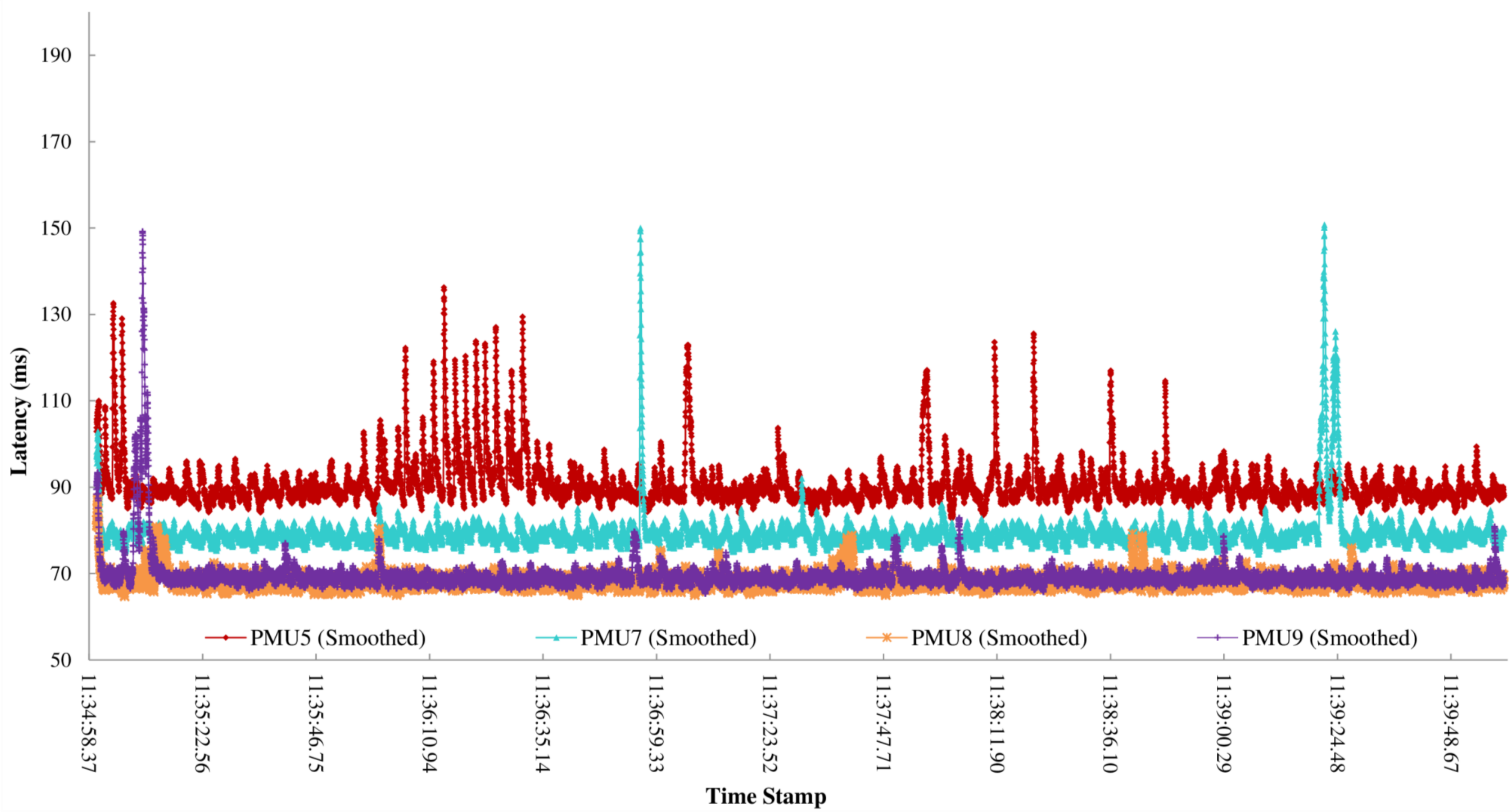


Figure 57 Latency of PMUs for 23.07.2012 11:35:00 – 11:40:00 AM

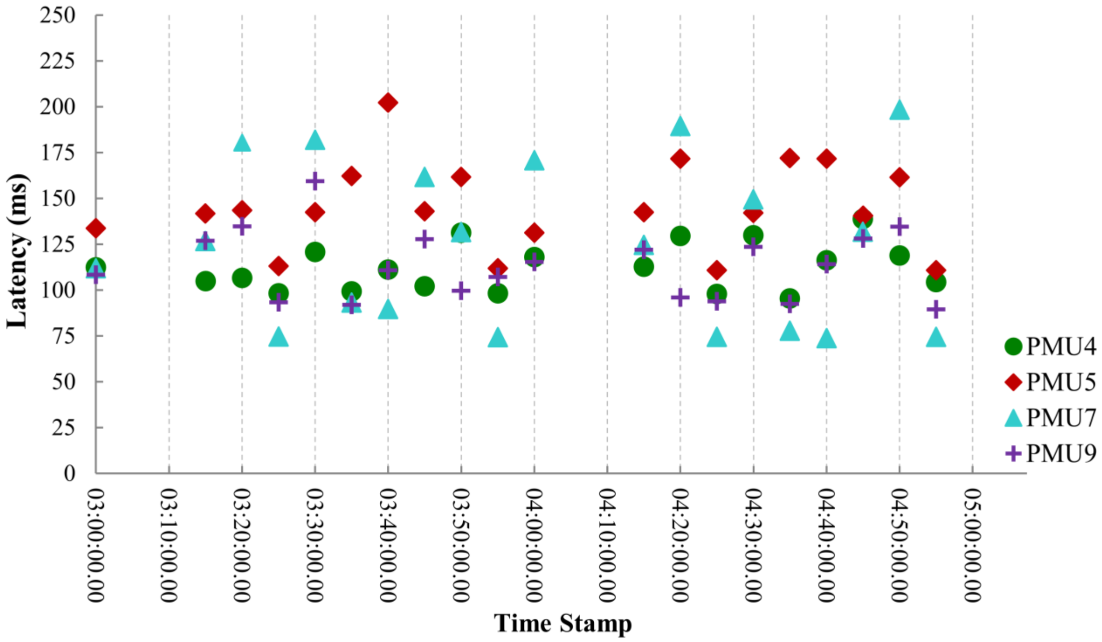


Figure 58 Maximum latency of PMUs for 2.11.2012 3:00:00 – 5:00:00 AM

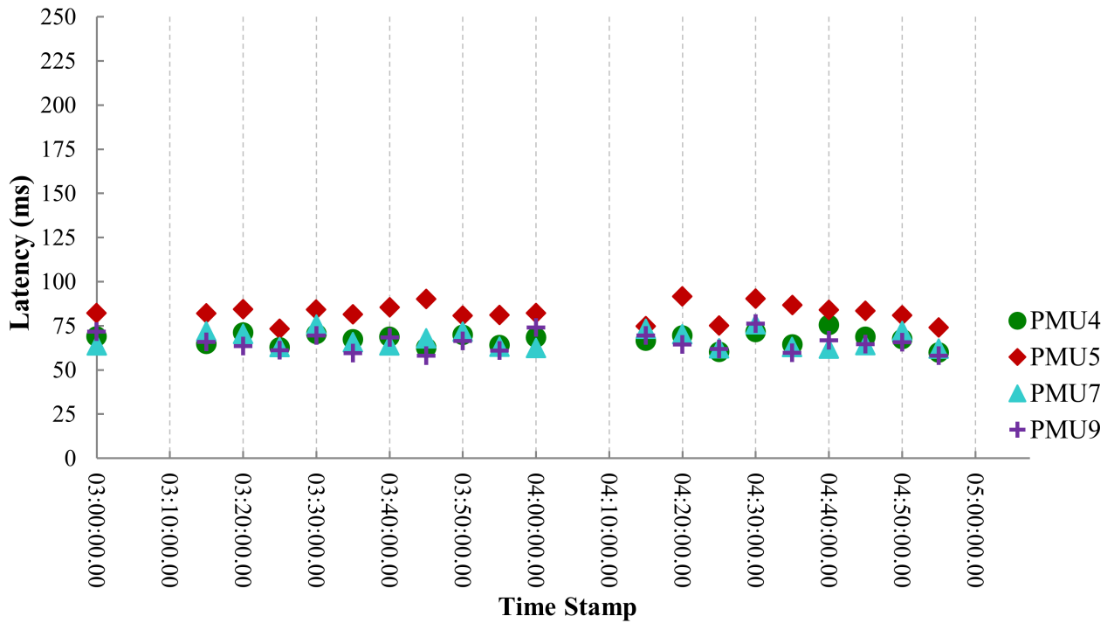


Figure 59 Minimum latency of PMUs for 2.11.2012 3:00:00 – 5:00:00 AM

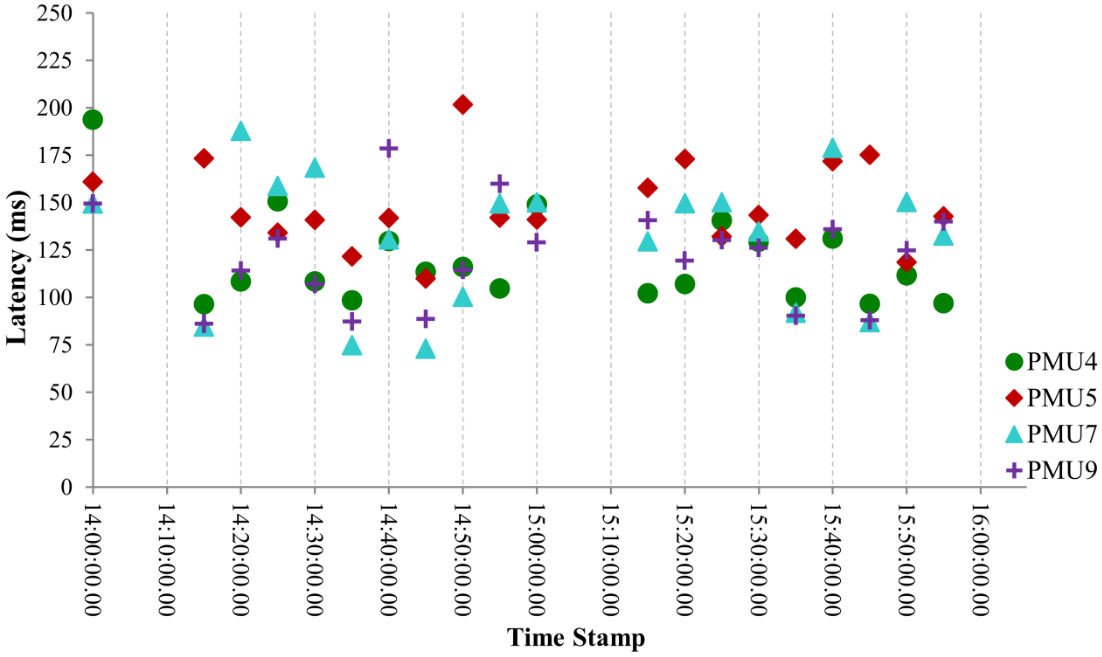


Figure 60 Maximum latency of PMUs for 2.11.2012 14:00:00 – 16:00:00 PM

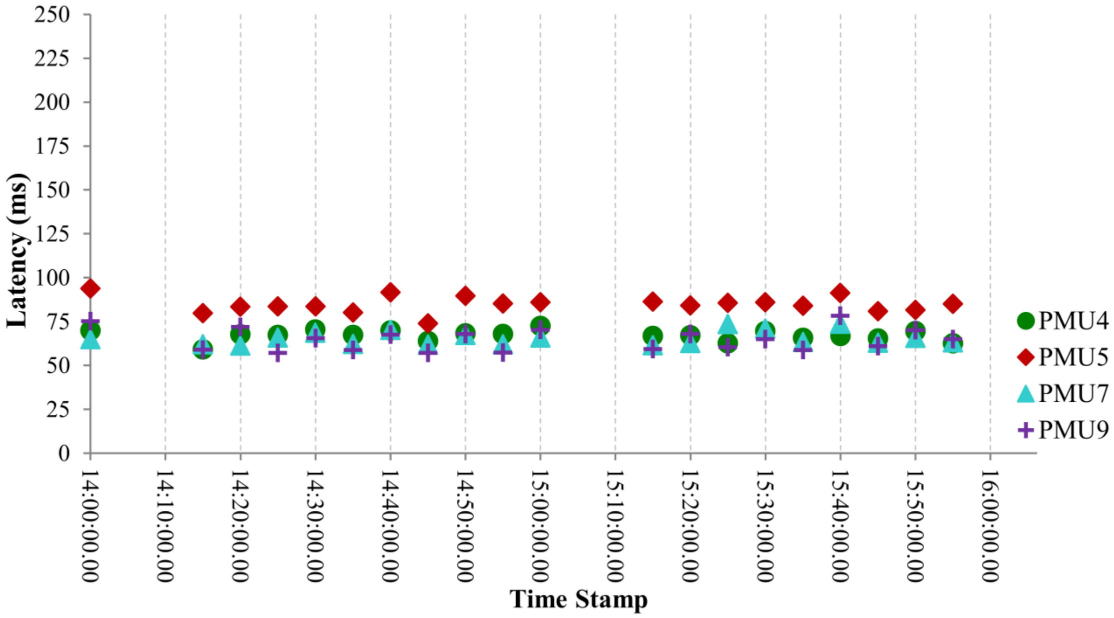


Figure 61 Minimum latency of PMUs for 2.11.2012 14:00:00 – 16:00:00 PM

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