Communication Network Design and Evaluation for WAMPAC in Smart Grid

by

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Declaration

This Thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

To

Dad, Mum,

My Wife

And

New Born Baby

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Finally, and always, I would like to thank my beloved wife Lou Yi. Without her love, dedication and sacrifice, all of this would never have become a reality. My research is also my gift for my new born baby; I wish her life full of love and happy dreams.

Abstract

A Wide Area Measurement, Protection and Control (WAMPAC) strategy offers great potential for the upgrade of the supervision, operation, protection and control of modern power systems. Forwarding high volume measurements as well as time-critical protection and control signals across a national area power infrastructure poses a major challenge. A flexible, reliable communication platform is the key to enabling these enhanced functionalities. Thus the research focuses on the issues of communication network topology and Quality of Service (QoS) control that enable the range of fully functional WAMPAC applications, ensuring that their requirements in terms of delay and throughput are satisfied. In the goal of designing a flexible and reliable platform, the appropriate network topology is designed and analysed laying the foundation for the investigation of the optimum placements of Phasor Measurement Units (PMUs) and the characterisation of network performance. Clustering algorithms are applied to determine the locations of the distributed network of PMUs based on the designed network topology not compromising the power infrastructure requirements. The assignments of traffic flows according to the IEEE C37.118 standard and proposed advanced WAMPAC applications are analysed through simulation for the existing United Kingdom power system. Performance of the system is verified in terms of link capacities, network topologies and QoS, and results prove the proposed solution guarantees the network performance required to support the spectrum of WAMPAC applications.

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List of Abbreviation

ACSI	Abstract Communication Service Interface
ADS	Adaptive Dependability and Security
ADSS	All-Dielectric Self Supporting
AF	Assured Forwarding
AGC	Automatic Generation Control
AHP	Analytic Hierarchy Process
ALF	Adaptive Loss of Field
AOS	Adaptive Out of Step
API	Application Program Interface
ARP	Address Resolution Protocol
ASBMON	Ancillary Service Business Monitoring
ASDU	Application Service Data Unit
B-A Model	Barabasi and Albert Model
BER	Bit Error Rate
BETTA	British Electricity Transmission and Trading Arrangement
BMS	Business Management System
BOI	Bus Observability Index
BPSK	Binary Phase Shift Keying
CBWFQ	Class-Based Weighted Fair Queuing
CCC	Central Control Centre
CCGT	Combined Cycle Gas Turbine

CIM	Common Information Model
CLO	Control of Large Oscillation
COIO	Control of Inter-area Oscillation
COMTRADE	Common Format for Transient Data Exchange
CT	Current Transformer
CVT	Constant Voltage Transformer
DCC	Distributed Control Centre
DER	Distributed Energy Resource
DFR	Digital Fault Recording
DFT	Discrete Fourier Transform
Diffserv	Differentiated Services
DMS	Distribution Management System
DNP	Distributed Automation Product
DSCP	Differentiated Services Code Point
EF	Expedited Forwarding
EIRP	Equivalent Isotropic Radiated Power
EM	Expectation-Maximization
EMS	Energy Management System
ETE Delay	End-to-End Delay
FACTS	Flexible Alternating Current Transmission System
FATE	Frequency and Time Error system
FEC	Forward Error Control
FFT	Fast Fourier Transform
FIFO	First-in-First-Out

FR	Frame Relay
FREQ	Frequency
GA	Genetic Algorithm
GBSO	Great Britain's System Operator
GOOSE	Generic Object Oriented Substation Event
GPS	Global Positioning System
GSSE	Generic Substation State Event
ICCP	Inter-Control Center Protocol
IED	Intelligent Electronic Device
IER	Ingress Edge Router
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
II	Intelligent Islanding
ILP	Integer Linear Programming
ILS	Intelligent Load Shedding
Intserv	Integrated Services
IP	Internet Protocol
ISO	Independent System Operator
ITC	Instrument Transformer Calibration
LAN	Local Area Network
LDP	Label Distribution Protocol
LEO	Low-Earth Orbiting
LLQ	Low Latency Queuing
LN	Logic Node

LoM	Length of Medium
LOS	Line-of-sight
LSP	Label-Switched Path
MAAI	Monitoring Approach of Apparent Impedance
MAC	Medium Access Control
MAP	Maximum a Posteriori
MILP	Mixed-integer Linear Programming
MMS	Manufacturing Message Specification
MPLS	Multiprotocol Label Switching
NETSO	National Electricity Transmission System Operator
NGET	National Grid Electricity Transmission
NLOS	Non-Line-of-sight
NoR	Number of Routers
OMS	Operational Metering System
OPGW	Optical Power Ground Wire
OSI	Open Systems Interconnection
PAN	Personal Area Network
PDC	Phasor Data Concentrator
PDF	Possibility Density Function
PDH	Plesiochronous Digital Hierarchy
PE	Parameter Estimation
PHB	Per-Hop Behaviour
PLC	Power Line Carrier
PMU	Phasor Measurement Unit

PQ	Priority Queuing
PSS	Power System Stabilizer
PSTN	Public Switch Telephone Network
QoS	Quality-of-Service
RAS	Remedial Action Scheme
RMS	Root Mean Square
ROCF	Rate-of-Change Frequency
RSVP-TE	Resource Reservation Protocol- Traffic Engineering
RTU	Remote Terminal Units
SA	Simulated Annealing
SBUZ	Supervision of Back-up Zone
SCADA	Supervisory Control and Data Acquisition
SCL	Substation Configuration Language
SDH	Synchronous Digital Hierarchy
SE	State Estimation
SNR	Signal to Noise Ratio
SONET	Synchronous Optical Networking
SONI	System Operator for Northern Ireland
SPT	ScottishPower Transmission
SSE	Seams between State Estimates
SV	Sampled Value
TO	Transmission Owner
TSO	Transmission System Operator
TVE	Total Vector Error

UTC	Universal Time Coordinator
VPN	Virtual Private Network
WAMPAC	Wide Area Monitoring, Protection and Control
WAMS	Wide Area Monitoring System
WASA	Wide Area Situation Awareness
WDM	Wavelength Division Multiplexing
WFQ	Weighted Fair Queuing
WiMAX	Worldwide Interoperability for Microwave Access
WLS	Weighted Least Square
W-S Model	Watts and Strogatz Model

Chapter 1

Introduction

1.1 Overview

A significant trend in today's power system is to integrate higher levels of intelligent automation with advanced telecommunication highways [1], especially evident within the power transmission system, where the configurations of parameters and the diagnosis of system operation will no longer wholly depend on the experience of the system operators. Real-time information will be collected from individual power links and devices and the system will be analysed from a global perspective so as to capture a complete awareness of its status [2].

As a consequence, the necessity for the deployment of reliable and flexible power supervision and control systems is a rapidly growing demand. Conventional monitoring and control technologies, predominately based on Supervisory Control and Data Acquisition (SCADA) [3] systems within a centralized control strategy, routinely requesting status information (normally just the amplitude of voltage and current) from Intelligent Electronic Devices (IEDs) at a slow updating rate (approximately 2-5 seconds), are not sufficient to manage the growing requirements of a highly flexible power system. After the invention of the Global Positioning System (GPS) [4] and many years of development of advanced power system technologies, time-stamped data (include phasor, frequency and rate of change of frequency.) are being retrieved from Phasor Measurement Units (PMUs) [5] at a rate close to the system frequency. These enhanced features not only eliminate the erroneous assumption that the power system remains static during the time of data collection, but also enables many advanced power protection and control functions to be implemented that improve the robustness and reliability of the system. Thus, a PMU-based Wide Area Measurement Protection and Control (WAMPAC) strategy becomes possible [5], the key to improving the robustness and flexibility in the transmission system.

The main objective of the research is to develop a roadmap to designing scalable and flexible end-to-end network solutions to support a range of fully-functional WAMPAC applications. An appropriately designed and implemented communication infrastructure is the enabler for intelligent monitoring and control functions within the modern power system [6]; thus, the research work explores the communication requirements for various WAMPAC applications.

A survey on the potential WAMPAC applications is undertaken at the outset of the work to capture the requirements of the supporting communication platform, categorized into time-critical or non-time-critical events. The placements of PMUs at locations throughout the basic power network are proposed for the existing power system topology in the United Kingdom [7]. In order to implement a flexible, robust WAMPAC framework, the problem is decomposed into four major sub-tasks: design of network topology; assignment of traffic flows; sizing of the line capacity; and the application of advanced traffic control algorithms. Several control-based network topologies are introduced in which all phasor information is exchanged and processed based on the requirements of WAMPAC. Appropriate clustering techniques are explored to construct sub-networks, solving the provision of network control more efficiently. Furthermore, traffic flow classifications are implemented to enable differentiated control of services, important since the information sources within WAMPAC are geographically scattered over a wide area and latency cannot be avoided in the communication paths. Hence, in order to optimize performance, advanced control strategies are applied to achieve high network utilisation whilst guaranteeing the required performance of a mix of highly demanding applications. In this Thesis, these scenarios are analysed through simulation using OPNET software [8] to assess the optimal solution for the communication architecture that meets the WAMPAC demands for future power systems. The analysed scenarios of PMU placements and network performance analysis are for the existing power system in the United Kingdom.

Chapter 2 provides the background research underpinning the understanding of the subsequent research. It starts with identification of the weaknesses in the existing power system coupled with a mapping of the monitoring/control technologies currently in use. The definition and model of 'Smart Grid' are also presented. The standards prevailing within modern power systems [9] are recognised as important to guide any evolution of the power system. Potential communication technologies, viewed as a key enabler for future smart grid operation are introduced; the advantages and disadvantages of different communication media are analysed. Finally, candidates for supervisory and control technologies are studied. SCADA and WAMPAC system, two of the most relevant schemes for monitoring and control purposes, are discussed at the end of the Chapter.

Chapter 3 starts by introducing the WAMPAC structure comprising PMUs, Phasor

Data Concentrators (PDCs) and the interconnecting communication interfaces, followed by the standards implemented to regulate the operation of the mix of applications. Potential power applications enabled through WAMPAC and the corresponding communication needs of each application are summarized in terms of throughput and latency.

Chapter 4 focuses on the placements of PMUs, the fundamental information sources in WAMPAC. The overall goal of PMU placement is to identify optimal locations that maximize the benefit across multiple applications, as well as offering the lowest-cost solution. Integer Linear Programming (ILP) [10] has been verified to be one of the most efficient algorithms to determine the optimum locations of PMUs. The ILP is used to calculate the placements of PMUs within the IEEE standard model [11] and the UK existing power network topology in order to gain full system observability.

Chapter 5 analyses the characteristics of a WAMPAC network topology. Similarities and differences in generic network and power system models are discussed in terms of network degree distribution, average path length and individual clustering coefficient, to understand the nature of the data source and of the resultant traffic generated. In order to provide network control, control strategies are proposed include centralized, decentralized and hybrid based network models [12]. Clustering algorithms are applied to find the optimal size of each sub-network. Finally, clustering analysis is applied based on WAMPAC for the United Kingdom power system.

Chapter 6 assigns traffic flows to the proposed WAMPAC application network. Control-based data flows with preferred source and destination are analysed.

Advanced Quality of Service control strategies, such as DiffServe [13] and IntServe [13] and Traffic scheduling algorithms [14] e.g. Priority Queuing (PQ) and Weighted Fair Queuing (WFQ), are proposed to achieve optimal system performance. The comparative performances of a number of candidate scenarios are analysed through simulation using the existing power system topology in United Kingdom as the basis. Chapter 7 concludes by summarizing the contributions, highlighting important results followed by suggestions for future work.

1.2 Contributions

Communication is one of the major elements underpinning the deployment of Smart Grid concept [1]. The motivation of the work is to design and characterise a flexible and scalable end-to-end communication platform able to meet the stringent requirements of a range of WAMPAC applications. The challenges encountered during the research include incomplete WAMPAC standards; the gap between the understanding of application requirements in power systems and communication network aspects; existing research either focuses on power applications, or present unrealistic communication network solutions in isolation from the needs of the power system. Therefore, a comprehensive roadmap for the analysis and design of an integrated system is developed throughout the work. Requirements from both the power system and communication network are taken into consideration in the solution.

The contributions are threefold;

- Implementation of Integer Linear Programming (ILP) to determine optimum

PMU placements across the existing UK power system (Chapter 4). Due to the high cost of installation, achieving full system observability with the minimum number of PMUs is a major challenge. The practical UK power infrastructures are investigated as the basis to find out the optimum placements of PMUs. The unique Observability Maximization algorithm is also implemented to figure out the best candidates. Compatibility is another key issue and existing deployments of optic fibres are taken into consideration.

- WAMPAC-inspired network topology design is presented and analysed (Chapter 5) and traffic flows are assigned to the proposed model (Chapter 6). Comparisons have been made with network architectures in IEEE standard models, and the resulting properties are used as key indicators that inform a robust and scalable network design. Clustering Algorithms are first to be considered in the design of a decentralized based WAMPAC control system. Both aspects, i.e. power system operation and communication performance, are considered to establish zonal control of the system.
- Through the analysis of the performance of full-functional WAMPAC applications, the queuing delay is identified as the critical contribution to the total delay of the network. Modifications to the network topology and implementing QoS lead to improved performance, meeting the requirements of all WAMPAC applications. Results obtained serve as design guidelines when deploying a WAMPAC system.

The performances of a full-functional WAMPAC system coupled with different network topologies and communication QoS control mechanisms are verified through the OPNET [4] simulator for the existing power system topology in United Kingdom as the basis.

1.3 Publications

2 D. Cao, A. Dyśko, C. Michie, I. Andonovic, “Communication Network Topology Design in Wide Area Monitoring, Protection and Control System in UK”, in preparation, to be submitted to IEEE Transactions on Smart Grid.

3 D. Cao, A. Dyśko, C. Michie, I. Andonovic, “Modelling Communication QoS Control Strategies in Wide Area Monitoring, Protection and Control System”, under review with IEEE Transactions on Smart Grid.

1 D. Cao, A. Dysko, C. Michie, I. Andonovic, "Flexible Network Design for Wide Area Measurement Protection and Control", the 2012 International Workshop on Smart Grid Security and Communications, Jeju, Korea, Nov. 22-25, 2012.

2 D. Cao, I. Andonovic, "Research on Backbone Communication Network in Smart Grid by using OPNET", IEEE International Conference on Smart Measurements for Future Grids, Bologna, Italy, November 14-16, 2011.

3 D. CAO, T. Wu, H. G. Goh, B. Stephen, K. H. Kwong, C. Michie, I. Andonovic, "Exploitation of Wireless Telemetry for Livestock Condition Monitoring", The 17th World Congress of the International Commission of Agricultural Engineering (CIGR 2010), Quebec City, Canada June 13-17, 2010.

4 T. Wu, D. Cao, B. Stephen, H. G. Goh, K. H. Kwong, C. Shen, W. Du, C. Michie, I. Andonovic, "A Practical Data Reporting Solution for Free-ranging Cattle Monitoring Applications Using Wireless Sensor Networks", ASABE 2010 Annual International Meeting, Pittsburgh, Pennsylvania, United States, 20 - 23 June 2010.

5 D. Cao, H. G. Goh, K. H. Kwong, C. Michie, and I. Andonovic, "Positioning System for Wireless Sensor Networks with Location Fingerprinting", Progress In Electromagnetic Research Symposium (PIERS 2009), Beijing, China, 23-27 March 2009.

6 D. Cao, F. Y. Meng, H. G. Goh, K. H. Kwong, C. Michie, and I. Andonovic, "An Evaluation of Positioning System for Wireless Sensor Networks in an Indoor Environment", Proceedings of the 10th Annual Postgraduate Symposium on The Convergence of Telecommunications, Networking and Broadcasting (PGNET 2009), Liverpool, United Kingdom, 22-23 June 2009, pp.10-13.

7 K. H. Kwong, T. Wu, K. Sasloglou, B. Stephen, D. Cao, H. G. Goh, S. K. Goo, M. P. Gilroy, C. Tachtatzis, I. Glover, C. Michie, I. Andonovic, "Implementation of Herd Management System with Wireless Sensor Networks", Joint International Agricultural Conference (JIAC 2009), Wageningen, Netherlands, 6-8 July 2009.

Chapter 2

Background

2.1 Introduction

The Chapter provides the background and summarizes related, relevant research in Smart Grid technologies. The Chapter starts with a survey on the weaknesses of the existing power system, with focus on the causes of large blackouts [15-22]. A conceptual model of a Smart Grid is given in which different power system domains are identified. The roadmap of existing standards is introduced, core to any evolution of the current system to include smart grid functionalities. Potential communication technologies, regarded as a key enabling platform for future Smart Grids, are introduced. Finally, supervisory and control techniques in current use or with potential in future evolutions of the power system are considered.

2.2 The Smart Grid

2.2.1 Vulnerability of the Original Power System

Between 1984 and 2008, 700,000 customers have been affected by outages annually; relatively outages occur much more frequently and affect tens to hundreds of customers every few weeks, while larger outages occur at least one in every nine years and effect millions [15]. In order to achieve a better understanding of the vulnerability in the system, four major blackouts are highlighted:

A. Blackout of 30th July, 2012 in India

The 2012 India blackout was the largest power outage in history, affecting over 620 million people, equivalent to 9% of the world population [16]. An estimated 32 GW of generating capacity was taken offline in the outage. The outage was triggered on the tripping of the 400 kV Bina-Gwalior line. Since the line feeds the Agra-Bareilly transmission section, the station was also tripped, cascading power failures throughout the grid. All major power stations were shut down in the affected states, causing estimated massive shortage.

B. Blackout of 11th March, 1999 in Southern Brazil

The 1999 Southern Brazil blackout was a widespread power outage which involved seven large cities and affected an estimated 97 million people [17].

A chain reaction initiated on a lightning strike at an electricity substation in Bauru, causing most of the 440kV circuits at the substation to trip. With a restricted number of routes for the power to flow from the generating stations via the 440kV system, a significant number of generators automatically shut down due to an absence of load. The world's biggest power plant at the time, Itaipu, attempted to support the load that was no longer being supplied by the 440kV power plants; further the 750kV AC lines and the 600kV DC lines that connected the plant to the rest of the system could not take the load and tripped too. South of São Paulo the consumers experienced an over-frequency, whereas the rest of the system experienced a much bigger problem, an under-frequency, since the system supported a substantial load and insufficient generation capacity. Some generators tripped because of the over-frequency, which aggravated the problem, and even after an automatic rejection of 35% of the sub-system load the under-frequency scenario remained.

C. Blackout of 14th August, 2003 in North America

The US-Canadian blackout affected approximately 50 million people in eight US states and two Canadian provinces. Roughly 63 GW of load was interrupted, which equates to approximately 11% of the total load served through the Eastern Interconnection of the North American power system [18, 19]. A generation plant in Eastlake, Ohio went offline amid high electrical demand, placing a strain on high-voltage power lines. This trip caused load to transfer to other transmission lines, which were not able to bear the load, tripping their relays. Once these multiple trips occurred, multiple generators suddenly lost parts of their loads, so they accelerated out of phase with the grid at different rates, and tripped out to prevent damage. During this event, over 400 transmission line and 537 generating units at 251 power plants were tripped.

D. Blackout of 28th September, 2003 in Italy

The sequence of events leading to this blackout began with a tree flashover and tripped a major tie-line between Italy and Switzerland [20-22]. The connection was not re-established because the automatic breaker controls refused to re-close the line. As a result, the phase angle difference across the line was too large due to the high volume of power that was being imported into Italy, resulting in an overload on a parallel path. Since power was not redistributed quickly and adequately, this cascading trend continued. Within a few seconds, the power deficit in Italy was such that Italy started to lose synchronization with the rest of Europe.

These outages left the Italian system with a power shortage of 6400 MW, which was level imported prior to the loss of the interconnecting lines. As a consequence, the frequency in the Italian power system started to fall and over the course of several minutes, the entire system collapsed causing a national wide blackout.

The causes that led to these national wide blackouts include failing equipment, line trips, or operational malpractice. At the start of system failure, the impact of the fault is still confined to a relatively small area and the whole system can be stabilized if proper automatic control measures e.g. network reconfiguration [23], are taken by operators or the system itself within seconds to minutes time frame. However, if the system fails to react on fixable faults timely, cascaded outages caused by additional failing equipment or mis-operation will split the power system into uncontrollable islands. Unbalanced conditions between generation and load lead to voltage and frequency collapse yielding unavoidable large area blackouts (Fig. 2.1).

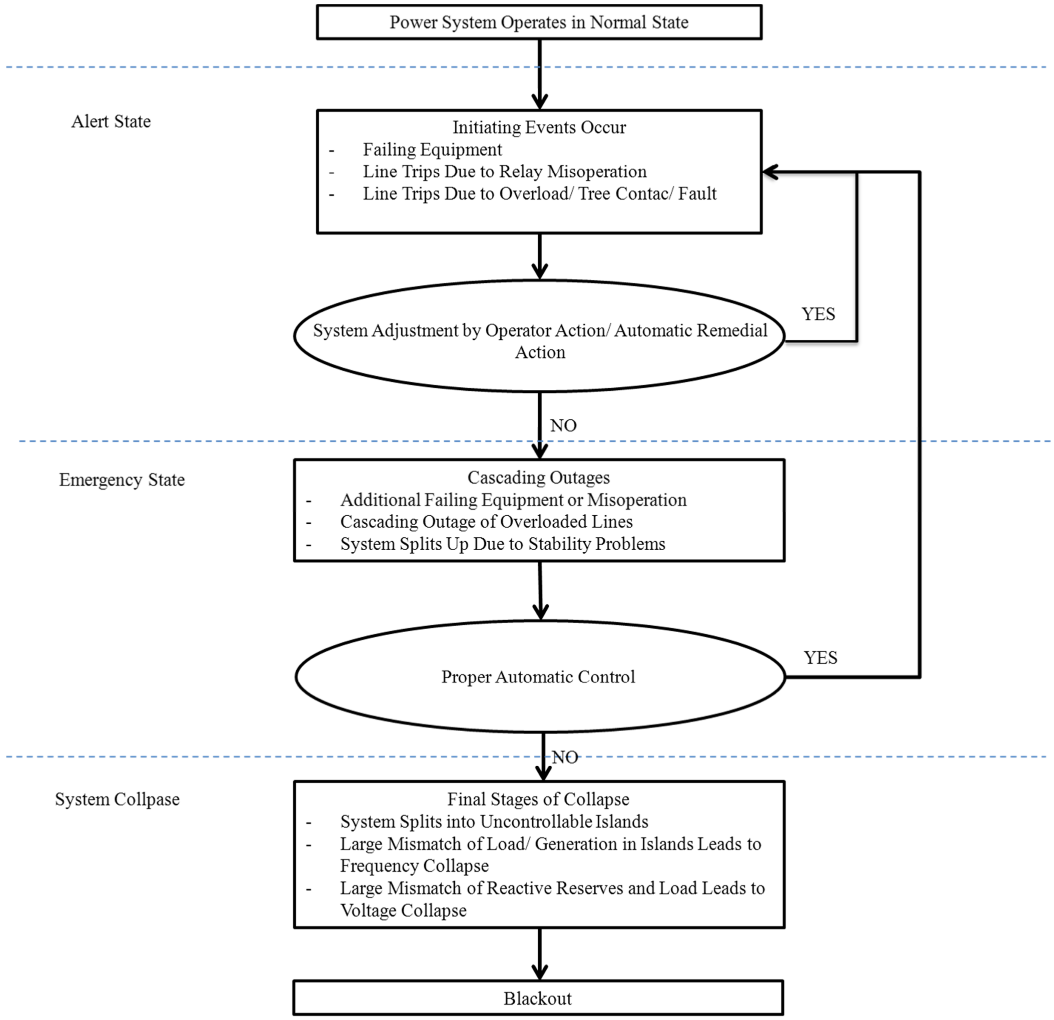


Figure 2.1 General sequences of events leading to a blackout. [24]

A large volume of research has shown that problems in real-time monitoring and operating control systems (37.04%), communications and information systems (32.10%), and delayed restoration (38.27%) contribute the highest percentage of the faults in the system [147]. Several reports [15-22] also analyse the causes of blackouts and make recommendations on possible corrective measures and control that would have prevented their onset:

- Better coordinated planning of outages of both state and regional networks, specifically under depleted condition within the inter-regional power transfer paths.

- Under-frequency and rate of change of frequency based load shedding relief in the utilities' networks.
- Dynamic security assessment and faster state estimation of the system at load dispatch centres for better visualization and planning of corrective actions.
- Measures to avoid mal-operation of protective relays, such as the operation of distance protection under load encroachment on outage days.
- Deployment of adequate synchrophasor based Wide Area Monitoring System and System Protection Scheme.

2.2.2 Advanced Smart Grid Systems

An automated, widely distributed energy delivery network is required to improve the performance of the existing power system. This goal promotes the concept of the "Smart Grid" which refers to the modernization of the electricity delivery system to include integrated monitoring, protection, automatically optimizing the operation of its interconnected elements from the central and distributed generation through to the high-voltage transmission network and the distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices [25].

The benefits of Smart Grid can be categorized into power reliability and power quality; safety and cyber security; energy efficiency; environmental and conservation;

and direct financial benefits.

In Figure 2.2, a conceptual model of the Smart Grid comprises markets, operations, service providers, bulk generation, transmission/distribution network and customers.

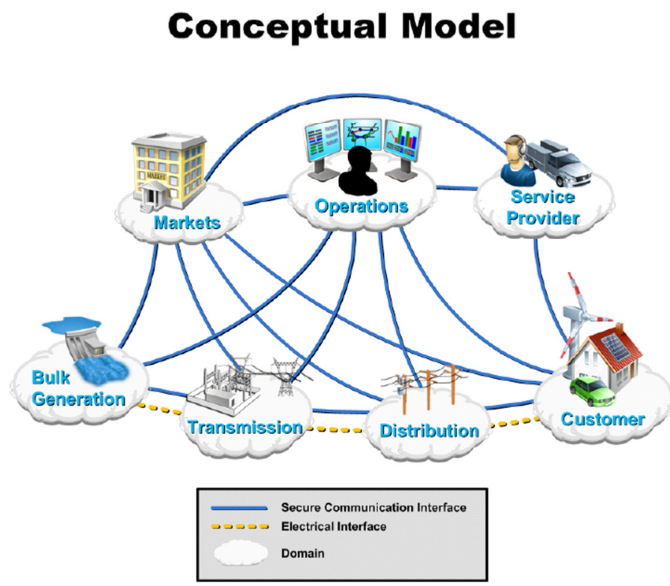


Figure 2.2 Smart grid conceptual model [25, 156].

There is no assurance of system reliability and efficiency if each domain in the Smart Grid operates independently, despite provisioning a superior range of applications. Co-operation through secure communication interfaces will enable embedding of intelligence through the system. Therefore, the Smart Grid requires a nation-wide flexible communication platform to interconnect all generators, transmissions paths, substations, controllers, consumers and the distribution segments of the network.

Communication technologies pertinent to the Smart Grid can be categorized through the following sub-systems:

- Data management [26]: to improve the calibration of recording instruments, especially in establishing time synchronization.
- Disturbance monitoring [18]: to facilitate improved insight into the causes of blackouts and to enable detailed post-mortem analysis, adequate and appropriate disturbance monitoring is required, e.g. Wide Area Monitoring, Protection and Control System (WAMPACS).
- Redundancy and reliability of remote control and telecommunication devices, employing automatic load shedding, etc., is a prerequisite [15].

2.2.3 Smart Grid Standardization

This Section presents the standards proposed for monitoring, protection and control applications in various areas of the power transmission and distribution grid. Established international standards used extensively include IEC 60870 [27] and IEC 61850 [28]. The IEC 60870-6 introduces the Inter Control-Center Protocol (ICCP), IEC 60870-5-101/104 being legacy protocols used for SCADA within substations and IEC 61850, a relatively new standard in substations. Other standards are emerging such as IEC 61400-25 for wind power plants [29], IEC 62056 [30] for meter reading, tariff and load control, IEC 61850-7-420 for data modelling in distributed energy resources (DERs) and IEC 61850-7-410 for data modelling in hydroelectric power plants.

2.2.3.1 Standards for Substation Protection and Automation

A. IEC 60870-5-104 [27]

The IEC 60870-5-104 standard defines a communication protocol between the Control Centre and substation devices and is considered as a legacy SCADA protocol that can be used over Internet and other TCP/IP based networks. It is used for power system monitoring, control and associated functions and can be implemented for multiple configurations such as point-to-point, star.

B. DNP3 Protocol [31]

The Distributed Automation Products (DNP3) was originally designed as a general SCADA protocol. DNP3 has variable length of application service data units (ASDU), which can carry different data types in the same frame, making it suitable as a communication protocol for the Logic Nodes (LNs) of IEC 61850. In a SCADA system, ICCP is used for inter-control station communications whereas DNP3 is primarily used for communications between a Control Centre and Remote Terminal Units (RTUs) or Intelligent Electronic Devices (IEDs).

C. IEC 61850 (parts 1-10)

IEC61850 (parts 1-10) [28] is a communication and data modelling standard for the design of substation automation systems using object oriented data models, substation configuration language (SCL), and the Abstract Communication Service Interface (ACSI). IEC 61850 defines 5 types of communication services as shown in Fig. 2.3; the time-critical applications are used in protection and control schemes within the substation. Sampled Values (SV) and Generic Object Oriented Substation

Event (GOOSE) protocols are mapped directly to the Data Link layer for reduced protocol overhead and hence increased performance and the Generic Substation State Event (GSSE) protocol features its own custom protocol mapping. The remaining two types of services, i.e., Time Sync and Client-Server Manufacturing Message Specification (MMS), treat time synchronization and management of the substation devices respectively.

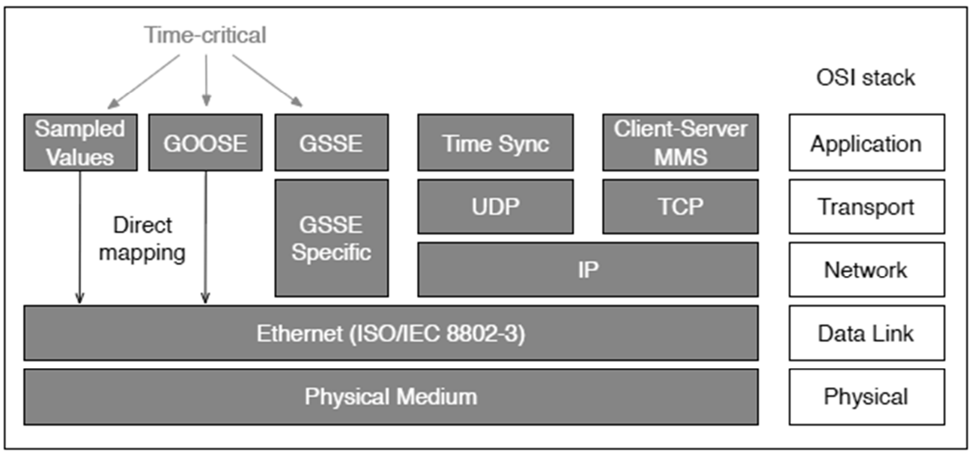


Figure 2.3 Communication services defined in IEC 61850 [32].

D. IEC 61850-90-1

The IEC 61850-90-1 standard published in 2010 describes the use cases of IEC 61850 for communication between substations [33]. Applications include line differential protection or distance protection with blocking/transfer trip schemes, Remedial Action Schemes (RAS), fault locator and out-of-step protection. This standard also provides the communication requirements, and guidelines for communication services and architectures.

E. Other Standards for Automation Control

IEC Technical Committee TC 38 (for Instrument Transformers), is currently developing the IEC 61859 series of standards; part-9 and 13 of the standard proposes digital interfaces to electronic instrument transformers [34]. IEC 62271 is a standard for high-voltage switchgear and control gear based on IEC 61850 published in 2006 [35]. IEC 62439-3 is applicable to high-availability automation networks based on the ISO/IEC 8802-3 or IEEE 802.3 Ethernet Technology and was published in 2010 [36]. IEC/IEEE 60255-24 proposes a Common Format for Transient Data Exchange (COMTRADE) [37].

2.2.3.2 Standards for Wide Area Situation Awareness (WASA)

The concept of a synchronized Phasor was standardized for the first time in the IEEE 1344 standard agreed in 1995 [38]. This was further developed and lead to the sychrophasor standard, IEEE C37.118 completed in 2005 [39], which proposes a method of evaluating a PMU measurement and requirements for steady-state measurements. Since IEC separates measurements and communications into different standards, it is split into two parts: 1) IEEE C37.118.1 [40] for dynamic Phasor and frequency measurement requirements; 2) IEEE C37.118.2 [41] includes data exchange and message/frame structure. Moreover, the IEEE C37.118.2 has being further enhanced using the IEC 61850 suite part 90-5, which intends to provide configuration methods, communication mapping and operation, remote controls, and security mechanisms over a wide area.

2.2.3.3 Interconnection of Distributed Energy Resources (DERs)

IEEE 1547 is a series of standards to provide criteria and requirements for the interconnection of distributed generation resources in the power grid, published since 2003 [42]. IEC 61850-7-420, as an extension of IEC 61850, defines the communication and control interfaces for all DER devices [43, 44]. IEC 61400-25 provides uniform information exchange for monitoring and control of wind power plants [45]. The standard has specified five mapping to communication protocol stacks in order to address the real wind power business needs in respect of communication. The communication model for a client-server methodology is shown in Fig 2.4.

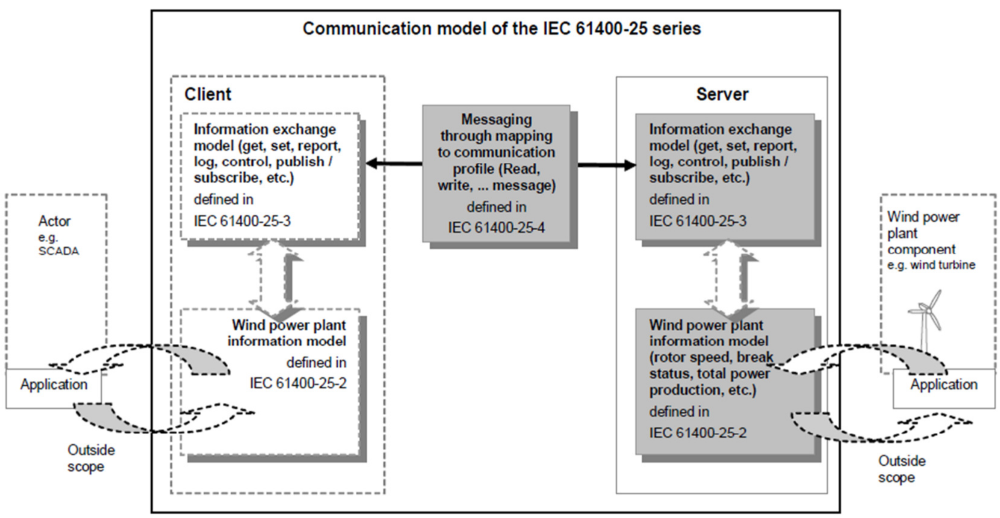


Figure 2.4 Communication model of the IEC 61400-25 series [45].

2.2.3.4 Interfaces with Supervisory Control

The IEC 61970 standard suite [46] provides Application Program Interfaces (APIs) for Energy Management Systems (EMS), published since April 2009, whereas the IEC 61968 series of standards [47] proposes system interfaces for Distribution Management Systems (DMS). A Common Information Model (CIM) is developed for exchanges of data between devices and networks, primarily in the transmission (IEC 61970) and distribution (IEC 61968) domains.

IEC 60870-6 or Inter-Control Center Communications Protocol (ICCP) [48] is designed for communication between Control Centres.

2.2.4 Challenges to Smart Grid Standardization

The major challenges and possible solutions for seamless interoperability of Smart Grid standards are:

Compatibility with current standards: New standards should not only be compatible with currently implemented standardized technologies, but should also facilitate interoperability and advanced configuration features. Standards must provide flexibility in order to give room for future advancements.

Accommodate differences in practices: Various power utilities across the world have differences owing to geographical and political issues. In order to take into account all practices worldwide, it is important to accommodate all practices during standardization, if possible, or provide case studies to apply the standard for various scenarios.

2.3 Potential Communication Technologies for the Smart Grid

2.3.1 Introduction

Advanced communication technologies are one of the key enablers in future Smart Grid implementations. Reliable communication interconnections between different power system domains ensure the proper functioning and management of power system applications. Under fault conditions, the resultant alarm signals need to be delivered to the system operator in a timely fashion, leading to a higher requirement on communication network performance. Therefore, understanding the nature and performance of a range of available communication technologies is essential to achieve fully robust, secure and functional Smart Grids and networks.

2.3.2 Type of Communication Infrastructures

Communication infrastructures implemented in the Smart Grid can be both wired (telephone lines, power lines and fibre-optics) or wireless (satellite, microwave mobile radio) [49]. The performance of the system can be judged in terms of two key metrics; the delay between the transmission of the signal and when it is successfully received and the Signal to Noise Ratio (SNR) which determines the quality of the signal and in turn its probability of being recovered successfully. Delay is an important specification and should be considered in any power system design or analysis, as excess end-to-end delays could compromise any control or protection procedures adopted to stabilize the power grid. The SNR of the link governs the

Quality of Services (QoS), also a vital factor in the operation of applications within the power system. The main communication medium candidates for Smart Grid implementations can be categorized as:

a) Leased Line

Leased telephone circuits are the most popular medium used presently by utilities to create a point-to-point or point-to-multipoint interconnection [50]. In the UK, leased lines are available at speeds from 64 kbps to 2.048 Mbps over a channelized E1 tail circuit and at speeds between 2.048 Mbps to 34.368 Mbps via channelized E3 tail circuits. Drawbacks include subject to breakage and water ingress rendering them only economical for short distances transmission.

b) Power Line Carrier

Power Line Carrier (PLC) [51] uses power transmission lines to transmit radio frequency signals in the range of 30 kHz to 500 kHz, offering the attractive possibility of transmitting data simultaneously with electricity over the same medium. Therefore, the only cost incurred by PLC deployments is the cost of additional terminal equipment, as well as any repeaters, as the physical connection already exits. Narrow band PLC usually offers low data rates (up to 200 kbps) whereas broadband PLC can establish a higher data rate, up to 2Mbps. The main drawback is the mismatch of the impedance of the power line which introduces high levels of noise compromising SNR and communication network quality [52].

c) Optical Fibre

Fibre optical transmission is universally preferred for the communication backbone in many utilities due to its high data rate and immunity to noise [49]. Two types of fibre optic cables are normally used in the power industry: Optical Power Ground Wire (OPGW), an optical fibre core within the ground or shield wire suspended above transmission lines; or the All-Dielectric Self-Supporting (ADSS) cable, a long-span of all-dielectric cables designed to be fastened to high voltage transmission line towers underneath the power conductors [49]. Optical fibre offers base data rates of 10 Gbps or even higher [53]. The disadvantage of using fibre-optics is the high investment cost.

The Plesiochronous Digital Hierarchy (PDH) [50] has been widely used in microwave radio or fibre optic systems in order to transport huge amounts of data, managing the transmission of data streams that are nominally at the same rate, which normally cannot be ensured. A new standard, the Synchronous Digital Hierarchy (SDH) [132] superseded PDH and become an international standard for transporting high speed digital signals over optical/electrical networks supporting variable capacities (Table 2.1). A synchronous system providing a more flexible, yet simple network infrastructure was specifically designed for the transport of telephony traffic. In the frame structure of SDH, the overhead section occupies about 2.96% of the frame size, and thus the payload transmission efficiency is high. Furthermore, maintenance and management sections within the frame structure provide a highly robust network.

Table 2.1 Physical media and link capacities [50].

Asynchronous	Synchronous–North American	Synchronous–International
PDH	SONET	SDH/CCITT
DS0: 64 kb/s	OC/STS-1: 51.85 Mb/s	E0: 64 kb/s
DS1: 1.544 Mb/s	OC/STS-3: 155.52 Mb/s	E1: 2.048 Mb/s
DS3: 44.736 Mb/s	OC/STS-9: 466.56 Mb/s	E2: 8.448 Mb/s
	OC/STS-12: 622.08 Mb/s	E3: 34.368 Mb/s
	OC/STS-18: 933.12 Mb/s	E4: 139.264 Mb/s
	OC/STS-24: 1.244 Gb/s	STM-1: 155.52 Mb/s
	OC/STS-36: 1.866 Gb/s	STM-4: 622.08 Mb/s
	OC/STS-48: 2.488 Gb/s	STM-16: 2.48832 Gb/s

d) Satellite

Satellite communication technology has been used for many years in the domains of telecommunications and networking, and the Low-Earth Orbiting (LEO) system [54, 55] can be harnessed in Smart Grid application. LEO communication can provide data rates ranging from 4 kbps to 7 kbps at a consistent delay of around 100ms. The wide communication coverage of LEO helps to establish connections across rural areas efficiently. However, constrains of narrow bandwidth and associated relatively large propagation delays make it difficult to fulfil the requirements of some control and protection operations.

e) Microwave

Microwave radio operates at a frequency above 1 GHz, offering high channel capacities and transmission data rates, with bandwidths ranging from a few hundred kbps to 10 Mbps. The channel capacity over microwave radio is proportional to the radio frequency used, but however, inversely proportional to the propagation distance. In addition, a line of sight is preferred between source and destination to guarantee transmission range and SNR.

f) WiMAX

The Worldwide Interoperability for Microwave Access (WiMAX) is a 3G telecommunication system based on the IEEE802.16 standard [56]. WiMAX technology enables the delivery of last mile wireless broadband access, an alternative to cable and DSL. It is also amenable to be implemented as backbone networks that provide connections for an extended range of coverage. The transmission range of WiMAX can reach 50 kilometres at a data rate up to 70Mbps, filling the gap between WLANs [57] (which provide very high data rate but over short ranges) and cellular systems [58] (which provide highly mobile, long range coverage but low data rate). As shown in Figure 2.5, two types of WiMAX connection were compared to other wireless technologies in terms of the round-trip time of packets across the networks; WiMAX (1) and WiMAX (2) represent point-to-point and Point-to-Multipoint links respectively [59].

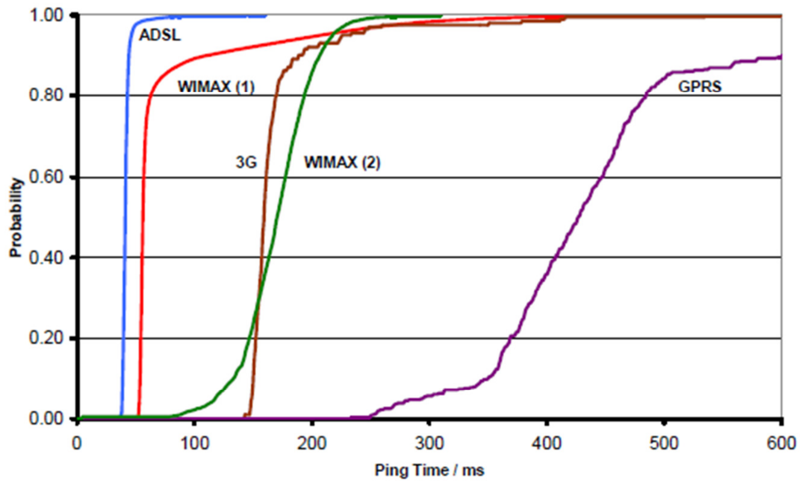


Figure 2.5 Round-trip times for packets traversing various access technologies [59].

2.3.3 Comparisons between Communication Technologies

All of the communication technologies described in the previous Section have potential uses within Smart Grids. A comparison based on physical characteristics for each medium is provided in Table 2.2 and the advantages/disadvantages are analysed in terms of transmission range, bandwidth, scalability, interoperability, noise/ interference and cost.

Table 2.2 Physical layer characteristics in different communication media.

	Coverage	**Bandwidth**	**Scalability**
Leased Line	Long distance	Up to 34.368 Mbps	Limited
Narrowband over PLC	Power line area	Up to 256 kbps	Limited
Broadband over PLC	Power line area	256 kbps to 2.7 Mbps	Limited
Optical fibre	Long distance	Up to 1600 Gbps	High
Satellite	Global coverage	128 kbps to 1 Mbps	Ultra High
Microwave	Up to 200m	250 kbps to 10 Mbps	Medium
WiMAX	Up to 50km	Up to 75 Mbps	High
	Interoperability	**Noise / Interference**	**Cost**
Leased Line	IPv4/6	High	Low
Narrowband over PLC	DPLC	High	Low
Broadband over PLC	DPLC	High	Low
Optical fibre	IPv4/6	Ultra Low	High
Satellite	IPv4/6	High	High
Microwave	6Lowpan	High	Low
WiMAX	IPv6	Low	High

- Coverage indicates the transmission range that can be reached. The transmission range of a wireless system is limited by the radio propagation path loss whilst satellite communication has outstanding performance in terms of coverage. For a LEO satellite, a radius of coverage of 1000km can be achieved.

- Bandwidth is another key factor for applications generating high data volumes. Narrowband over PLC has the worst performance providing up to 256 kbps whereas the bandwidth of optical fibre is ~1600 Gbps in a Wavelength Division Multiplexing (WDM) implementation [174].
- Scalability is defined as the ability to maintain network performance irrespective of the ‘size of the network’. Satellite communication provides the highest scalability.
- Interoperability is the ability of diverse systems to cooperate and inter-operate with each other e.g. with PLC, carriers can change its transmission system from analogue to digital to enable Internet Protocol (IP) devices. 6LoWPAN [60] is a standard that governs IPv6 over low power wireless Personal Area Networks (PANs), defining encapsulation and header compression mechanisms that allow IPv6 packets to be exchanged over IEEE 802.15.4 based networks. All other technologies support IPv4/ IPv6 without additional configurations.
- Optical fibre networks operate with extremely high SNR since the medium is highly immune to the electrical noise interference. WiMAX with MIMO antenna technologies can achieve a high SNR by sending duplicate signals to manage the loss of packets. The impact of noise and interference for media such as PLC and telephone lines is much more detrimental to network performance.
- The cost of the system can be further segmented into installation and maintenance cost. Optical fibre and WiMAX techniques have a higher cost

for installation [50] whilst the cost for satellite communication is high for both manufacturing and maintenance [54].

The end-to-end signal delay introduced on a connection through an individual communication medium is not listed in the Table 2.2 since it is a combination of transmission, queuing and propagation delays [61]. The propagation delay depends on the medium itself and thus is a function of the physical distances separating the transmitter/receiver. The low data rate in telephone lines and satellite links may cause traffic congestion during transmission, especially with large volume of data exchange. Even though PLC can provide speeds of up to 2.7 Mbps, its low SNR owing to an enormous amount of interference brings down achievable data rates to a few kbps. The performance of fibre optic cables and WiMAX will not affected by the delay associated with the length of the data packet because of the high data rates offered, and hence the associated transmission delay can be considered negligible.

2.3.4 Communication Requirements in Smart Grid

2.3.4.1 Data Delivery Timeliness

Some control functions present stringent latency requirements, e.g. restoration actions after faults need to be taken as soon as possible, ideally within a second [5]. Thus any communication system needs to be properly managed to guarantee timely data delivery and service differentiation to meet diverse latency requirements.

2.3.4.2 Interoperability [62]

An important feature of Smart Grids is the interconnection of a potentially large number of disparate energy distribution networks, power generating sources and energy consumers. As traffic will traverse different types of networks, interoperability is the key to achieving seamless connectivity. Interoperability can be most readily achieved by either using a gateway [62] for the transition between two different communication islands, or by standardizing the service such as data format, protocols and medium. The level of interoperability affects the performance of the service in terms of delay and packet loss.

2.3.4.3 Scalability [62]

The design and provision of a scalable network in Smart Grids cannot be overemphasized. Grid extent, applications and the number of constituent components are expected to grow rapidly as standards mature and infrastructure is modified or added. System performance must not be detrimentally affected as components and capabilities scale.

2.3.4.4 Compatibility

The design of the Smart Grid should be compatible with the existing power system architecture, communication infrastructure, and the provision of existing supervisory and control devices. Due to the revolution of the power system will continue over a long period, the existing system/devices cannot be replaced overnight. Thus, it is essential to build the compatibility between the proposed applications/devices with the legacy equipment in the system. Moreover, the reliability cannot be guaranteed with some advanced applications which have only been proven theoretically, and therefore, the existing system needs to perform as a backup under certain system emergencies. Last but not least, a compatible design will be cost-effective to maximize the performance with the use of legacies from the original system.

2.3.4.5 Reliability and Robustness

Communication infrastructures are often regarded as one of the vulnerable segments in traditional power systems. A number of reasons contribute to this view; inappropriate deployment of a communication medium with often outdated communication technologies. With the increasing requirement of seamless connectivity between different applications, a reliable and robust communication network needs to be installed to cover both the transmission and distribution segments of the power system.

2.3.4.6 Self-Organization

Owing to the wide scale and extensive deployment of the communication network, the system process and the requirement to analyse ever increasing volumes of data generated locally or remotely, the network needs an inherent ability to adapt to dynamic changes in data flows. The network is not only expected to support the efficient exchange of monitoring and control information, but also as an enabler of new services and applications. Such a self-organizing network should support functions such as communication resource discovery, negotiation and collaboration between network nodes, connection establishment and maintenance to provide the performance guarantees required by new Smart Grid applications.

2.3.4.7 Privacy and Security

Security of this critical infrastructure has always been an issue. As Smart Grid solutions experience an enormous increase in the exchange of data both for observability but also for controllability, the security of the data exchange and the physical components underpinning the exchanges become an increasing design factor with major impact on the acceptable solution.

2.4 Smart Grid Supervisory and Control Technologies

2.4.1 SCADA Systems

Supervisory Control and Data Acquisition (SCADA) [3, 157] is currently used for monitoring purposes in industries such as telecommunications, water and waste control. The main role of SCADA is to gather control data and report any failures that may occur, such as a leak in a gas pipe line, or failure of a power transformer in the electricity network. As far as the power system is concerned, electric utilities use SCADA systems to detect current flow and line voltage, to monitor the operation of circuit breakers, and based on that data to take sections of the power grid online or offline. The functions included in a SCADA system are data acquisition, networked data communication, data presentation and control.

SCADA systems are generally composed of the following elements:

- Field-based monitoring and control devices such as Remote Terminal Units (RTUs) which collect measurements from the field e.g. actuating devices such as relays and circuit breakers.
- Communication between the control centre and field-based RTUs. The communication network comprises equipment such as routers, switches, modems utilising communication media such as telephone lines, optic fibre, and microwave radio.

A central control station usually composed of one or more servers that represent the interface between the operator and the SCADA system. The role of the central station is the processing of data collected from different field-based control devices such as RTUs and presenting them in a readable format to the operator.

The current design of the SCADA system results in a convoluted and excessive amount of data processing, with some of the legacy monitoring data having to be manually retrieved through dial-up systems such as the public switch telephone network (PSTN). This arrangement also make data comparisons between sites unnecessarily complicated. Figure 2.6 is a schematic of a SCADA system deployed in the UK, comprising the following components: Frequency and Time Error System (FATE), Operational Metering System (OMS), Ancillary Service Business Monitoring (ASBMON), Protection Relays and Reactive Power Control.

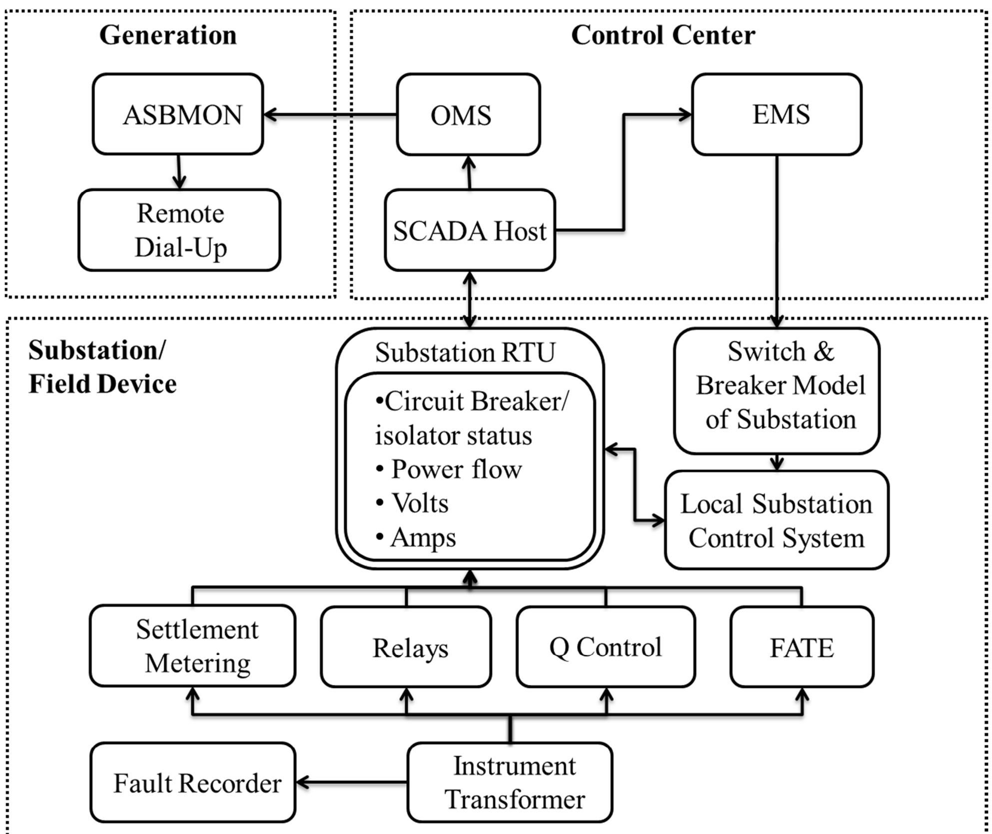


Figure 2.6 Substation SCADA system structure in UK [63].

A. Frequency and Time Error System (FATE)

The system operating frequency at present is monitored through the FATE [63]; local frequency data is reported from around 10 field-based RTUs and this information is aggregated at the Control Centre for evaluating system frequency. The data is refreshed every 2-5 seconds, insufficient to track dynamic changes in the system. As the frequency information is not time synchronized, direct comparisons cannot be made between disperse areas of the network. Moreover, the online analysis and comparison for those geographically distributed segments of the network impacts on the control of system faults and adds a significant overhead on the capacity of the system through increased traffic load. Also, the concomitant delay owing to the heavy load compromises timely control and protection operations especially for emerging power system conditions and wide area situational awareness.

B. Operational Metering System (OMS)

The OMS [63] is intended to provide both the Independent System Operators (ISOs) and the generation units with real-time information on power flow, to and from connection points all around the network, in order to execute on system control and offline modelling, vital to accurately controlling the system. The current system only processes the output from the settlement meter - which is currently prone to errors of - around +/-1% - whereas a time synchronized measurement at source will increase the accuracy significantly.

C. Ancillary Service Business Monitoring (ASBMON)

ASBMON [63] is a standalone system installed at generation sites to evaluate the contracted frequency response as provided by the generators. Again, data are provided from the settlement metering equipment and in this case, the information is manually retrieved, disjoint from the central system.

D. Protection Relays

Thus far, relays are only monitored and controlled locally and many protection applications/algorithms are constrained due to the lack of a wide area protection strategy. Thus full integration with the rest of the systems permits a number of unique protection applications to be deployed.

E. Reactive Power Control

With the ever increasing complexity of the power network, the control of voltage becomes more vital to the stability of the entire system. Time-synchronized measurements will aid operators to understand more accurately the exact requirements of the power system and to minimize catastrophic loss of power under major fault conditions.

SCADA is designed to observe power grid status approximately every 2-5 seconds, deemed too slow to track dynamic events. In addition, the measurements collected at substations and grid connection points are based on the outdated technology which operates at a lower accuracy e.g. only Root Mean Square (RMS) values without any phase angle information. The communication technologies constituting deployed SCADA system is fast becoming obsolete; the star topology with low channel capacity channels is not able to meet the increasing traffic demand generated from a growing number of field-based RTUs [64].

2.4.2 The SCADA Network Architecture in the UK

The existing SCADA system uses a hierarchical network topology to interconnect all RTUs located in primary and secondary substations [65-67]. The SCADA host sits at the highest layer of the telecommunications stack, monitoring the status of the national power system. All RTUs in grid or primary substations serve the host via star connections. The secondary substations connected to the grid substation utilize multi-drop links to further extend the monitoring capability into the distribution network. The current SCADA provisions in ScottishPower and EDF Energy networks [67] are presented in the next Sections. The architectural requirements of the underlying communication systems are identified and described.

2.4.2.1 ScottishPower SCADA Communication Networks

A. Communication between Control Centre and grid substations

The communication network between the Control Centre and grid substations is composed of a number of different type of channels implemented through fibre optic links, BT leased lines and microwave radio with a capacity not exceeding 2 Mbps [67].

The topology exhibits a certain level of redundancy and communication reliability between grid substations and the Control Centre can be guaranteed. The topology of the communication network for ScottishPower connecting grid substations to the Control Centre is depicted in Figure 2.7. As shown, there are multiple end-to-end routing paths between the Control Centre and some of the grid substations. The grid substations are equipped with a RTU concentrator to retrieve measurement data and instrument status from downstream RTUs whilst at the same time, aggregating signals from the upstream Control Centre to execute control and protection operations.

B. Communication between grid substations and primary substations

Grid substations are located at the 132/33KV level of the power network and communicate with primary substations at the lower level (33/11KV). Unlike grid substations, primary substations have a maximum of two modems, one communicating with the upstream controller, the other with downstream RTUs. The upstream controller is generally either a grid substation if the primary substation is connected directly to the higher voltage network (132/33KV) or another primary substation if it communicates in the multi-drop mode. The main channels used to connect primary substations with the grid substations and between primary substations are BT phone lines, typically at 1200/2400 bps [67], as a higher bandwidth is generally not required to transmit a few to tens of bytes supported by the current SCADA system.

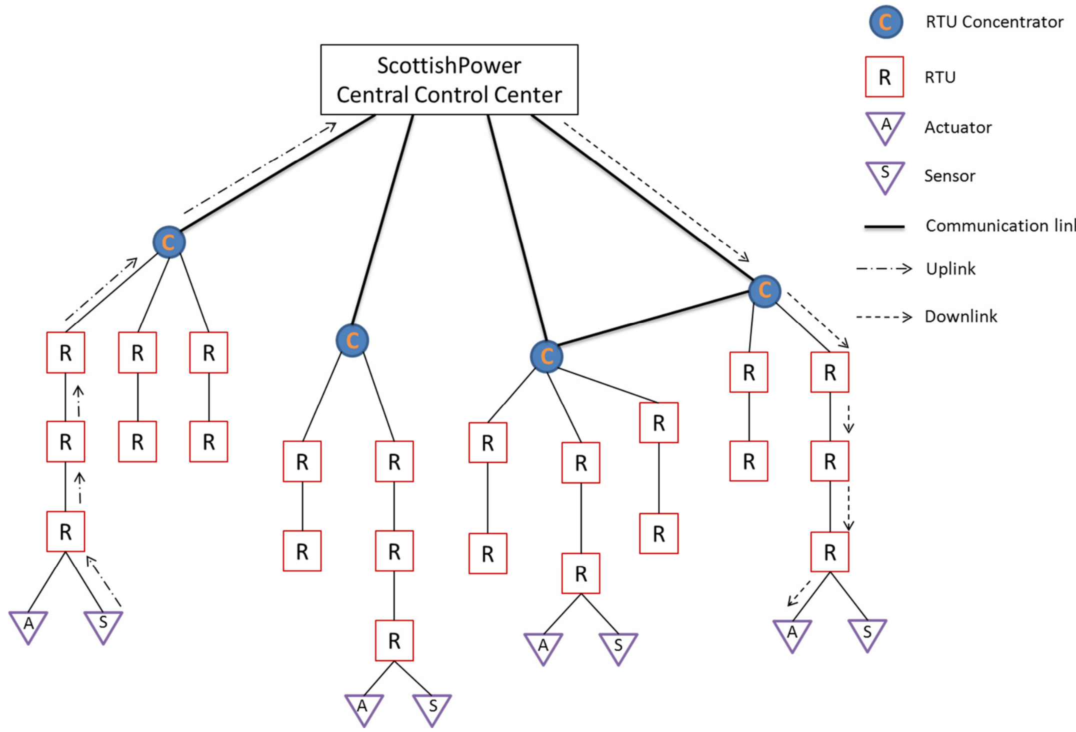


Figure 2.7 The ScottishPower SCADA network [67].

2.4.2.2 EDF Energy SCADA Network

Compared to the ScottishPower network, the EDF communication architecture is simpler [67];

- The connection between the Control Centre and grid substations (132KV/33KV) is through satellite channels (25 kb/s). The primary RTUs are scanned every 15-20 seconds.
- The typical architecture between the Control Centre and RTUs at primary substations (33KV/11KV) is a star. RTUs at primary substations are connected to the Control Centre through satellite channels (25 kb/s).
- The typical architecture between the Control Centre and RTUs at secondary substations (11KV/LV) is also a star. A cellular radio system (9.6 kb/s) is

implemented to connect both sides. RTUs at secondary substations are polled to test for availability and report exceptions when they occur.

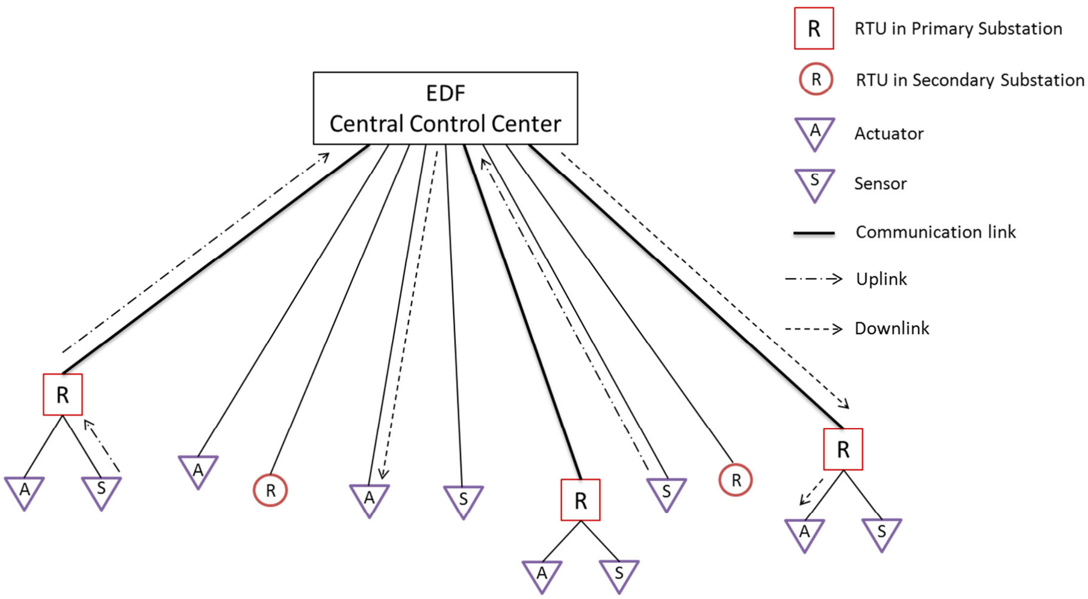


Figure 2.8 EDF SCADA network [67].

2.4.3 Communication Patterns in SCADA Systems

Network monitoring and control operations can be classified into two main categories:

- Data acquisition: performed continuously to gather measurements on the state of the power network. RTUs at the primary substations are generally scanned every 20 sec.
- Supervisory control: commands triggered either by the Control Centre to change the state of the power network or control procedures pre-programmed at primary substations as a reaction to an event detected on the power

network.

Data acquisition and supervisory control operations generally present different communication characteristics as defined by their traffic patterns since data acquisition operations generate continuous data traffic whilst control commands are event driven. However, under some power network scenarios, for example in the case of measurements between primary substations, the control command emanating from the central Control Centre must be sent within a certain time interval, also a function of the nature of the command. For example, commands are grouped by the control system at ScottishPower into three categories numbered from 1 to 3 according to the properties and the delivery requirements of those classes of commands; Category 1 control commands require to be delivered within a time delay that must not exceed 6ms, while the time delay for Category 2 and 3 control commands need to be under 15ms and 30ms respectively.

2.4.4 Wide Area Measurement, Protection and Control (WAMPAC) System

A WAMPAC strategy yields great potential for the upgrade of the supervision, operation, protection and control of modern power systems. It is becoming increasingly significant for power systems and is widely accepted as an emerging competitive advantage to enable intelligent transmission for Smart Grids [5, 68, 69]. Phasor Measurement Units (PMUs) based monitoring and control system enables dynamic state estimation as well as advanced protection and control technologies.

Measurement data are exchanged among information sources, aggregating points and servers for processing and logging purposes. Feedback control signals are sent from measurement sources and central servers to controllable devices.

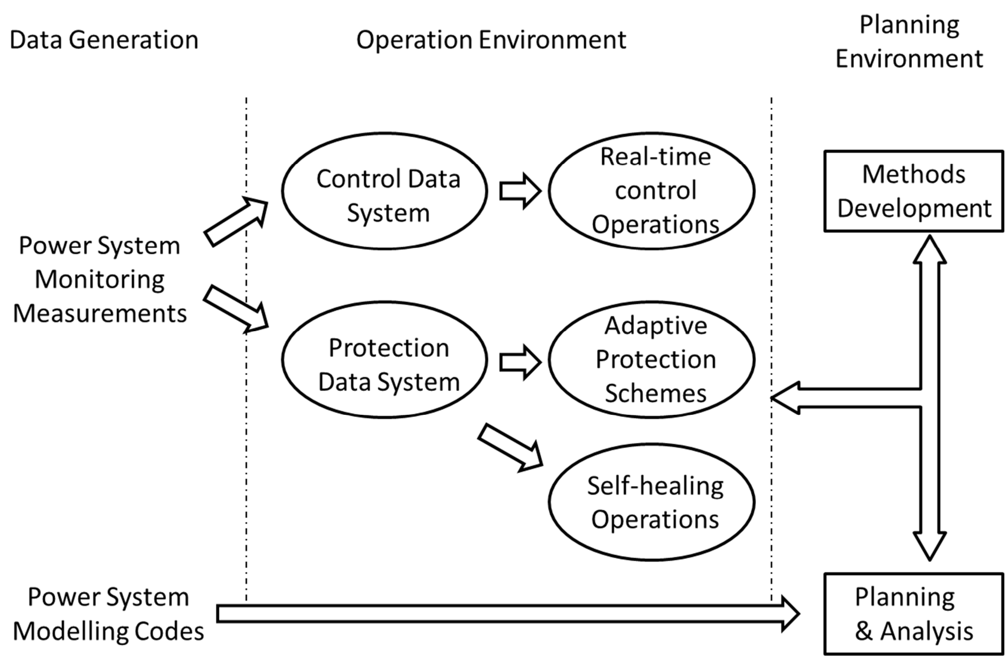


Figure 2.9 WAMPAC in advanced power system.

A significant volume of research has been carried out in developing WAMPAC concepts. Phadke [5, 6, 68, 69] has been instrumental in developing synchrophasor technology and in defining the applications within wide-area measurements as relevant to Smart Grid control and monitoring. In [94], various applications in protection, monitoring and control are presented; stimulating contributions from other research areas e.g. power system design [71, 175, 178], communication infrastructure installation [80, 177], and communication network integration [79, 81, 82]. As most fault events requiring action by protection and control system arise from transients in the system, the potential applications and communication requirements are further verified in [70] and [71]. Information architectures for future power grids are given in [61, 147, 150], presenting proposals for different ways to structure interactions between Control Centres and substations, and reliability analysis of different schemes. However, the communication mechanisms underpinning these interactions have not been considered; a simple assumption has been used in the analysis that a network is available without through consideration of the impact of reliability and latencies. GridStat [72-75] is a publish-subscribe middleware [148] framework that has been designed to meet the data delivery requirements for the electric power grid. But there are limitations in deploying GridStat in real power systems; (1) The middleware approach introduces significant network communication overheads required to support key functions such as the sharing of network status (rate, latency, and redundancy), object and service discovery, and the brokering of inter-object calls within multiple processes running across networks [149]. The performance of the approach is further exacerbated and compromised as the temporal dynamics of the power grid increases and under real-time operation; (2) A "Status router" [72] is required to support functions such as multicast, rate filtering, and subscription modes, which limit implementation of GridStat to a dedicated communication infrastructure. As a consequence, the additional installation cost becomes a major issue in deploying the system; (3) GridStat needs coherent network architecture to support its operating principles [75, 150].

Some research has demonstrated WAMPAC applications in a real environment, e.g. US [76], China [77] and Nordic regions [78-83]. [76] presents the performances of

WAMPAC for a specific network topology, specific data bandwidth and protocol choice. [77] tests the latency in forwarding phasor data between different monitoring sites. Both results are based on the existing deployments of PMUs in US and China without considerations of the growing size of the network, and the results cannot be directly used in the design of other systems. [79] and [80] also present research regarding the WAMPAC architecture utilizing a large number of PMUs in the Nordic Region. The system architecture is introduced through deployments [78] and developments [79], but the scope of the work is limited to just the design of network architecture without considerations of the constituent communication mechanisms.

Thus, in this Thesis the focus is on the designs and characterization of a flexible and scalable end-to-end communication platform able to meet the stringent requirements of a range of WAMPAC applications. Potential placements of PMUs are investigated to fulfil the growing demands of a rapidly expanding power system. The designs of the system are verified in terms of network topologies, communication link types and QoS control mechanisms. The methodologies of designing a distributed network are investigated and an integrated structure is proposed. The comparative performances of a number of candidate solutions are analysed through simulation using the existing power system topology in United Kingdom as the basis.

2.5 Conclusions

In this chapter, the limitations of the existing power system have been introduced in terms of monitoring and control. Evidence indicates that most if not all, nationwide blackouts can be avoided if proper automatic control actions are taken by operators or autonomously in a properly designed system within an acceptable time frame. Consequently advanced supervisory and control techniques with wide area awareness of the system status are required.

The development of a communications platform that meets the requirements of advanced monitoring and control must take into consideration existing standards which present legacy issues in future evolutions. Existing and developing Smart Grid standards must be a primary consideration in any proposed solution. A wide range of potential communication technologies are candidates in the implementation of the platform able to support Smart Grid applications. The advantages and disadvantages of candidate communication solutions are summarized in Table 2.3, from which conclusions as to the most appropriate are drawn in respect of the Smart Grid.

Table 2.3 Communication candidates' advantages/disadvantages

	Advantages	**Disadvantages**
Leased Line	• Economical for short distances	• Limited channel capacity • Inflexible network configuration
Power Line Carrier	• Located where the circuits are required • Economically attractive for low numbers of channels extending over long distances	• High levels of noise as carrier frequencies often not protected • Will not propagate through open disconnects

	Advantages	Disadvantages
Optical fibre	• Immune to electromagnetic interference • High channel capacity • Low operating cost	• Inflexible network configuration • High installation costs
Satellite	• Wide area coverage • Easy access to remote sites • Cost independent of distance • Low error rates • Adaptable to changing network patterns	• Less control over transmission • Transmission time delay • Continuous leasing costs
Microwave	• Transport high data rates • Easy to install	• Line of sight transmission • Limited capacity
WiMAX	• Transport high data rates • Propagation over non-line-of-sight paths	• Subject to interference from co-channel transmitters • Limited path length because of restrictions on RF power output

Mapping of existing supervisory control techniques is summarized in Table 2.3. SCADA systems are in use widely for monitoring purpose but closer inspection of capability indicates that these existing solutions cannot fulfil the increasing requirements of the power system. As a sequence, WAMAPC has been developed as an alternative to classical SCADA based solutions and the goal is to define the requirements, design a suitable architecture and analyse the performance of a communications platform that will support the range of WAMPAC applications, in so doing enabling more flexible and intelligent power delivery. On inspection of Table 2.4, WAMAPC has higher requirements in terms of data throughput, latency and packet loss. Referring to the communication media in Table 2.3, optical fibre is the most obvious candidate that provides a high level of throughput, data rate and low SNR. Deployment techniques such as ADSS and OPGW fastened to high voltage transmission line towers reduce the cost of installation.

Table 2.4 Comparison of communication requirements for SCADA and WAMPAC system

	SCADA	**WAMPAC**
Throughput	Low (Updating every 2-5 seconds)	High for supervisory applications (Uploading 30/60 packets/sec)
Delay (Latency) tolerance	High	Low for most of protection and control applications
Error/ Packet Loss Tolerance	High	Low for most of protection and control applications
Protocol standards	DNP3 [31] IEC 60870 [27]/ IEC 61850 [28]	IEEE C37.118-2011 [40, 41] IEC 61850-90-5 [33]

Chapter 3

Wide Area Measurement, Protection and Control (WAMPAC) System

3.1 Introduction

A Wide Area Measurement, Protection and Control (WAMPAC) strategy yields great potential for the upgrade of the supervision, operation, protection and control of modern power systems. WAMPAC monitors the status of power systems via PMUs located at critical locations along the power transmission path [84]. The traditional usage of PMUs has been in post events processing. The logged phasor data in the server helps to aid understanding of system operation and records the cause of any power fluctuations and blackouts. After enjoying years of development, currently a Global Positioning System (GPS) based high-precision PMU can support an enhanced wide area monitoring, protection and control applications [5].

3.2 Core Elements of WAMPAC

In a broad sense, WAMPAC is defined as a system capable of acquiring phasor data via PMUs delivered to a central location across a wide area at a rate appropriate for the intended applications [79]. PMUs located at critical points along the power transmission paths, upload measurement data to the phasor data concentrator (PDC) for validation and analysis. Normally, a PDC located in the central Control Centre collects time-stamped phasor measurements throughout the network. Further classification and processing are carried out for different protection and control purposes.

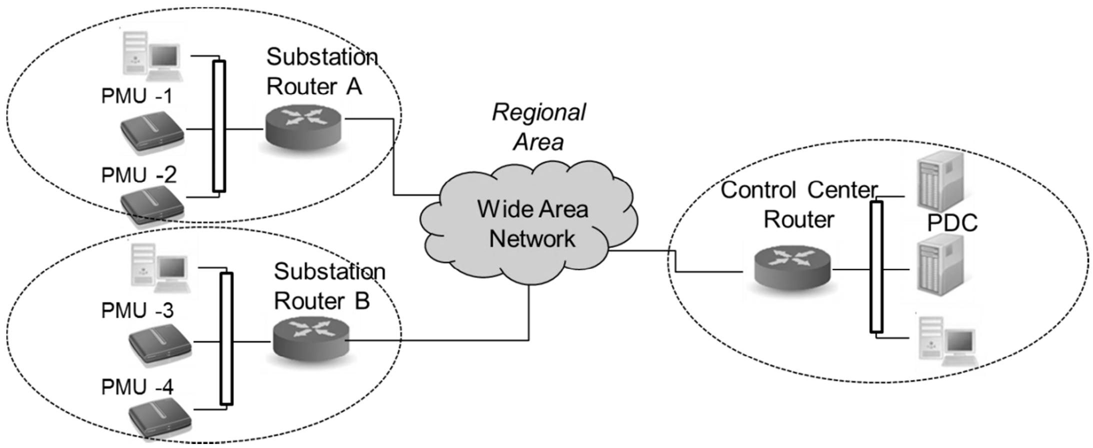


Figure 3.1 Generic WAMPAC system configuration.

3.2.1 Phasor Measurement Unit

3.2.1.1 Phasor Measurement Units History

Phase angles of voltage phasors of power network buses are a key to improving the stability of power systems and enable innovative power protection and control technologies. One reason is that the active power flow in a power line is nearly directly proportional to the sine of the angle difference between voltages at the two terminals of the line [88]. As operational and analysis considerations are directly linked to the flow of real power, measuring angle differences across transmission lines has been core for many years. The earliest modern application involving direct measurement of phase angle differences was reported in early 1980s [85-87]. Using the difference of measured angles on a common reference at two locations, the phase angle difference between voltages at two buses was established. However, since no attempt was made to measure the prevailing voltage phasor magnitude, nor any account taken of the harmonics contained in the voltage waveform, these methods of measuring phase angle differences are not suitable for wide-area phasor measurement systems.

The first paper to identify the importance of positive-sequence voltage and current phasor measurements, and some of the uses of these measurements, was published in 1983 [88], and can be viewed as the starting point of modern synchronized phasor measurement technology. GPS was beginning to be fully deployed around the same time and became clear that this system offered the most effective way of synchronizing power system measurements over great distances. The first prototypes of the modern PMUs using GPS were built in early 1980s [5]. At present, a number of manufacturers offer PMUs as a commercial product, and deployment of PMUs on power systems is being carried out in earnest in many countries around the world.

3.2.1.2 Phasor Measurement Concept

A pure sinusoidal waveform can be represented by a unique complex number known as a phasor. Consider a sinusoidal signal;

$$x(t) = X_m \cos(\omega t + \phi) \tag{3.1}$$

the phasor representation of this sinusoid is given by;

$$X \equiv \frac{X_m}{\sqrt{2}} e^{j\phi} = \frac{X_m}{\sqrt{2}} (cos\phi + jsin\phi) \tag{3.2}$$

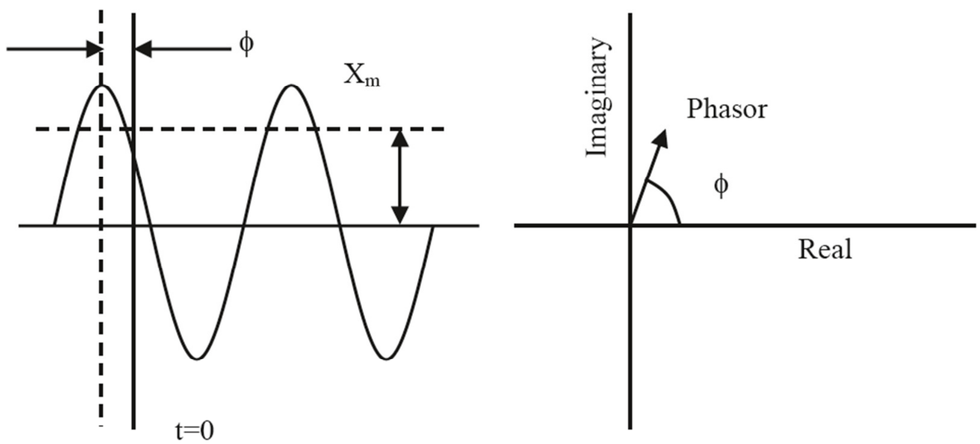


Figure 3.2 A sinusoid and its representation as a phasor [5].

Phasor representation is only possible for a pure sinusoid; in practice a waveform is often corrupted with other signals at different frequencies. It then becomes necessary to extract a single frequency component of the signal and represent it by a phasor. In sampled data systems, the Discrete Fourier Transform (DFT) is often used to extract a single frequency component.

A sinusoid $x(t)$ with frequency kf_0 can be through a Fourier series;

$$\begin{aligned} x(t) &= a_k \cos(2\pi k f_0 t) + b_k \sin(2\pi k f_0 t) \\ &= \left\{\sqrt{(a_k^2 + b_k^2)}\right\} \cos(2\pi k f_0 t + \emptyset) \end{aligned} \tag{3.3}$$

where $\emptyset = \arctan(\frac{-b_k}{a_k})$.

The phasor representation of the signal of Equation 3.3 is;

$$X_k = \frac{1}{\sqrt{2}}\left\{\sqrt{(a_k^2 + b_k^2)}\right\} e^{j\emptyset} \tag{3.4}$$

Using the Fourier series coefficients within the DFT, the Phasor representation of the k*th* harmonic component is given by:

$$X_k = \frac{1}{\sqrt{2}} \cdot \frac{2}{N} \sum_{n=0}^{N-1} x(n\Delta T) e^{-\frac{j2\pi kn}{N}} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x(n\Delta T) \left\{\cos\left(\frac{j2\pi kn}{N}\right) - sin(\frac{j2\pi kn}{N})\right\} \tag{3.5}$$

Using the notation $x(n\Delta T) = x_n$ and $\frac{2\pi}{N} = \theta$ (θ is the sampling angle measured in terms of the period of the fundamental frequency component);

$$X_k = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_n \left\{\cos(kn\theta) - jsin(kn\theta)\right\} \tag{3.6}$$

If the sum of cosine and sine factors is defined as:

$$X_{kc} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_n \cos(kn\theta) \tag{3.7}$$

$$X_{ks} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_n sin(kn\theta) \tag{3.8}$$

then the phasor X_k can be represented by;

$$X_k = X_{kc} - jX_{ks} \tag{3.9}$$

Since the principle interest in Phasor measurements is to calculate the fundamental frequency component, k = 1 is set to produce a phasor obtained from the sample set x_n (for a pure sinusoidal waveform) as follows:

$$\begin{aligned} X_c^J &= \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_{J+n}\cos\left(n\theta\right) = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} X_m \cos(n\theta+\phi)\cos\left(n\theta\right) \\ &= \frac{\sqrt{2}}{N} X_m \sum_{n=0}^{N-1}[\cos(\phi)\cos^2\left(n\theta\right) - \frac{1}{2}\sin\left(\phi\right)\sin\left(2n\theta\right)] = \frac{X_m}{\sqrt{2}}\cos(\phi) \end{aligned} \tag{3.10}$$

$$\begin{aligned} X_s^J &= \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_{J+n}\sin\left(n\theta\right) = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} X_m \cos(n\theta+\phi)\sin\left(n\theta\right) \\ &= \frac{\sqrt{2}}{N} X_m \sum_{n=0}^{N-1}[\frac{1}{2}\cos\left(\phi\right)\sin\left(2n\theta\right) - \sin(\phi)\sin^2\left(n\theta\right) = \frac{X_m}{\sqrt{2}}\sin(\phi) \end{aligned} \tag{3.11}$$

Therefore, the fundamental frequency phasor can be represented as;

$$X^J = X_c^J - jX_s^J = \frac{X_m}{\sqrt{2}}\left[\cos\left(\phi\right) + jsin\left(\phi\right)\right] = \frac{X_m}{\sqrt{2}}e^{j\phi} \tag{3.12}$$

Equation 3.12 gives the fundamental frequency phasor estimate; the subscript k = 1 has been dropped for the sake of simplicity.

3.2.1.3 Phasor Estimate Measurement Update

When updating the Phasor estimate on the acquisition of newer data samples, two algorithms can be used to calculate the change of Phasor in the system viz. non-recursive and cursive algorithms [5].Non-recursive is defined as Phasor calculations performed anew for each window without using any data from earlier estimates. For example, formulas for calculating Jst and (J+1)th phasors by the non-recursive algorithm are;

$$X^{J} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_{J+n} e^{-jn\theta} \tag{3.13}$$

$$X^{J+1} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_{J+n+1} e^{-jn\theta} \tag{3.14}$$

Non-recursive algorithms are numerically stable, but are wasteful of computation resource [5].

A recursive calculation can be obtained by multiplying both sides of a non-recursive algorithm by $e^{-j\theta}$:

$$\begin{aligned} \hat{X}^{J+1} &= X^{J+1} \cdot e^{-j\theta} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_{J+n+1} e^{-j(n+1)\theta} \\ &= X^{J} + \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} \left(x_{J+n+1} e^{-j(n+1)\theta} - x_{J+n} e^{-jn\theta} \right) \\ &= X^{J} + \frac{\sqrt{2}}{N} (x_{J+N} - x_{J}) e^{-j(0)\theta} \end{aligned} \tag{3.15}$$

where $e^{-j(0)\theta} = e^{-jN\theta}$.

A recursive update on the previous Phasor needs to be made to determine the value of the new Phasor, which reduces the computational resources significantly. For instance, when the last sample in the data window is (N+r), the updated Phasor can be represented by;

$$\hat{X}^{J+1} = X^{J} + \frac{\sqrt{2}}{N}(x_{J+N+r} - x_{J+r})e^{-jr\theta} \tag{3.16}$$

For a constant input where x_{N+r} equals to x_r, the Phasor remains stationary.

3.2.1.4 System Oscillation effects on Phasor measurements

A steady-state condition can be represented by a phasor, not always true in a practical power system. Most integrated power systems operate in a relatively narrow band of frequency, within 0.5 Hz from its nominal value (Figure 3.3 shows the PMU measurement records in Glasgow and Manchester). Under a fault condition, for example, when small islands of generators and load are isolated from the rest of the network, the frequency excursions may be as large as +/-10 Hz. Where the islands are primarily powered by hydroelectric generators, the system may operate at large frequency deviations for extended periods [5].

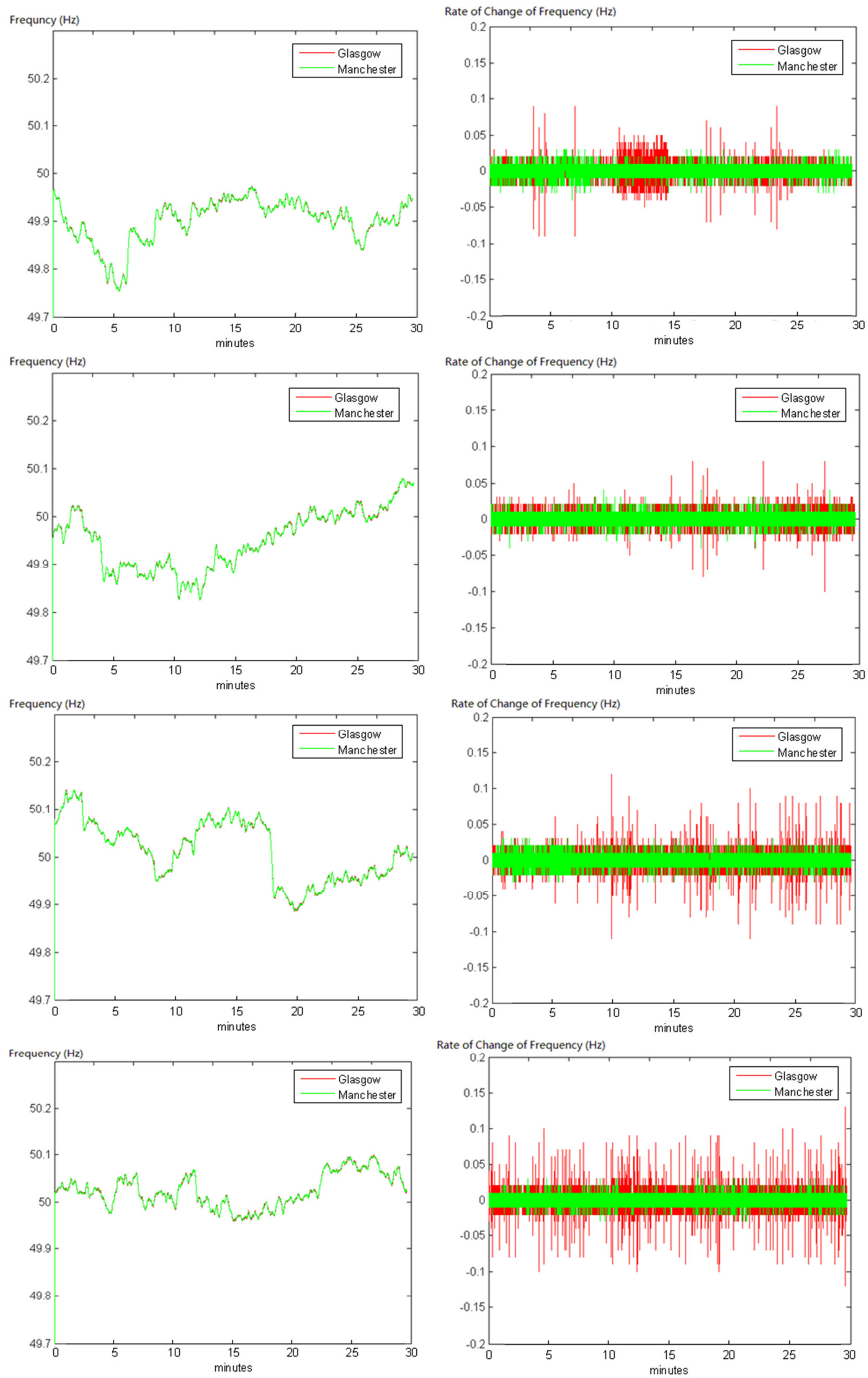


Figure 3.3 Record of PMU frequency (50Hz) and Rate of Change of Frequency in Glasgow and Manchester on 1st Dec 2011 (between 00:00hs and 02:00hs).

Phasor representation of a sinusoid is independent of the frequency of the signal as long as the Fourier coefficients constitute sines and cosines of the same period i.e. if the sampling rate is matched to the power system frequency, there is no error in phasor estimation.

3.2.1.5 Phasor Measurement Unit Structure

PMUs are normally located in power system substations, and provide measurements of time-stamped positive-sequence voltages and currents of all monitored buses and feeders (as well as frequency and rate of change of frequency).

In Figure 3.4, the analogue inputs are currents and voltages obtained from the secondary windings of the current and voltage transformers. All three-phase currents and voltages are acquired in positive-sequence measurements. Each data will be encapsulated with a GPS time stamp and measurements are retrieved through either wired or wireless communication interfaces.

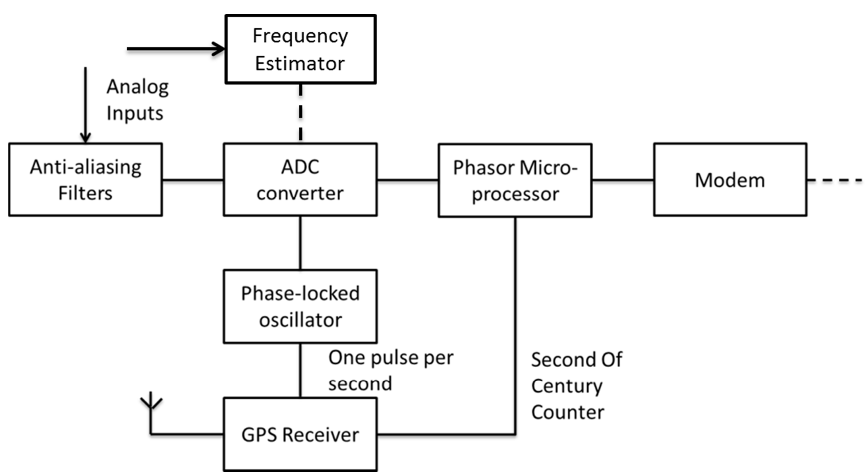


Figure 3.4 Structure of a Phasor Measurement Unit.

The sampling process is another key factor to ensure estimation accuracy and immunity to the off-nominal frequency. One option is to make the sampling clock phase-locked with the GPS clock pulse; the estimation accuracy can then be guaranteed, but not immunity to off-nominal frequency. Further filtering techniques are required to eliminate the latter errors.

Another option is to track the power system frequency, and alter the sampling clock to match the period of the prevailing frequency [90]. An issue with this technique is an accurate correlation between the measured phasor and the time-tag with which the measurement must be associated.

3.2.1.6 Phasor Measurement Unit Standards

The IEEE C37.118 standard published in 2011 is the latest concerning PMUs in electric power systems [40, 41]. The standard has evolved from the IEEE 1344 completed in 2001 [38] and IEEE C37.118-2005 [39] containing a complete description regarding measurement, the method of quantifying the measurements, testing and certification requirements for verifying accuracy, and data transmission format and protocol for real-time data communication. Presently the IEEE C37.118-2011 is the world-wide standard for synchrophasor data. This standard has being updated and published in two parts (C37.118.1 for Measurement and C37.118.2 for Data Transfer) with the intent of creating a harmonized standard between C37.118.2 and IEC 61850-90-5. The latter standard provides important enhancements to communicating phasor data whilst still addressing the core data transfer requirements identified in C37.118.

1) IEEE C37.118-2005 [39]

The IEEE C37.118 proposed in 2005 a method of evaluating a PMU measurement and requirements for steady-state measurement. The standardized definition of synchrophasor and computation of Total Vector Error (TVE) are described in Equation (3.17) and Equation (3.18) respectively;

$$\bar{X} = \left(\frac{x_m}{\sqrt{2}}\right) e^{j\phi} \tag{3.17}$$

where, $\frac{x_m}{\sqrt{2}}$ is the root mean square (rms) value of the signal x(t) and $\emptyset$ is its instantaneous phase angle relative to a cosine function at the nominal system frequency synchronized to the Universal Time Coordinator (UTC).

$$\text{TVE} = \sqrt{\frac{(X_r(n) - X_r)^2 + (X_i(n) - X_i)^2}{X_r^{\,2} + X_i^2}} \tag{3.18}$$

where $X_r(n)$ and $X_i(n)$ are the measured values and X_r and X_i are the theoretical values of the input signal at the instant of time of the measurement. Total Vector Error considers errors in both the magnitude and phase angle, by comparing PMU Phasor estimates with its theoretical Phasor equivalent. This standard provides only steady-state testing conditions and allows TVE of 1% in various steady-state scenarios. The steady sate performance requirements for various test scenarios include: signal frequency, magnitude, phase angle, harmonic distortion, and rejection of out-of-band interferences. These testing parameters are classified in two performance ranges: Level 0 (reduced performance ranges to allow less filtering and faster response); and Level 1 (higher performance ranges, better filtering and suitable for accurate and slow monitoring applications).

The standard also specifies the structure of the different message/frame types, which include: Data, Command, Configuration, and Header [39]. The command and configuration structure governs data transmission between the Phasor Data Concentrator (PDC) and Phasor Measurement Unit (PMU). The preferred data communication standard is IP protocol based (over UDP or TCP layers) (Table 3.1) [91];

- Data messages; represent PMU measurements.
- Configuration; a machine-readable message describing the data the PMU/ PDC sends, also providing calibration factors.
- Header information; human-readable descriptive information sent from the PMU/PDC but specified by the user.
- Commands; machine-readable codes sent to the PMU/PDC for control or configuration.

Table 3.1 Data frame organization based on IEEE C37.118-2005 [39].

Field	Size (Bytes)	Comments
SYNC	2	Synchronization byte
FRAMESIZE	2	Number of bytes in frame
IDCODE	2	PMU ID
SOC	4	Second of Century time stamp
FRACSEC	4	Time fraction and quality flag
STAT	2	Bitmapped flag
PHASORS	4·PHNMR / 8*PHNMR	Values are 4 or 8 bytes each depending on fixed or floated format in use.
FREQ	2 / 4	Frequency (fixed or floated)
DFREQ	2 / 4	Rate of change of frequency
ANALOG	2·ANNMR / 4·ANNMR	Analogue data
DIGITAL	2·DGNMR	Digital data
CHK	2	Cyclic Redundancy Checks

2) IEEE C37.118.1 - 2011 [40]

This standard addresses dynamic Phasor measurement and frequency measurement requirements. The PMU measurement bandwidth is determined by modulation tests where the power system signal is modulated with a sinusoidal signal for both magnitude and frequency, as:

$$X_a = X_m(1 + K_m \cos(\omega t)) cos[\omega_0 t + K_a \cos(\omega t - \pi)] \qquad (3.19)$$

The response of PMU measurements should be tested under abnormal conditions e.g. the power system with sudden generation-load imbalance; and step-tested of magnitude and phase in case of power system switching events. The bounds for errors in Frequency (FREQ) and Rate-of-Change Frequency (ROCF) measurements will also be specified.

3) IEEE C37.118.2 - 2011 [41]

This standard includes data exchange and the message/frame structure, which is compatible with IEEE C37.118-2005. A method for real-time exchange of synchronized phasor measurement data between power system equipment is defined. This standard specifies messaging that can be used with any suitable communication protocol for real-time communication between Phasor Measurement Units (PMUs), Phasor Data Concentrators (PDC), and a range of applications. It defines message types, contents, and mapping into TCP or UDP packets (Figure 3.5). Communication options and requirements are also described in terms of bandwidth and latency (Table 3.2).

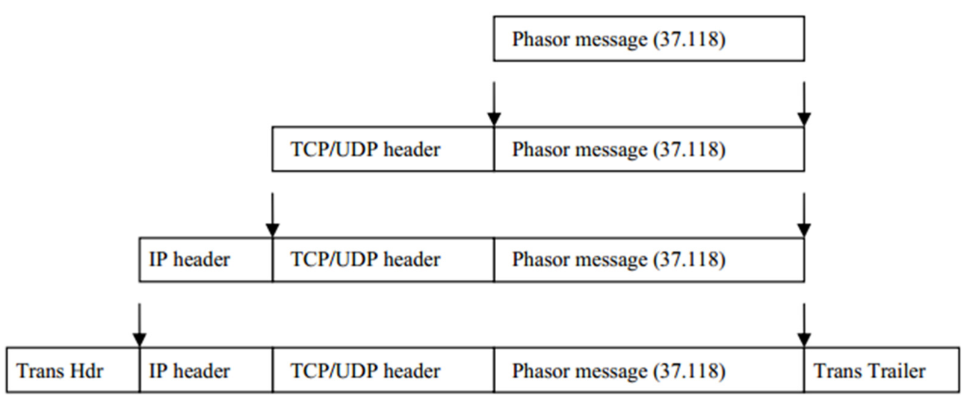


Figure 3.5 Mapping of IEEE C37.118 - 2011 data into a TCP or UDP packet [41].

Table 3.2 Summary of causes of delays and typical ranges [41]

Cause of Delay	Typical Range of Delays
Sampling window (delay ½ of window)	17 ms to100 ms
Measurement filtering	8 ms to 100 ms
PMU processing	0.005 ms to 30 ms
PDC processing and alignment	2 ms to 2+ s
Serializing output	0.05 ms to 20 ms
Communication system I/O	0.05 ms to 30 ms
Communication distance	3.4 μs/km to 6 μs/km
Communication system buffering and error correction	0.05 ms to 8 s
Application input	0.05 ms to 5 ms

4) IEC 61850-90-5

The IEEE C37.118 standard and its parts only specify messages, their content/structure and some basic control/command signals. The adoption of IEEE C37.118.2 in the IEC 61850 suite [28] is intended to provide configuration methods, communication mapping and operation, remote controls, and security mechanisms over a wide area. Phasor data are generally transmitted as continuous streaming, compatible with Sampled Value (SV) models [28] proposed in the IEC 61850 standard. Moreover, IEC 61850 GOOSE [28] can also be used to achieve fast and efficient communication of commands over a wide area. However, SV and GOOSE are communicated over Ethernet LANs, and in order to transmit over WAN, it has to have an IP routing capability [33].

3.2.2 Phasor Data Concentrators (PDCs)

Devices at the next level of the hierarchy are commonly known as Phasor Data Concentrators (PDCs) [5]. Typical PDC functions are to gather data from several PMUs, reject bad data, align time–stamps, and create a coherent record of simultaneously recorded data from a wider part of the power system. There are local storage facilities in the PDCs, as well as application functions operating on PMU data.

3.2.3 Control Centre

The communication network architecture used by Control Centres and distributed measurement devices are in the transitional phase from the currently centralized to a distributed architecture [92]. A conventional Control Centre has two groups of main functions; the first group of functions is for power system operation inherited from the traditional Energy Management System (EMS) [64], further segmented into data acquisition, generation control, and network analysis and control. Typically, a SCADA system collects measurements of voltage current, real power, reactive power, breaker status, transformer taps. Indeed, due to SCADA system limitations, more useful data remains in substations that would be very valuable to feed into Control Centre operations as a consequence of the data download bottleneck owing to the current communication systems. Automatic Generation Control (AGC) [64] is used to balance power generation and load demand instantaneously. The second group of functions is for business applications, known as the Business Management System (BMS), including market clearing price determination, congestion, financial and information management.

The existing Control Centres have to be coordinated both in terms of their geographic coverage and functionalities [92]. From Figure 3.6, some critical technologies are listed needed to achieve a comprehensive and proactive online analysis system.

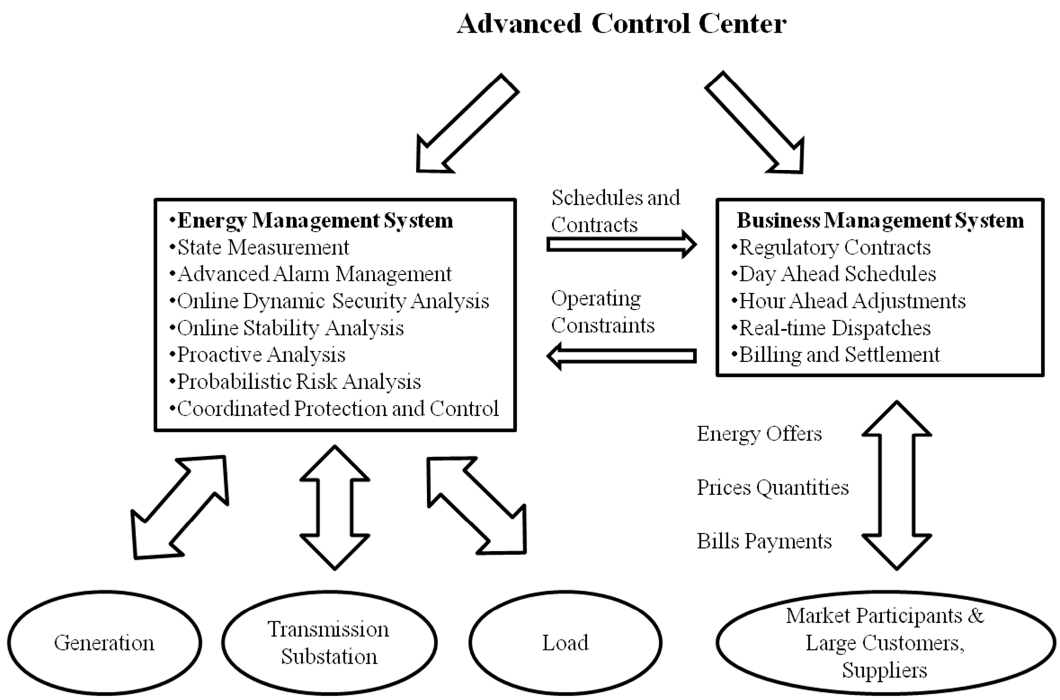


Figure 3.6 Next generation of Control Centre with advanced applications.

- *Dynamic State Estimation:* State measurement is the foundation that enables real-time stability assessment. To accomplish state measurement, the transmission system needs to install an adequate number of synchrophasor measurements and establish an appropriate enabling communication infrastructure.
- *Advanced Alarm Management*: Existing alarm management methods are not effective and become overloaded with useless information [93]; an advanced

system should track on-going root causes and only present information critical to grid operators.

- *Online Dynamic Security Analysis:* Future Control Centres shall carry out both steady-state and dynamic security assessment in real time, to support system operators to determine operating boundaries such as thermal, voltage stability and small-signal stability limits.
- *Online Stability Analysis:* The broad implementation of disturbance-monitoring technologies, such as PMUs, open new opportunities for measurement-based analysis. The analysis function may adopt both simulation-based and measurement-based approaches, complementary to each other.
- *Proactive Analysis:* Online analysis may take a proactive approach to perform look-ahead simulation on future system conditions.
- *Probabilistic Risk Analysis:* The present technology applies N-1 contingency in a deterministic approach [93]. In the future, cascading failure may be considered with probabilistic risk analysis.
- *Coordinated Protection and Control:* The present implementations of protection and control technology lack system-wide coordination, and are designed to only solve a single problem [93]. The future system should be able to fully utilize real-time, system-wide information, dynamically adjust the protection and control to achieve optimal control performance with minimum control interventions.

Furthermore, Control Centres must be able to cope with large number of new influencers in a dynamic market environment, such as regulatory agencies, energy markets and independent power producers [93].

3.3 WAMPAC Applications and Communication Needs

The traditional use of PMUs has been in post-event analysis. The logged phasor data on the server is the foundation to understanding system operation and the causes of any abnormal conditions, power fluctuations or blackouts. After enjoying years of consistent development, WAMPAC has enabled the feasibility of several applications to be proposed and proven through theoretical analysis [5]. The communication needs for each application have been discussed in [6] and [94].

3.3.1 Dynamic Disturbance Recording

Experience has shown that synchronized wide-area system recordings of dynamic events is invaluable in analyses of system performance, in understanding of system behaviour and the types of control actions required during large-scale disturbances [92]. Compared with traditional Digital Fault Recording (DFR), WAMPAC is more flexible and efficient. Firstly, synchronization is achieved amongst the PMUs and central control stations. Furthermore, since the function is globally organized, a holistic view of network conditions and triggered events can be captured. Last but not least, dynamic disturbance recording can be combined with other functions to obtain further information and understanding of the system. For instance, recorded data can be used for low-frequency oscillation analysis, model/parameter identification, and simulation validation [77].

3.3.2 Dynamic State Estimation

A. PMU-based State Estimation

Power system State Estimation (SE) [95], developed in the 1960s, is one of the most critical online applications needed for an efficient Energy Management System (EMS). Real and reactive power in line flows and injection points are acquired so as to estimate the bus voltage angles and magnitude [5]. In traditional state estimation, data is scanned from Remote Terminal Units (RTUs) through a SCADA system every 2-5 seconds. The power system is assumed to be static during the scan, which is not the case for real systems; PMU data is time stamped at source and the static assumption removed. Since voltage and current measurements are linear functions of the system state, estimation is based on linear weighted least squares [96] which requires no iterations. Moreover, phasor data can be flagged at source as bad data based on one of a number of causes which affects data accuracy.

The advent of state estimation enables many real-time Control Centre functions, including scheduling generation and interchange, monitoring outages and scheduling alternatives, supervising scheduled outages, scheduling frequency and time corrections, coordinating bias settings, and emergency restoration of the system.

The number of PMUs required to achieve full network observability is normally 1/3 of the total number of buses in the grid [10]. New measurements as often as 30 packets per second for a 60 Hz system or 25 packets per second for 50 Hz system would provide a truly dynamic and linear estimation [176]. According to the IEEE 37.118 standard [39-41], each Phasor is represented by a maximum of 54 bytes (3-phase in float format) and each data frame contains a 48 bytes header and trailer. Since the first step of the SE function is to enable control and protection functions, only delays of less than 100 milliseconds can be tolerated [94].

B. Seams Between Neighbouring State Estimates

In addition to Phasor-based state estimation, PMU data can also contribute to achieving the synchronization of phase angle between neighbouring state estimates [95]. This is often needed for EMS tasks such as contingency analysis [6]. Thus a potential solution might simply distribute the separate estimators on a common reference by measuring the phase angle between separate references. In this case, two PMUs are required to be installed on the same bus, able to be viewed by both operators. A second possibility is to concentrate on the buses at the boundary between the two systems (Figure 3.7), more suitable for phase synchronization in a distributed control system. The reference phase at the boundary buses can be used to estimate the difference in reference angles.

The packet structure of PMU data for synchronization between neighbours remains the same as for data for state estimation. However, latency can only be tolerated up to a second [94].

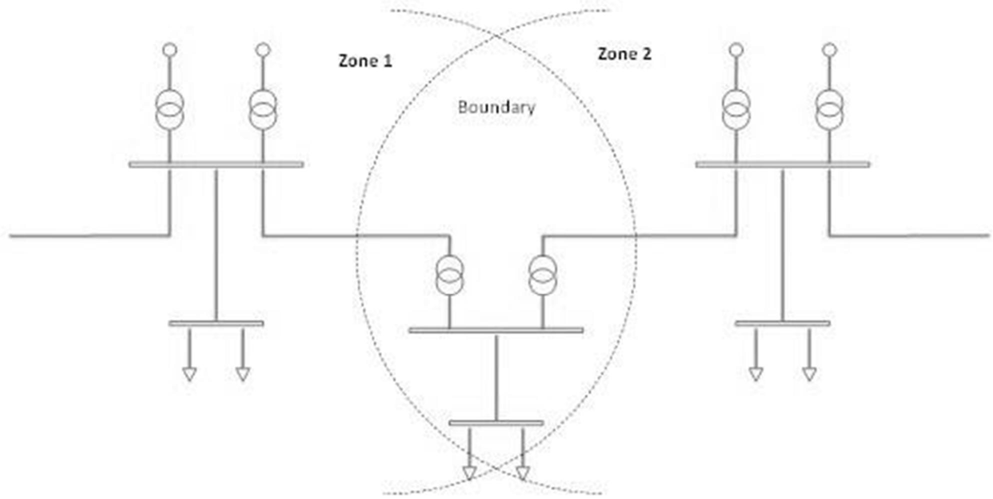


Figure 3.7 Common buses at the boundary of two operating systems.

C. Calibration of Instrument Transformers

By using PMU data and tested calibration data from few instrument transformers, it is possible to obtain accurate calibration of current and voltage transformers. Simulations have shown that measurements under light and heavy loading conditions combined, provide the best performance for evaluation of instrument transformer calibration [84]. The entire process can be carried out as often as necessary in order to achieve calibration under different ambient temperatures, different burdens, and under different aging conditions [6].

With sufficient number of measurements captured from SE, a Weighted Least Square (WLS) function can be implemented to calculate the ratio correction factor [95]. The same sets of data can be used for both tasks. Since all needed information has been transmitted and stored in a Control Centre and the pre-stored data can be addressed every 12 hours when doing a calibration calculation, data transfer delay is not a major concern for the application.

D. Real-Time Network Model Parameters Measurement and Estimation

In traditional parameter estimation (PE) approaches, the power system model parameters are estimated from available measurements. The implementation of synchronized PMUs enables real-time estimation of unknown parameters, hence improving the overall state estimation process. By improving measurement redundancy, more accurate system model parameters can be derived. Furthermore, network parameters can be updated in real time for better state estimation and other applications [6]. As in the calibration calculation, measurements can be calculated from PMU state estimation data and no delay criteria are required.

3.3.3 Real-Time Congestion Management

Congestion management is a critical function performed by power schedulers in advance energy markets and by grid operators in real time [6]. It involves generation dispatch (in day-ahead markets) and re-dispatch (in real-time markets) to satisfy the demand in an economic manner without violating the generation or transmission limits [6]. The goal of the real-time congestion management is to maintain real-time flows across transmission lines and paths within reliable transfer capabilities through optimal dispatch adjustments. Prior to the traditional offline calculation of transfer capability [6], PMU based calculations provide more accurate path limits in real time. Higher scan rates and improved precision of data enhance the speed and quality of real-time transfer applied to the most critical stability-limited and voltage-limited paths.

3.3.4 Wide Area Protection

Disturbances in power systems usually develop gradually; but the time scale in which the dynamics of the disturbances that affect the underlying power network may range from several minutes to milliseconds, depending on the type of disruptive event. In all cases, the sequence of actions needed for effective protection and control consist of the following [6]:

- Identification and prediction
- Classification and location of the disturbances
- Decisions and actions to be undertaken to arrest the degradation of the system state and assure a return to the secure state.

Knowledge of the complete state of the power system, represented by several network parameters, requires real-time state measurements as inputs. Among the parameters are:

- Active (or reactive) power flows in the network;
- Reactive power reserves at major power generating plant;
- Voltage magnitudes in selected locations (effective for detecting equipment overloads, voltage collapse conditions, etc.);
- Phase angle differences between locations of interest (often ends of major transmission links, used for detection of out-of-step conditions and development of cascading events);
- Driving point impedances from certain locations (used in designing out-of-step tripping or blocking schemes);
- Resistances and their rates of change (used for speedup of out-of-step detection);

- Frequency and rate of change of frequency;
- System spinning and cold reserves (for under-frequency load shedding schemes, system separation, and controlled islanding schemes);

In an environment where the protected area is large, to design a protective or emergency control scheme based on fixed parameter settings is challenging. An adaptive approach is preferred in such circumstances, possessing the ability to adjust to changing conditions [94]. Protection systems that can derive great benefit from PMUs include control of backup protection of distance relays, protection functions concerned with angular voltage stability of networks, adaptive voting schemes where dependability and security could be reassessed based upon the stress of the system [94].

A. Adaptive Dependability and Security

The principle is to adjust the balance between dependability and security of a protection system at critical locations throughout the power system [94]. Assuming that the redundant protection scheme at such critical locations include three independent relays, their trip outputs connected in logical 'OR' function providing high dependability, most appropriate when the power system is in a normal state. However, when it is determined at the System Control Centre that the system is in an emergency state, the trip output logic is changed to a 'vote' mode, requiring that two out of the three relays provide a trip decision before a trip is issued.

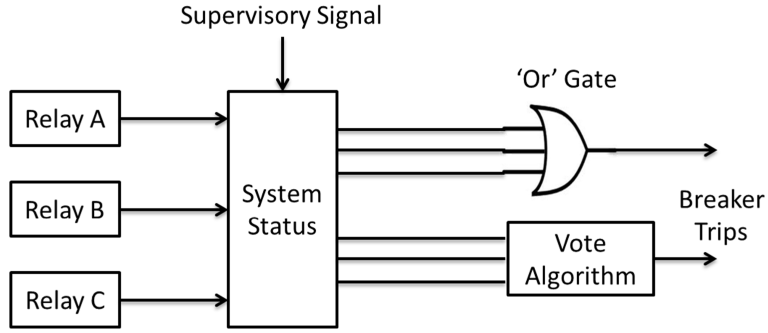


Figure 3.8 Adaptive dependability and security control algorithm.

The communication needs for this functionality are modest. Upon detection of the emergency status, a message is sent to the critical relay to alert of the transition from normal state to emergency state. The transmission of data is not related to any system fault or other transient, so that its arrival time or latency is of no consequence. An Acknowledgement is required to identify whether the state of the system is updated successfully.

B. Monitoring approach of apparent impedances toward relay characteristics

Relay characteristics are determined by protection engineers off-line, and these settings are only available before the power system conditions are updated or are required to be reviewed and revised periodically. PMUs located at critical relays could help to calculate the apparent impedance at those locations, and if a particular relay setting is inappropriate for prevailing system conditions, the PMU can detect the onset of the apparent impedance towards the relay trip characteristic. When the apparent impedance falls within a pre-set limit of the characteristic, an alarm is generated and a message is issued to the relay engineer of the need to review the setting in question. Since only the alarm needs to be transmitted, the amount of data is minimal and the operation can be done at a non-critical time.

C. Adaptive out-of-step

The task is a two-step process: 1) Rotor angles of all major generators are monitored in real time. The reporting rate of the measurements is normally set to be 30 measurements per second for a 60 Hz system. 2) If the difference between the centres-of-angle exceeds a limit of around 120-150 degrees, a major transient stability event is declared. In the event of instability, islanding of coherent groups of components is performed [94].

Thus if there are N large generators in the network, it is necessary to transmit '2N' of Phasor data, including positive sequence currents and voltages, to the Control Centre. Considering each Phasor is represented by 54 bytes of data and each data frame has 48 bytes header and trailer, the total amount of data would be 2N * 102 * 30 bytes for a 60 Hz system. Latencies of 50 milliseconds are acceptable for this application.

D. Supervision of back-up zones

Mis-operation of a trip event is one of the major factors in power system blackouts. Unusual load flows and power swings during the progression of events following major disturbances are mistaken to be faults in the back-up zones of the distance and over-current relays. As the back-up zones of relays are determined by the apparent impedance presented at these relay locations, additional line trips occur, leading to cascading failures and a descent into a black-out.

One of the solutions to this problem is using a counter-measure based supervision function. If indeed the event is a fault in the back-up zone of the distance relay, the apparent impedance will be identified in one of the specific zone area by more than one remote PMU. The more PMUs record the fault in the same back-up zone, the more reliable the trip events will be. Thus such supervision will prevent false trips at critical junctures in the progression of a cascading failure.

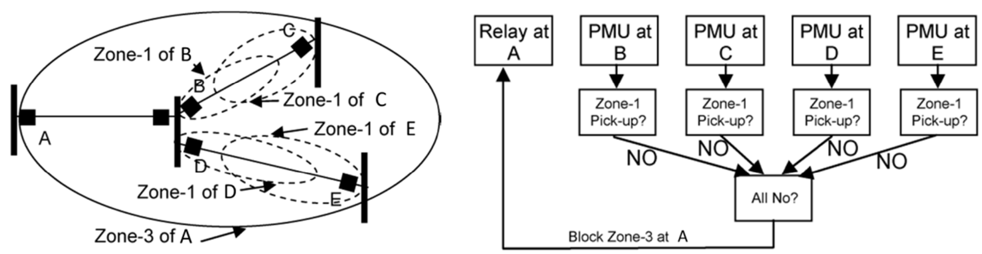


Figure 3.9 Counter-measure based supervision function [6].

The signal will only be transmitted from the Control Centre to the relay when a fault event is identified in a back-up zone and each transmission could be easily accommodated within a 100 byte message, while at the Control Centre, at most, 10 times that data volume will be received.

E. Adaptive loss-of-field

Loss-of-field relay is applied at the terminals of large generators to avoid steady-state instability of the unit due to a defect in the excitation circuit. Those critical transmission lines are monitored by the Control Centre, and upon determining that a significant change has taken place in the Thevenin impedance, a signal sent to the loss-of-field relay to change to the appropriate setting group [94]. At most, a 100 byte message is needed to accomplish this task. Since it is assumed that this condition occurs when a major catastrophic event is in progress, the latency of the signal delivery is critical and a delay of more than 50ms is not acceptable.

Furthermore, PMUs can track local frequencies at different locations, providing useful data for estimation and location of disturbances for further control actions. These may contribute to intelligent load shedding and islanding [85-87].

F. Intelligent load shedding

Load shedding is used to balance limited generation with heavy load when a system island is formed. If the increase in the tie-line flows is greater than a pre-calculated limit, it is necessary to reduce system load in order to avoid a break-up and formation of an islanded system. Tie-line flows are calculated by the PMUs using the current and voltage at the tie buses and the data are sent back to the Control Centre. A 100 bytes data frame is sufficient to contain the necessary information. System break-up due to instability should not develop in less than a few hundred milliseconds, so that data latency under 50 milliseconds is acceptable.

G. Intelligent islanding

An intelligent islanding scheme is required when forming system islands since instability is inevitable [94]. Decisions need to be communicated to appropriate circuit-breakers for tripping of lines or transformers. The total size of packet containing the decision is no more than 100 bytes and the latency needs to be controlled under 50 milliseconds.

3.3.5 Wide Area Control

The possibility of accurate monitoring of power flows of interconnected areas and heavily loaded lines by PMUs offers the opportunity to operate closer to stability limits with confidence of accurately knowing the operating point. Additionally, as the global operating condition is known with more confidence, system operators in turn can identify stability margins of the power system with greater confidence, particularly in terms of angular and voltage stability [94].

The use of PMUs has enabled monitoring of the dynamic behaviour of power systems, identifying inter-area oscillations modes in real time. The ability to detect and identify these oscillation modes has encouraged power engineers to study inter-area oscillation control using Power System Stabilizers (PSSs) and Flexible Alternating Current Transmission System (FACTS) technologies [6]. The ability to detect and control inter-area oscillations furnishes the system operator with more confidence to exploit the full transmission capacity more efficiently.

A. Control of sustained oscillations

Damping of low frequency inter-area oscillations through the use of remote synchronized phasor measurements is an attractive first application of PMUs in power system control. The number of remote measurements needed for control is still a research topic but 5 control devices and a total of 25 remote measurements seem to be an approximate upper bound to assess ultra-low frequency modes of any power system [94]. Remote measurements might have to be transported across hundreds of miles (from adjoining ISO’s) so the actual transmission delay is significantly greater than in state estimation. The low frequency of the oscillations is an advantage in this control application. With periods of oscillation in excess of a second latency, 200-300ms delays are tolerable. Repetition rates of 30 times a second are recommended.

B. Control of large oscillations

The research necessary to make precise statements about the control of major disturbances such as transient instability events that lead to islanding or even blackouts has not been completed. Some system disturbances that fall in this category include [71]:

- Transient instability (less than a second);
- Dynamic instability (less than a few seconds);
- Frequency instability (less than a few seconds);
- Poorly damped or undamped oscillations (less than some seconds);
- Voltage instability (less than a few minutes);
- Severe thermal overload (less than some minutes)

The proportional control used to damp small signal oscillations is unlikely to stop a system from islanding. Just as in the damping of inter-area oscillations, distant measurements are communicated to a central location where appropriate logic and computation determines the required control action. The number of remote measurements and control devices will be at least as large as that needed for inter-area oscillations because while the parts of the system involved in a 0.34 Hz oscillation, for example, are known and largely unchanging, the potential major disturbances are much harder to predict. The remaining difficulty is that the frequency content of the measurements during a major disturbance is higher than for ultra-low frequency inter-area oscillations. The authors of [94] proposed that a total of 50 measurements and control signals at 30 times a second (in a 60Hz system) are required at a delay tolerance of fewer than 50 milliseconds.

3.3.6 Summary

The monitoring applications that enable dynamic estimation of the system through synchronized phasor data can also act as the first step in implementing advanced protection and control. The three main monitoring applications are State Estimation (SE), Seams between State Estimates (SSE) and Instrument Transformer Calibration (ITC). In the SSE application, the PDC collects reference angles from adjoining Independent System Operator (ISO) to synchronize the state estimation for different areas. As for ITC, all the required information is uploaded by the SE function periodically and that pre-sorted data is refreshed every 12 hours when executing calibration calculations. Hence, the data exchange required in SE and ITC applications can be derived from the same traffic profile.

Typical protection applications include Adaptive Dependability and Security (ADS), Monitoring Approach of Apparent Impedances (MAAI), Adaptive Out of Step (AOS), Supervision of Back-up Zone (SBUZ), Adaptive Loss of Field (ALF), Intelligent Load Shedding (ILS) and Intelligent Islanding (II). Depending upon the communication latency needs, all are categorized into non critical applications which can tolerate up to one second delay, e.g. ADS, MAAI, and time-critical applications, the maximum acceptable delay being below 50ms.

Wide area control is the most attractive application as real time control, significantly decreases the probability of large area blackouts; existing applications include Control of Inter-area Oscillation (COIO) and Control of Large Oscillation (CLO). Both applications transport distant measurements from adjoining ISOs (hundred miles away) to a central location where logic and computation determines the appropriate control action, which is then communicated to distant controllable devices.

Table 3.3 WAMPAC applications and their associated communication requirements.

Applications	**Throughput (Bytes/sec)**	**Latency (msec)**	**Reliability Req.**	**ACK**
SE	3060 x No. PMUs	<100	Medium	None
SSE	102 x No. Boundary PMU	Not Critical	Medium	None
ADS	<100	Not Critical	High	ACK required
MAAI	<100	Not Critical	Low	None
AOS	3060 x No. Generators	50	Medium	None
SBUZ	<1000	50	High	ACK required
ALF	<100	50	High	ACK required
ILS	3000 x No. Tie Lines	50	Medium	None

II	100 x No. Circuit Breakers	50	High	ACK required
COIO	91800	200	Medium	None

As shown in Table 3.3, the requirements of all WAMPAC applications are summarized in terms of throughput, latency, reliability and feedback control. Throughput represents the sum of the data traffic to be exchanged across the network. The arrival rate of various applications ranges from a few hundred bytes to few mega-bytes every second. For example, the centralized PDC collects a large amount of data from all PMUs in the SE application; and control functions such as COIO only require ‘sufficient’ data to make a decision and the number of measurements retrieved from the remote PMUs directly influence the accuracy of the determination. In contrast to those high load applications, adaptive protection operations only require one packet to be transmitted containing the system status or emergency signal from the Control Centre. In this case the throughput of the data flow is no more than few hundred bytes.

Reliability is identified as the level of assurance in forwarding data packets. Those applications sensitive to packet losses or errors have a higher specification on the reliability in forwarding data and vice versa [94]. With appropriate Forward Error Control (FEC) [91] and acknowledgements, a high level of reliability can be assured [6].

3.4 Conclusions

The Chapter starts by introducing the generic structure of a WAMPAC system. Major elements such as PMUs, PDCs and the Control Centre are presented and the principles of Phasor measurements are developed.

With an understanding of the basics of WAMPAC, a range of potential applications in flexible power networks are introduced. Compared to conventional functions, significant improvements have been made in the mix and functionality of potential applications. The operation of monitoring application migrates from static logging based functions to dynamic real-time estimation. In protection applications, stand-alone actuators are controlled based on local information in conventional systems. With WAMPAC, adaptive protection functions are implemented on actuators enabling a global view of system status. Furthermore, control functions will also collect real-time data from adjoining ISOs so as to monitor system oscillations dynamically. Since higher data volume and lower response times are required to enable the applications, challenges in communication network performances are a major issue. Thus the corresponding communication needs are highlighted mainly in terms of throughput, latency and reliability in the end of the chapter.

Chapter 4

Placements of Phasor Measurement Units (PMUs)

4.1 Introduction

Recently, the most significant investments in the power system have shifted from renewing the hardware power infrastructure to deploying systems that execute on information collection and intelligent control [97]. The design and implementation of a real time monitoring and rapid response control systems is one of the major challenges in the evolution of future transmission networks. In recent years, researchers have proposed Wide Area Measurement, Control and Protection (WAMPAC) strategies to fulfil the requirements and PMUs are the key measurement elements that provide raw data on the status of the entire power system.

The overall goal in PMU placement is to identify optimal locations that maximize their benefit across multiple applications, as well as offering the least-cost solution by leveraging existing and planned infrastructure upgrades across the power company's footprint and its neighbouring systems. To achieve this objective, a methodology based on the 'Analytic Hierarchy Process (AHP)' [98] and the 'Weighted Average Criterion' for prioritizing topology design has been adopted. AHP is a systematic approach for priority setting and decision-making that decomposes any complex decision problems into more easily comprehensive sub-problems. Based on AHP, a detailed mapping of the decision criteria for network topology design is shown in the Figure 4.1. Hence, the criteria for designing optimum PMU placement can be categorized into 'Application Requirements' and 'Infrastructure Considerations'.

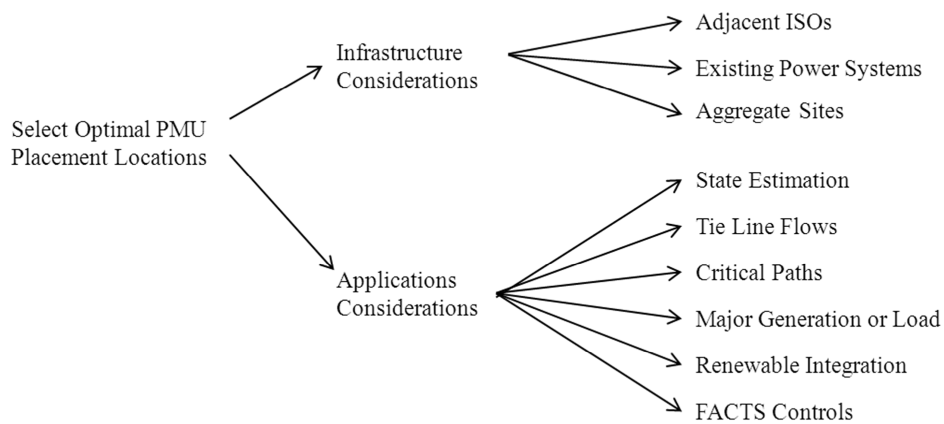


Figure 4.1 The Analytic Hierarchy Structure for PMU placement decision criteria.

4.2 Phasor Measurement Units Placements for State Estimation

If an estimate could be determined through PMU data only, then issues of data scan and time skew can be easily eliminated [99]. Since PMU data is time-tagged by GPS devices, an estimate might be obtained shortly after the measurements are acquired because of communication delays but it is nevertheless an estimate of the state of the system at the instant the measurements were made.

PMUs located within substations access line currents in addition to bus voltages;

sampling both voltages and currents at the same instants ensure that all Phasors are related to the same reference. Using a model of the transmission line, knowledge of the line current is used to compute the voltage at the other end of the line (Figure 4.2). Measuring line currents extend the voltage measurements to buses with no installed PMUs [5].

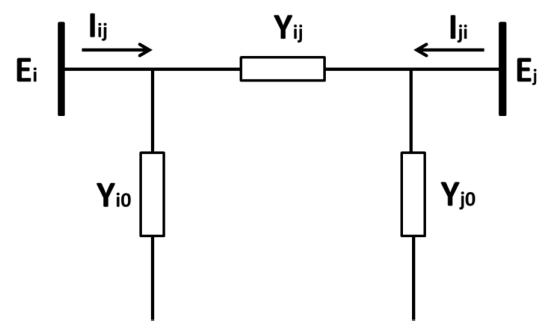


Figure 4.2 Equivalent circuit for a power transmission line [5].

Equation (4.1) represents the correlation between the line current and voltage at the ends of transmission lines;

$$\begin{bmatrix} I_{ij} \\ I_{ji} \end{bmatrix} = \begin{bmatrix} Y_{ij} + Y_{i0} & -Y_{ij} \\ -Y_{ij} & Y_{ij} + Y_{j0} \end{bmatrix} \begin{bmatrix} E_i \\ E_j \end{bmatrix} \tag{4.1}$$

Therefore, using the smallest number of PMUs to indirectly measure all bus voltages, the objective shifts to determining the optimum PMU locations to achieve this, the subject of this Chapter. The goal is to place PMUs so that at each stage, the selected location satisfies specific design criteria. One criterion is the degree of unobservability, a measure of the distance a bus is from a PMU. Calculations of optimal PMU placements involve integer programming [100] and the network incidence matrix [68].

4.2.1 Overview of PMU Placement Methodologies

Due to the high cost of a single PMU and the corresponding supporting communication infrastructure, a major design effort have been devoted to maximizing the observability of the network for a minimum number of deployed PMUs. Baldwin and Mili [100] proposed a dual search algorithm that uses a modified bisecting search and a Simulated Annealing based method to find the placement of a minimal set of PMUs to make the system measurement observable. They concluded that when the system parameters are known accurately, PMUs are required in only 1/4 to 1/3 of all network buses to ensure full observability. In addition to Simulated Annealing (SA) and Genetic Algorithm (GA) [101], the Tabu Search [101] and other meta-heuristic approaches have been applied to accomplish the objective of minimum number of PMUs for full observability. Nuqui [102] made use of spanning trees of the power system to identify the optimal location of PMUs by generating and searching a large amount of trees; an extension of the analysis was based on simulated annealing in order to meet the communication facility restrictions. Xu and Abur [103] employed Integer Programming to solve the optimization of PMU placement. In order to properly take advantage of zero injection buses, topology transformation and nonlinear Integer Programming were applied. Table 4.1 gives summarized advantages and disadvantages of each method. The choice of algorithms is dependent on the size of the problem and type of application.

Table 4.1 Placement algorithms advantages and disadvantages [104, 155].

Technique	Advantage	Disadvantage
GA based [105-107]	Robust, adaptable, IGA provides optimal solution	Long execution time
Binary search [108]	Exhaustive search, deals well with conventional measurements	Time consuming, not tested on larger IEEE-bus systems
Integer Programming [10, 103, 109]	Computationally fast method, adaptable	Constraints are non-linear
Particle Swam Optimisation [110]	Optimal solution reached	Doesn't consider computational time or contingencies, Not User Friendly. Not adaptable
Tree Search and Topology [100, 102]	Simple logic and PMU implementation	Generally suitable for power systems already equipped with a few observable islands. Some Results not optimal.

From Table 4.2, most reported algorithms can derive the optimum number of PMUs and methods with adaptability and user friendliness are often selected as candidates in defining PMU placements. Here, Integer Linear Programming (ILP) is adopted as the optimization methodology for further analysis.

Table 4.2 Minimum PMU placement algorithm comparison [104].

Technique	IEEE 14-Bus	IEEE 30-Bus	IEEE 57-Bus	IEEE 118-Bus
Optimal Number [104]	3	7	11	28
GA based	3	7	12	29
Binary search	3	7	-	-
Integer Programming	3	7	11	28
Particle Swam Optimisation	3	7	11	28
Tree Search and Topology	3	7	11	-

'-' indicates the algorithm hasn't been tested in the standard model.

4.2.2 PMU Placement with Full Observability

The observability of a bus depends on the installation of properly located PMUs, at that bus or one of its incident buses. The placement problem for complete observability can be solved through Integer Programming [10]. For an n-bus system, the PMU placement can be formulated as:

$$min\sum_{i}^{n} f_i^T \cdot x_i \quad (4.2)$$

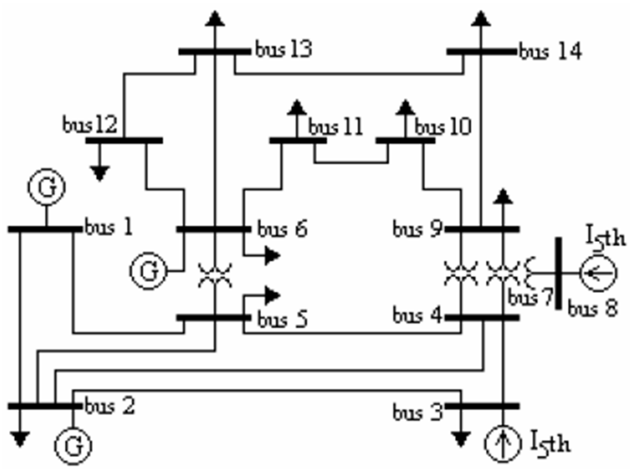
subject to $\mathbf{Ax} > 0$

where

$\mathbf{x}$ is the binary decision variable vector. f_i^T indicates the cost of PMU installation at the bus, equalling 1 in normal cases. The network incidence matrix $\mathbf{A}$ is a square matrix with the dimension of the number of buses;

$$a_{i,j} = \begin{cases} 1 & \text{If } i \text{ equals to } j \\ 1 & \text{if buses } i \text{ and } j \text{ are connected} \\ 0 & \text{otherwise} \end{cases}$$

For Example, the network incidence matrix A for an IEEE 14 bus system is shown in Fig. 4.3.



$$A = \begin{bmatrix}
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1
\end{bmatrix}$$

Figure 4.3 The 14x14 bus-bus incidence matrix for the IEEE 14 bus [10].

Based on Equation (4.2), the network incidence matrix can be represented as a set of inequality functions:

$$
\begin{aligned}
f_1 &= x_1 + x_2 + x_3 \\
f_2 &= x_1 + x_2 + x_3 + x_4 + x_5 \\
f_3 &= x_2 + x_3 + x_4 \\
f_4 &= x_2 + x_3 + x_4 + x_5 + x_7 + x_9 \\
f_5 &= x_1 + x_2 + x_4 + x_5 + x_6 \\
f_6 &= x_5 + x_6 + x_{11} + x_{12} + x_{13} \\
f_7 &= x_4 + x_7 + x_8 + x_9 \\
f_8 &= x_7 + x_8 \\
f_9 &= x_4 + x_7 + x_9 + x_{10} + x_{14} \\
f_{10} &= x_9 + x_{10} + x_{11} \\
f_{11} &= x_6 + x_{10} + x_{11} \\
f_{12} &= x_6 + x_{12} + x_{13} \\
f_{13} &= x_6 + x_{12} + x_{13} + x_{14} \\
f_{14} &= x_9 + x_{13} + x_{14}
\end{aligned}
\tag{4.3}
$$

The operator "+"serves as the logical "OR" function and all functions listed are required to be larger than zero to ensure that at least one of the variables appearing in the sum is non-zero.

The placements of PMUs also need to be compatible with the existing devices in the system. In this case, the bus with the installed PMU and those connected to it can be directly or indirectly measured. For example in an IEEE 14 bus system, an existing PMU is installed at bus 1. The optimal placement of PMUs can be derived with equation (4.3) with $f_1 = x_1 + x_2 + x_3 = 1$.

4.2.3 PMU Placement with Partial Observability

A novel concept - partial observability - introduced in [102], refers to the network condition in which the number and location of the PMUs are insufficient to determine a complete set of bus voltages. Also, the depth of unobservability is a measure of the distance of an unobserved bus from its observed neighbours; the concepts of depth-of-one and depth-of-two unobservability are illustrated in Figure 4.4.

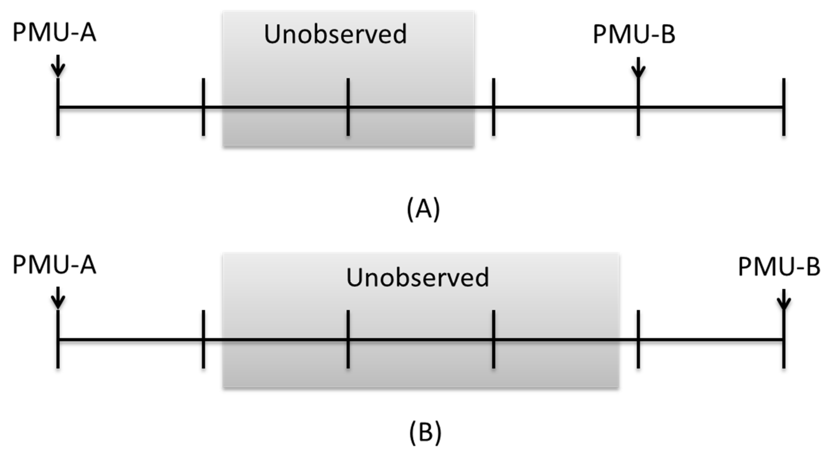


Figure 4.4 (A) Depth-of-one unobservability; (B) Depth-of-two unobservability.

Theorem: The *ij* entry in the nth power of the incidence matrix for any graph or diagraph is exactly the number of different paths of length *n*, beginning at vertex *i* and ending at vertex *j* [106].

For example, in the case of *n*=2, the network incidence matrix for the IEEE 14 bus system becomes:

$$sign(A^2) = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 \end{bmatrix}$$

Thus for a depth-of-n unobservability;

$$min \sum_{i}^{n} f_i^T \cdot x_i \tag{4.4}$$

$$\text{subject to } (\mathbf{A}^{n+1})\mathbf{x} \geq 1$$

where $\mathbf{x}$ is the binary decision variable vector and f_i^T indicates the cost of PMU installed at each bus.

4.2.4 PMU Placement with Multiple Observability

The loss of packets or bad data from a PMU plus errors incurred during communication lead to uncertainties in the network status [10, 153]. In order to enhance the reliability of the system, each bus is recommended to be observed by multiple PMUs. Within the ILP framework this can be treated by multiplying the right hand side of the inequalities by N redundant PMUs. Equation (4.2) thus becomes:

$$min \sum_{i}^{n} f_i^T \cdot x_i \tag{4.5}$$

$$\text{subject to } \mathbf{Ax} \geq N$$

For instance, all buses will remain observable when a single PMU is lost as long as N equals or is larger than two. Network reliability is increased at the expense of additional cost of duplicate PMUs.

4.2.5 Observability Maximization

The optimization of PMU placement determined through an ILP formulation yields multiple optimal solutions; the selection of the optimum solution can be found using the Bus Observability Index (BOI) [10] as a performance indicator on the quality of the optimization. The BOI for bus-I (B_i) is defined in [10] as the number of PMUs able to observe a given bus. Consequently, the maximum bus observability index is limited to maximum connectivity (n_i) of a bus plus one, i.e.;

$$B_i \leq n_i + 1 \tag{4.6}$$

The System Observability Redundancy index (SORI) is defined as the sum of bus observability for all the buses of a system;

$$SORI = \sum_{i=1}^{n} B_i \tag{4.7}$$

Maximizing SORI has the advantage that a larger portion of system remains observable in the case of a PMU outage.

4.3 IEEE Standard Test System

The performance of the Integer Programing Algorithm is examined on the IEEE 14-, 30-, 39-, 57-, and 118-bus test systems. Three different conditions are considered, i.e. complete observability; depth-of-1 unobservability and loss of measurement. Tomlab's Mixed-integer Linear Programming (MILP) solver [113] has been used to solve the problem (Table 4.2).

All simulation cases use the following assumptions [151];

(1) No bus limitations for the placement of PMUs, i.e. every bus are assumed to be a candidate for PMU placement.

(2) Installation costs of all PMUs are the same. Due to lack of any robust costs data, all PMUs are given the same weight in the optimization.

(3) Current Phasors along all branches incident to a bus are measured by the PMU at that bus.

These assumptions are made for convenience in carrying out the optimisation.

The general formulation in TOMLAB for a problem is:

$$\min_{x} f(x) = c^T x \tag{4.8}$$

$$\textit{subject to} \quad \begin{array}{c} x_L < \mathbf{x} < x_U \\ b_L < \mathbf{Ax} < b_U \end{array} \tag{4.9}$$

$c^T = [1,1,1,1.....1]$ represent the costs of PMU installations, set to be ones in the simulation. $\mathbf{x}$ is the binary decision variable vector, thus x_L, x_U are set to 0 and 1 respectively. The network incidence matrix A indicates the connectivity of the buses and b_L and b_U are the constrains on the linear matrix **Ax**. In the scenario of complete observability, **Ax** is required to be larger than 0; for the case of loss of single measurement, **Ax** needs to be larger than 1. The depth of n unobservability uses n*th* power of network incidence matrix to ensure $(\mathbf{A}^{n+1})\mathbf{x}$ is larger than 0.

Table 4.3 shows that the loss of measurement requires a higher number of PMUs in comparison with the complete observability option, because more than half of buses are installed with PMUs in order to obtain reliable measurement and hence accurate state estimation.

In Table 4.3, the optimal number of PMUs is listed, useful in the planning of the communication network that needs to support the exchange of resultant data taking note that the corresponding costs may be excessively high.

Table 4.3 Number of PMUs in different Observability scenarios using IEEE standard test systems

Test System	Size (Buses/Lines)	Complete Observability	Depth of 1 unobservability	Loss of Measurement
IEEE 14 Bus	(14,20)	3	2	9
IEEE 30 Bus	(30,41)	7	4	22
IEEE 57 Bus	(57,80)	11	8	35
IEEE 118 Bus	(118,186)	28	13	72

4.4 UK Power Network

In addition to the role as the Transmission Owner (TO) in England and Wales, The National Grid Electricity Transmission (NGET) became Great Britain's System Operator (GBSO) on 1st April 2005, following implementation of the British Electricity Transmission and Trading Arrangements (BETTA) [7]. On 24th June 2009, following the 'Go Active' for offshore transmission, National Grid became the National Electricity Transmission System Operator (NETSO), extending its GBSO operation to include the Offshore Transmission System. [7] ENTSO-E now has 42 Transmission System Operators (TSOs) members across 34 countries, sharing an interconnected transmission grid to the EU. Four UK TSOs are: Scottish and Southern Energy (SSE), National Grid (NGET), ScottishPower Transmission (SPT) and the System Operator for Northern Ireland (SONI). Figure 4.5 illustrates the locations of some installed PMUs in west Europe. In the near future, more PMUs will be deployed to support a fully-functional WAMPAC system.

Figure 4.5 Geographical locations of installed PMUs in west Europe.

The transmission system in UK operates at 400KV, 275KV and 132KV; the transmission network architectures for each of the transmission licensee's areas are listed in Table 4.4.

Table 4.4 Transmission system architecture transmission licensee's areas.

Network Operator	Location	Voltage level	Numbers of buses	Number of links
SHETL Network	North of Scotland	275 KV	7	12
SPT Network	Middle belt of Scotland	275 KV	23	31
		400 KV	11	16
NGET Network	England & Wales	400 KV	113	320

Currently there are four HVDC External Interconnections linking the NETS with External Systems [7]:

- Connecting converter stations at Sellindge in Kent and Les Mandarins near Calais in France
- Connecting converter stations at Auchencrosh in the south of the SPT system and Islandmagee in Northern Ireland
- Connecting converter stations at the Isle of Grain in Kent and Maasvlakte in the Netherlands.
- Connecting converter stations at Arklow substation in County Wicklow and Pentir Substation in North Wales.

Until the 1930's electricity supply in Great Britain was the responsibility of a multiplicity of private and municipally owned utilities, each operating largely in isolation. The Electricity Supply Act (1926) recognized that this was a wasteful duplication of resources. By interconnecting separate utilities through the high voltage transmission system, the pooling of both generation and demand occurred, providing a number of economic and system benefits.

4.4.1 Placement of PMUs in the SHETL Network

The SHETL area includes a significant amount of existing hydro, thermal power and other new renewable generation. Demand in this area is significantly lower than the installed generation; consequently this zone is normally an exporting zone [7].

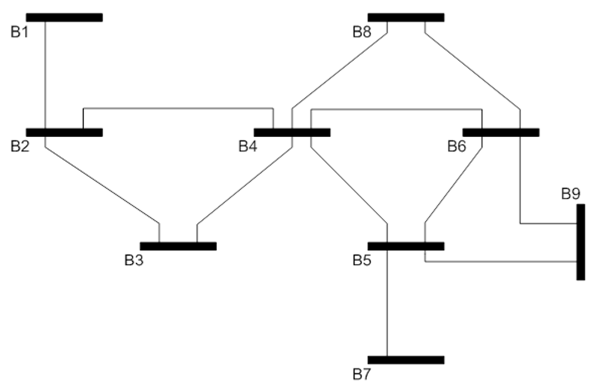


Figure 4.6 SHETL interconnected transmission system [7].

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

Table 4.5 Observability of SHETL network in different states.

System	SHETL Network	
Size (Bus/Lines)	(9, 12)	
Scenario	No of PMUs	PMU Locations
Full Observability PMU Placement	3	(2,6,7); (2,5,8); (2,5,6); (2,4,5); (1,4,5)
Depth-of-1 Unobservability	1	(4)
PMU Outages (Loss-of-one case)	6	(1,2,4,5,6,7)

4.4.2 Placement of PMUs in SPT-275 Network

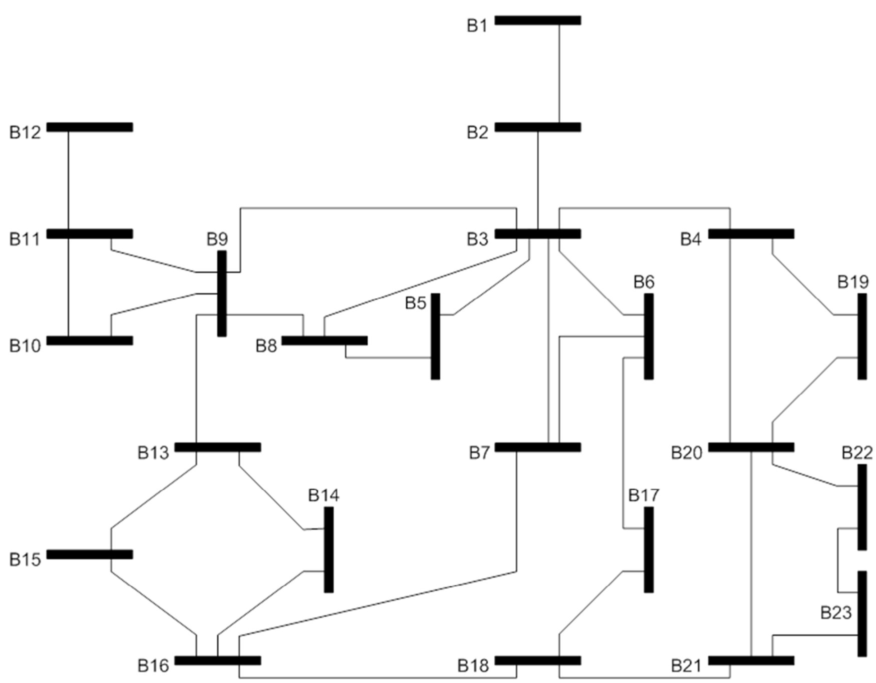


Figure 4.7 SPT-275KV interconnected transmission system [7].

$$A=\begin{bmatrix}
1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&1&1&1&1&1&1&1&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
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0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&1&1\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&1&1
\end{bmatrix}$$

Table 4.6 Observability of SPT-275 network in different states.

System	SPT-275 Network	
Size (Bus/Lines)	(23, 32)	
Scenario	No of PMUs	PMU Locations
Full Observability PMU Placement	7	(2,3,11,13,18,20,23); (2,3,11,13,18,20,22); (2,3,11,13,18,20,21); (2,3,11,13,18,19,23); (2,3,11,13,18,19,22); (2,3,4,11,13,18,23); (2,3,4,11,13,18,22); (1,3,11,13,18,20,23); (1,3,11,13,18,20,22); (1,3,11,13,18,20,21); (1,3,11,13,18,19,23); (1,3,11,13,18,19,22); (1,3,4,11,13,18,23); (1,3,4,11,13,18,22)
Depth-of-1 Unobservability	3	(3,9,21); (2,9,21); (1,9,21)
PMU Outages (Loss-of-one case)	15	(1,2,3,8,9,11,12,13,16,17,18,19,20,22,23)

4.4.3 Placement of PMUs in SPT-400KV Network

The SPT-400KV network is the primary importing corridor from Scotland (SHETL Network) to England (NGET Network) in the UK.

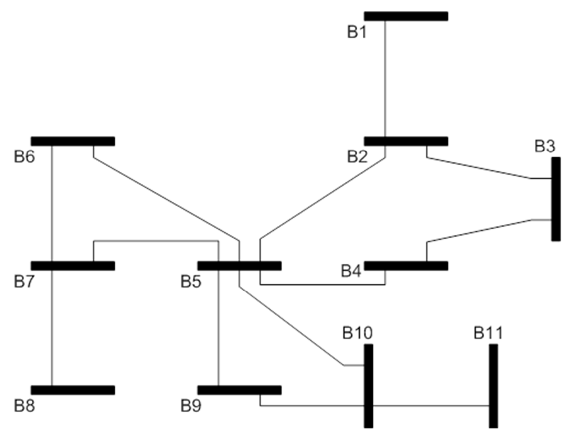


Figure 4.8 SPT-400KV interconnected transmission system [7].

$$A=\begin{bmatrix}1&1&0&0&0&0&0&0&0&0&0\\1&1&1&0&1&0&0&0&0&0&0\\0&1&1&1&0&0&0&0&0&0&0\\0&0&1&1&1&0&0&0&0&0&0\\0&1&0&1&1&1&1&0&1&1&0\\0&0&0&0&1&1&1&0&0&0&0\\0&0&0&0&1&1&1&1&0&0&0\\0&0&0&0&0&0&1&1&0&0&0\\0&0&0&0&1&0&0&0&1&1&0\\0&0&0&0&1&0&0&0&1&1&1\\0&0&0&0&0&0&0&0&0&1&1\end{bmatrix}$$

Table 4.7 Observability of SPT-400 network in different states.

System	SPT-400 Network	
Size (Bus/Lines)	(11, 13)	
Scenario	No of PMUs	PMU Locations
Full Observability PMU Placement	4	(2,5,8,11); (2,5,8,10); (2,5,7,11); (2,5,7,10); (2,4,7,10); (2,3,7,10); (1,4,7,10); (1,3,7,10)
Depth-of-1 Unobservability	1	(5)
PMU Outages (Loss-of-one case)	8	(1,2,4,5,7,8,10,11); (1,2,3,5,7,8,10,11)

4.4.4 Placement of PMUs in NGET Network

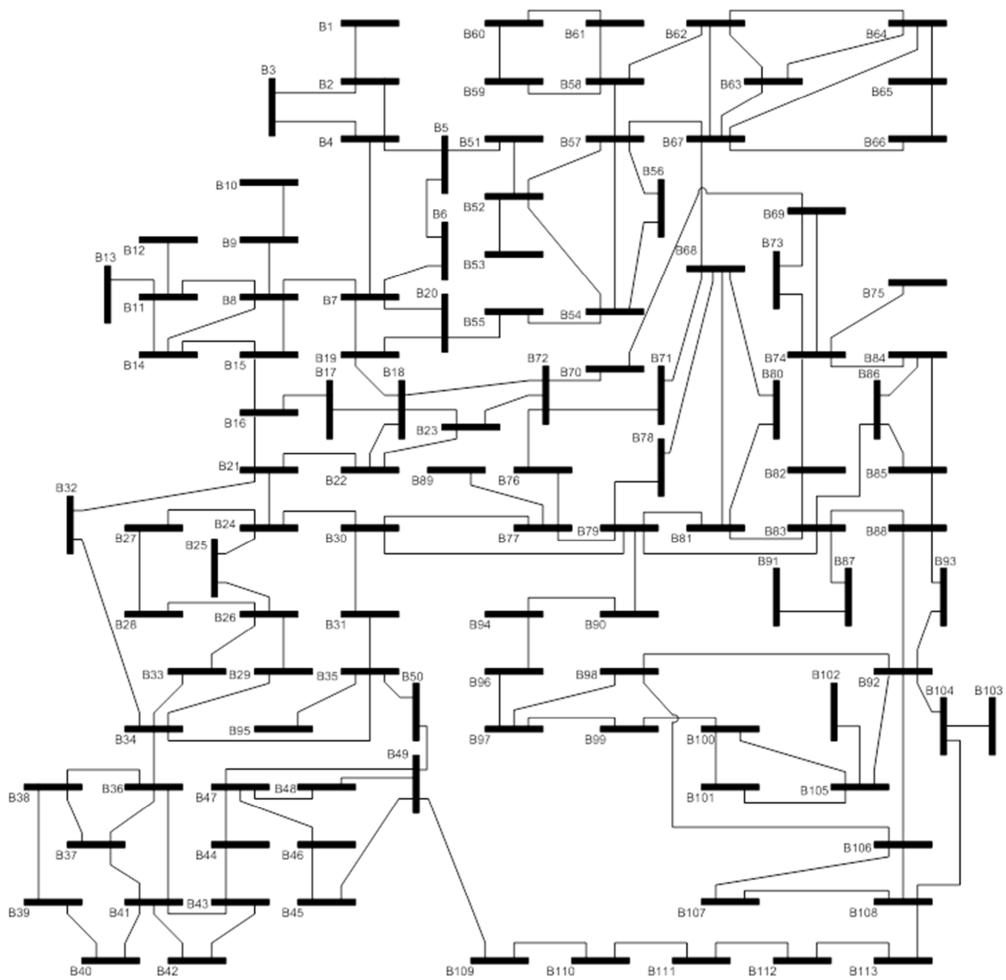


Figure 4.9 NGET interconnected transmission system [7].

Table 4.8 Observability of NGET network in different states.

System	NGET Network	
Size (Bus/Lines)	(113, 320)	
Scenario	No of PMUs	PMU Locations
Full Observability PMU Placement	36	(2,5,7,9,11,16,18,24,26,34,35,38,41,47,49,52,54,58,60,64,67,68,72,74,77,79,86,87,88,94,97,104,105,106,110,113)
Depth-of-1 Unobservability	16	(1,8,16,26,34,41,45,52,60,67,76,84,87,92,96,111)
PMU Outages (Loss-of-one case)	69	(1,2,4,5,7,9,10,11,12,13,14,16,18,20,21,24,26,27,31,33,34,35,38,39,41,43,45,47,49,52,53,54,57,58,59,61,64,65,67,68,69,72,74,75,77,79,80,83,85,87,88,89,90,91,92,95,96,97,100,102,103,104,105,107,108,109,110,111,113)

4.5 Results and Analysis

Table 4.9 lists the number of PMUs required to achieve a certain degree of observability. For placements with full-observability, a total of 48 PMUs are required split into 3 in SHETL, 7 in SPT-275, 4 in SPT-400 and 34 in NGET.

Table 4.9 Placements of PMU units across the UK transmission power grid.

	SHETL	SPT-275	SPT-400	NGET
Voltage	275 KV	275 KV	400 KV	400 KV
Number of Buses	9	23	11	113
Number of Links	12	32	13	320
Full Observability	3/(5)	7/(14)	4/(8)	36/(1608)
Depth-of-1 unobservability	1	3	1	16
PMU outages	6	15	8	69

The bracket indicates the number of groups of candidates which achieve full observability with minimum numbers of PMUs. In these cases, the Bus Observability Index is used to maximize the redundancy of observations (Table 4.10) e.g. there are 1608 sets of placement locations in NGET that can achieve a minimum number of PMUs with full observability. However, only one placement with the maximum SORI is selected as the optimal solution.

Table 4.10 System observability redundancy index for full observability placements.

	Min SORI	PMU placements for minimum SORI	Max SORI	PMU placements for maximum SORI
SHETL	11	(2, 6, 7)	15	(2, 4, 5)
SPT-275	13	(1, 4, 7, 10)	19	(2, 5, 7, 10)
SPT-400	28	(1,3,11,13,18,19,22)	32	(2, 3, 11, 13, 18, 20, 21)
NGET	134	(2, 5, 7, 9, 11, 16, 18, 23, 24, 26, 34, 35, 38, 41, 45, 47, 51, 53, 54, 60, 62, 66, 68, 70, 74, 77, 86, 90, 91, 92, 97, 104, 105, 108, 109, 112)	145	(2, 5, 7, 9, 11, 16, 18, 24, 26, 34, 35, 38, 41, 47, 49, 52, 54, 58, 60, 64, 67, 68, 72, 74, 77, 79, 86, 87, 88, 94, 97, 104, 105, 106, 110, 113)

The geographical locations of PMUs are shown in Figure 4.10; these locations are also presented in latitude and longitude in Appendix 1. Power systems have traditionally used dedicated telecommunications for almost everything. As in the transmission level, fibre optic cables within the earth conductor are common [49]. From Figure 4.10, the interconnected links represent the existing deployed fibre communications between each site. HVDC External Interconnections links are also taken into consideration (Figure 4.10). The calculated distribution and interconnections are combined as the reference architecture underpinning the analysis presented in Chapter 5.

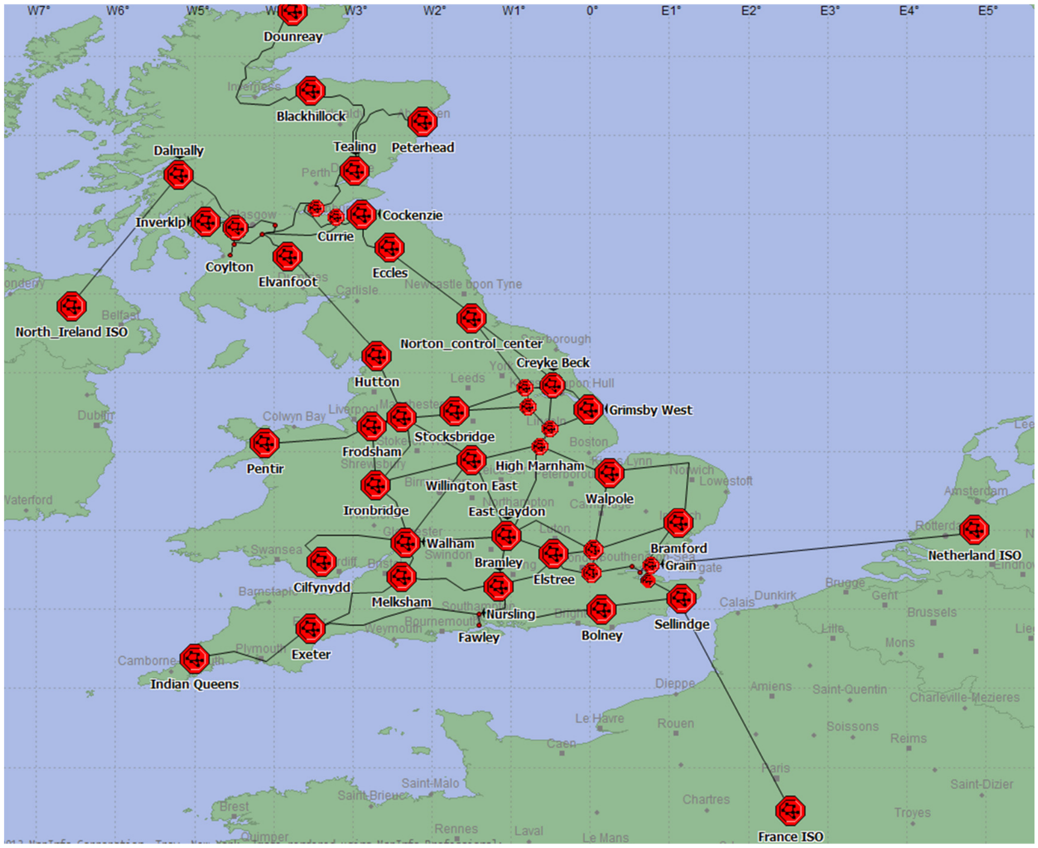


Figure 4.10 Optimised placements of PMUs in the United Kingdom.

4.6 Conclusions

This Chapter identifies the optimal locations of PMUs so as to maximise the range of applications that can be implemented, at the lowest cost. Due to the high cost of a single PMU and supporting communication infrastructure, a major design goal is to maximise the observability of the network for a minimum number of deployed PMUs. Most of the reported algorithms can determine the optimum number of PMUs but ILP is the most adaptable and user friendly and has been used in this research.in determining the placements of PMUs across the UK power network.

Optimized PMU placements are analysed for full network observability, incomplete network observability and redundant monitoring. Different placements schemes enable dynamic state estimation of the entire system and at the same time is core to the planning of the communication network needed to support the exchange of data, noting that the concomitant costs may prove to be excessively high.

ILP methods are applied in IEEE standard model and the deployed UK power system. The Bus Observability Index is also used to maximise the redundancy of observations. Results indicate a total of 48 PMUs are required to achieve a full observability of the UK system. Additional remote PMUs located in North Ireland, France and Netherland mean that a total of 51 PMUs are needed as the basis for provisioning WAMPAC protection and control applications.

Compatibility is another key issue in designing a reliable and cost-effective system. Power systems have traditionally used fibre optic cables within the earth conductor in the transmission level. These existing communication infrastructures provide reliability through years of practical tests and conveniences in deploying a new system. Therefore, the proposed network architecture makes use of these existing communication infrastructures to interconnect the PMUs in WAMPAC system.

Chapter 5

Control-based Topology Design for WAMPAC Systems

5.1 Challenges in Designing a Communication System

Designing an end-to-end communication system involves not only collecting and delivering PMU measurements with a certain Quality of Service (QoS), but also has to take into consideration legacy infrastructure e.g. easy interfacing with existing Energy Management Systems (EMSs). The solution must provide information exchange amongst substations and/or Control Centres in the same layer, as well as cross-layer interfacing between substations and Control Centres, as shown in Figure 5.1.

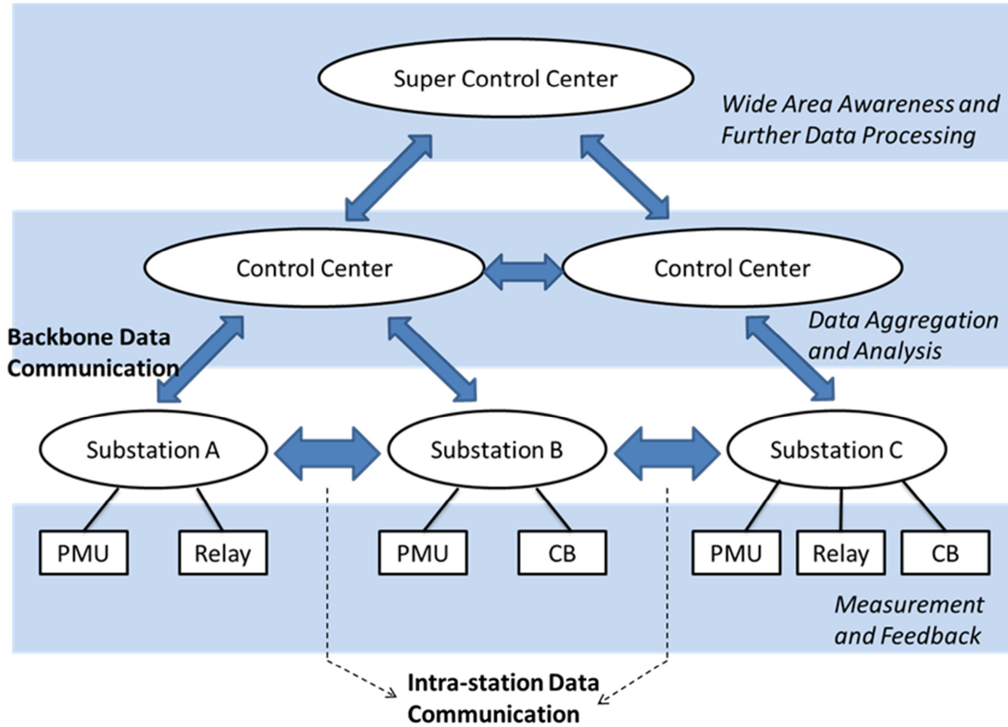


Figure 5.1 Typical WAMPAC system.

In terms of WAMPAC system implementation, several major concerns have been highlighted in [114] and the issues relative to the communication aspects are summarized as:

Key Issue 1: High Data Volume. In a modern substation the amount of data collected is significant. Considering the number of substations within the power grid, the overall amount of data poses serious challenges. Transferring this amount of data through communication links at speeds required by some applications is at best problematic, even with the use of modern communication technologies.

Key Issue 2: Data Validation. It is important that the data be validated and guaranteed in terms of accuracy and timeliness prior to use by the range of applications. Again because of the growing amount of data, distributed validation and characterization of the data become major challenges.

Key Issue 3: Application-based QoS control. Various applications require data at different rates, accuracy and latency. It is important to recognize that the savings accomplished by providing WAMPAC solutions to the most demanding applications must support data transfer to service other, less demanding applications.

Key Issue 4: Distributed Network Topology. Certain targeted applications for WAMPAC require data at fast rates, accurately synchronized at small latencies. Because the power grid is a geographically dispersed system spanning across large distances, latencies cannot be reduced below transmission times inherent to the communication path. The challenges will be to develop distributed WAMPAC applications that can use data in the vicinity of the application to circumvent issues arising with extended latencies.

Understanding the nature of the source and of the traffic generated is key to enabling the decentralized control of WAMAPC applications. The analysis framework adopted to determine the communications requirements for WAMPAC applications utilises a statistical model for power networks as a simulation tool to generate a range of test cases, as well as an analytical tool to determine the characteristics and class of communication network topologies needed to provide network control efficiently. The roadmap for the design and implementation of a flexible and robust WAMPAC communication network can be decomposed into three major sub-tasks:

- Task 1: Defining network topology (including clustering sub-networks and defining the placement of the cluster head);
- Task 2: Assigning traffic flows over network links;

- Task 3: Sizing line capacities, based on the topology and estimated traffic flows;
- Task 4: Utilizing advanced traffic flow control techniques to improve performance.

Task 1 will be covered in this Chapter, while tasks 2-4 will be addressed in Chapter 6.

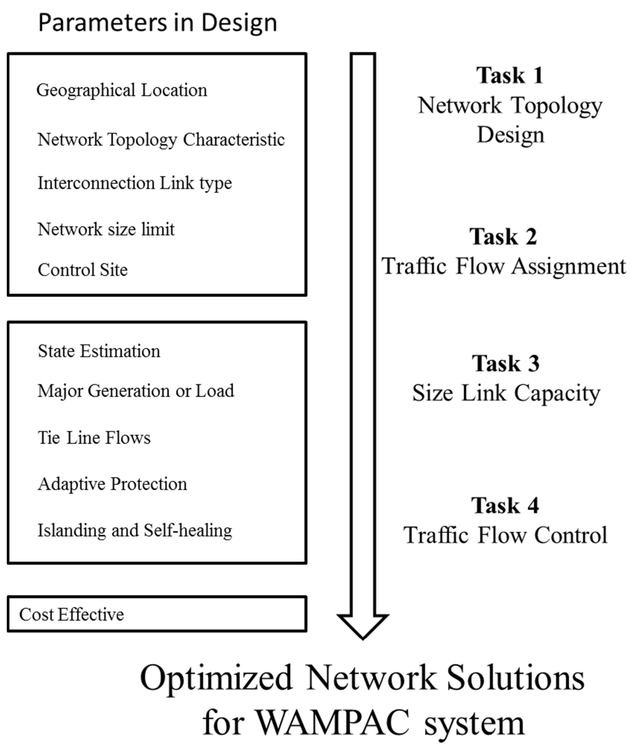


Figure 5.2 The roadmap for the design of network topology to support WAMPAC applications.

5.2 Statistical Characteristics of Network Topologies

Network topologies determine various network properties and functionalities. Two representative network models - small world [115] and scale-free [117] - are introduced and the mechanisms for their characterisation are explained. Although these two models fall short of representing real world network operation, their properties can be used as key indicators that inform successful network design. To better understand the behaviour of complex networks, the detail of the networks' statistical properties are covered in the following Sections.

5.2.1 Network Degree Distribution

The degree of a node in a network is the number of connections or edges the node has to other nodes. For an unidirectional network G, the set of nodes and the set of edges are represented by $V = \{v\}$ and $E = \{e\}$ respectively. The degree d_v of a node v is the number of edges adjacent to node v, i.e.

$$d_v = \sum_{e \in E} \delta_e^v \tag{5.1}$$

where

$$\delta_e^v = \begin{cases} 1 & \textit{edge}\text{ e is adjacent to node v} \\ 0 & \text{otherwise} \end{cases}$$

The degree of distribution is another important topological network parameter. The simplest network model, for example, a random network topology, in which each of n nodes is connected with independent probability p, has a binomial distribution of degree [116]:

$$P(k) = \frac{(n-1)!}{k!\left(n-1-k\right)!} p^k (1-p)^{n-1-k} \tag{5.2}$$

A scale-free network is a network whose degree distribution follows a power law. $p(k) \cdot k^{-\gamma}$ where γ is a parameter whose value ranges from 2 to 3 [116].

5.2.2 Network Average Path Length

The distance between two nodes is defined to be the number of edges in the shortest path connecting the two nodes. The diameter of a network is defined as the maximum distance between any pair of network nodes.

For an un-weighted network, w_{ij} denotes the shortest distance between v_i and v_j, where $v_i, v_j \in v$ .N denotes the number of vertices in G. Thus the average path length L of a network is the average distance of all possible pairs of nodes in the network:

$$L = \frac{1}{N(N-1)} \sum_{i,j \in v} w_{ij} , \tag{5.3}$$

$w_{ij} = 0$ if $v_1 = v_2$ or v_2 cannot be reached from v_1.

5.2.3 Network Clustering Coefficient

The clustering coefficient measures the degree to which nodes in a network tend to cluster together. For a node i, let k_i be the number of its adjacent nodes. Then there are potentially $k_i(k_i - 1)/2$ edges between these k_i nodes. Let t_i be the number of edges that exists, then the clustering coefficient C_i for node i is defined by;

$$C_i = \frac{2t_i}{k_i(k_i - 1)} \tag{5.4}$$

Correspondingly, the clustering coefficient C for the whole network is defined as an average of the clustering coefficients of all nodes. Only when the network is completely connected, the clustering coefficient is one [116].

5.2.4 Small-World Networks

The small-world network model was first proposed by Watts and Strogatz in 1988 [115]. Networks constructed by Watts and Strogatz are obtained by operations on regular networks, and fall in between regular and random networks. For a node in a regular network, one of its adjacent edges is chosen with probability p, which will be rewired to a randomly chosen node. Hence, regular networks and random networks are special cases of such networks corresponding to p being 0 and 1 respectively [116]. Compared with regular networks and random networks, small-world networks exhibit small average path lengths and large clustering coefficients; this phenomenon is called the small-world effect [115].

Table 5.1 Comparisons between different network models

Statistical Characteristics	Regular Network (p=0)	Small-world Network (0<p<1)	Random Network (p=1)
Clustering Coefficient	Large	Large	Small
Average Path Length	Large	Small	Small

Figure 5.3 illustrates the average path length changes as a function of network size and probability p. Compared to a regular network (p=0), small world networks have a smaller average path length between 2 to 10. Conversely, with increasing network size, the average path length increases. The clustering efficiency for small world networks is plotted in Figure 5.4, changing in the range of 0.45 for the random network to 0.63 for the regular network.

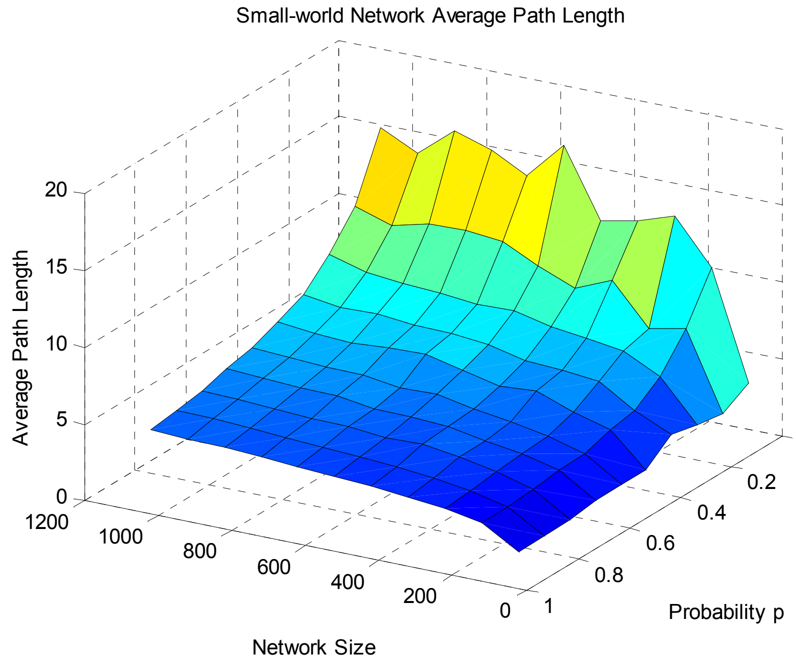


Figure 5.3 Small-world network average path length.

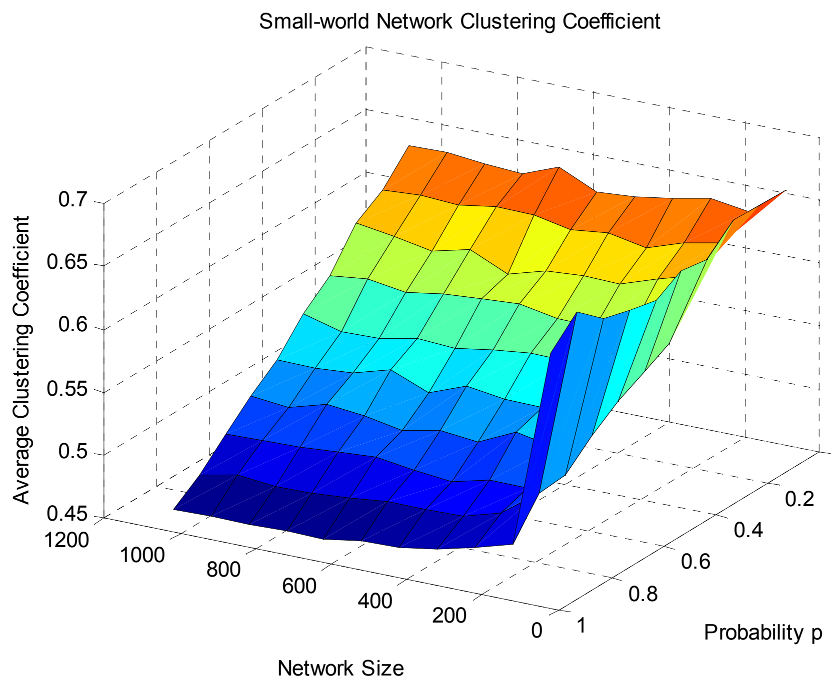


Figure 5.4 Small-world network clustering coefficient.

Real-world networks' average path lengths L are close to those of random networks and their clustering coefficients C are much larger than those of random networks [116].

5.2.5 Scale-Free Networks

Although a small-world network can better describe some features of complex networks in the real world, the major limitation of the model is that it produces an unrealistic degree distribution. Real networks are often inhomogeneous in degree, having most of the nodes with low degrees and only a few nodes having a lot of adjacent edges (Figure 5.5), mapping well to a power-law degree distribution (Figure 5.6). Networks characterized by the power-law degree distribution are referred to as scale-free networks [116].

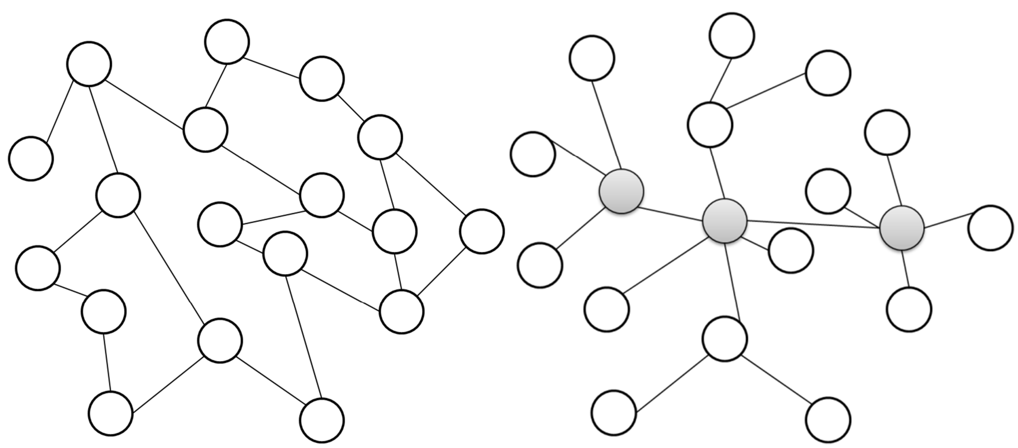


Figure 5.5 Random network (a) and scale-free network (b). In the scale-free network, the larger hubs are highlighted.

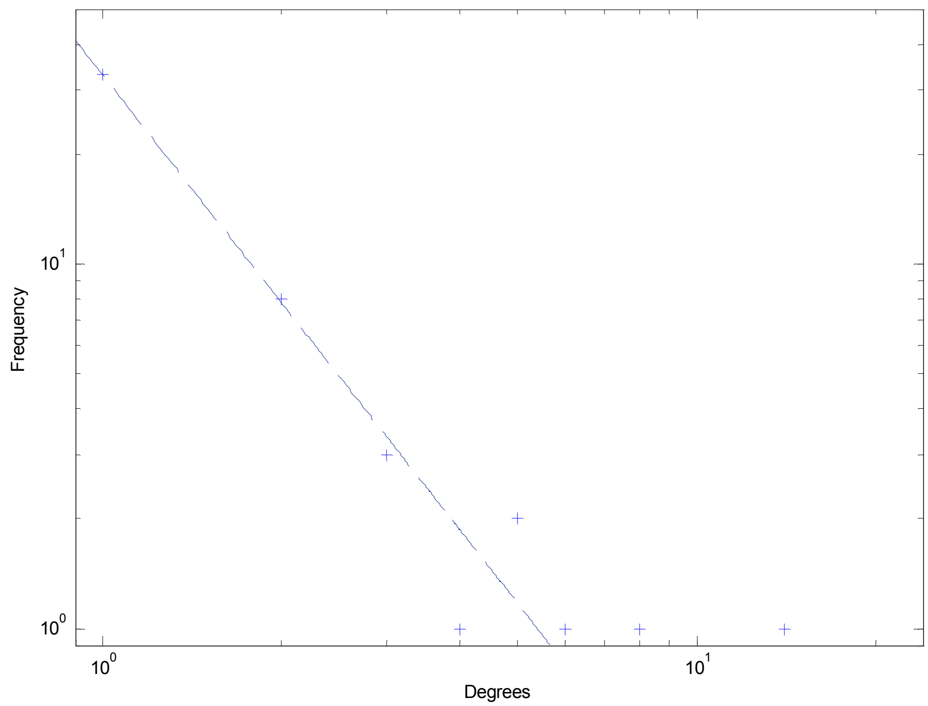


Figure 5.6 B-A network degree distribution.

Barabasi and Albert (B-A) proposed a model [117, 118] incorporating two critical dimensions to generate a network, viz. the growth and preferential attachment (Fig. 5.7). Growth means that new nodes are added sequentially to the existing network, and preferential attachment means that a newly added node is biased to be linked to nodes in the network with higher degrees [116].

The Barabási–Albert model fails to produce the high levels of clustering observed in real networks (Fig. 5.8), a limitation not shared by the Watts and Strogatz (W-S) model. Neither the Watts and Strogatz nor the Barabási–Albert model should be viewed as fully realistic.

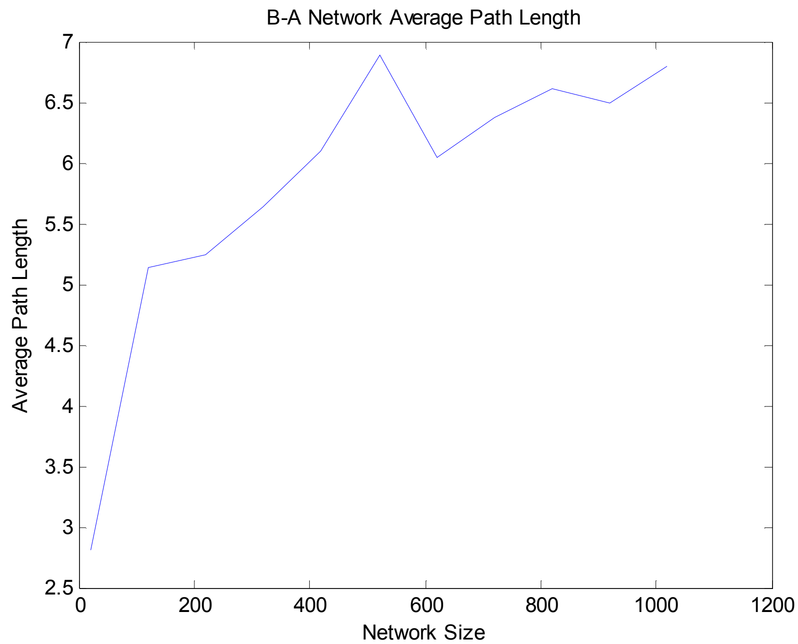


Figure 5.7 B-A network average path length.

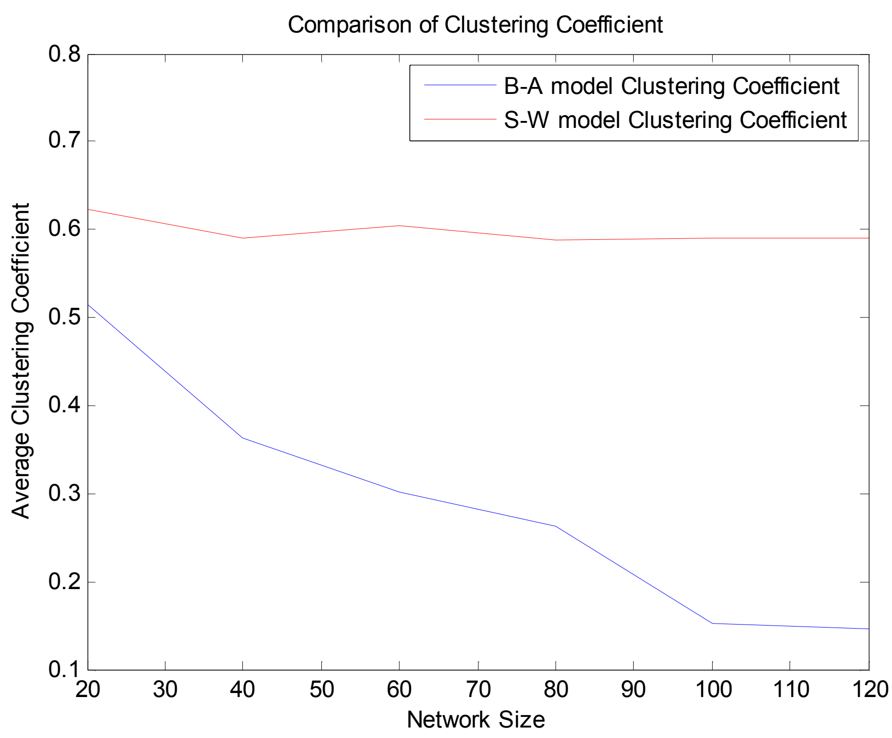
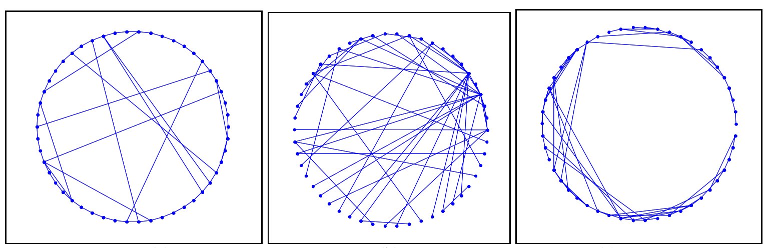


Figure 5.8 Comparison of clustering coefficient for S-W model and B-A model.

5.2.6 Standard and Real System Network Model

Table 5.2 presents the topological characteristics of several empirical power network models such as the IEEE standard test model system [11] and the deployed UK system introduced in Chapter 4. A Kirk graph [128] is a simple but effective way to depict a network topology where all nodes are sequentially and evenly spread around a circle and links between nodes are drawn as straight lines inside the circle. Fig. 5.9 depicts three representative network topologies using a Kirk graph; a small-world network, a free-scale network and UK WAMPAC network. The three networks are of the same size and approximately the same total number of links.



(a) (b) (c)

Figure 5.9 Kirk plot of (a) Small-world network and (b) Free-scale network (c) UK WAMPAC network.

Typical metrics are adopted to analyse the features of the network: network size (number of nodes N and number of links m), the average nodal degree <d>, the average path length <l>, the average clustering coefficient <c>, and the fraction of the nodal degrees [121] larger than the average degree of a node at the end of a randomly selected link, i.e. $r\{d_i > \overline{d}\}$. The definition for the fraction of nodal degree is:

$$\overline{d} = (2m)^{-1} \sum_i (d_i)^2 \tag{5.5}$$

$$r\{d_i > \overline{d}\} = \frac{\left\| \{d_i ; d_i > \overline{d}\} \right\|}{N} \tag{5.6}$$

Table 5.2 Comparisons of IEEE standard power system

	(N, m)	<d>	<l>	<c>	$r\{d_i > \overline{d}\}$
IEEE 14	(14,20)	2.86	2.37	0.37	0.2755
IEEE 30	(30,41)	2.74	3.31	0.23	0.2333
IEEE 57	(57,80)	2.74	4.95	0.12	0.2281
IEEE 118	(118,186)	3.02	6.33	0.16	0.1949
UK Network	(50,71)	2.77	5.432	0.153	0.2367

The nodal degree distribution of a WAMAPC network across the UK is presented in Fig. 5.10 and indicates an exponential tail analogous to that of the geometric distribution [121]. However, for the range of small node degrees, i.e. with a degree ≤ 3, the relationship deviates from that of a geometric distribution.

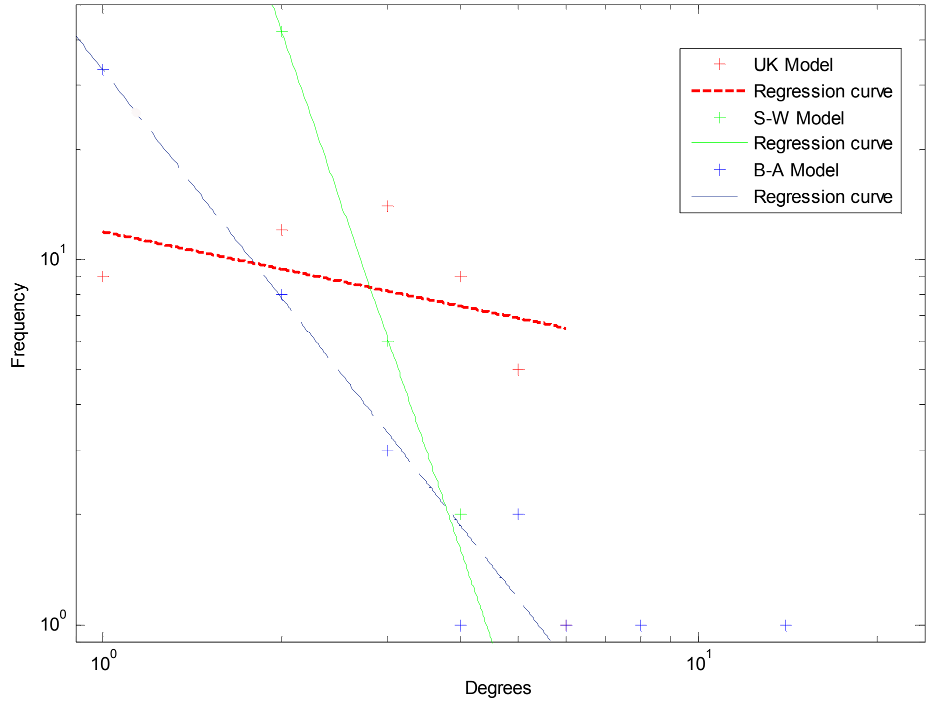


Figure 5.10 Degree distribution and regression curve for three different network models.

Two observations pertaining to the topology of the grid must be noted:

1) Power grids are sparsely connected. The average nodal degree does not scale as network size increases. Instead, it falls within a very restricted range, and is a function of the particular area the network belongs to rather than the network size. The small-world model has scaling property that cannot be validated by power grid topologies, because the average nodal degree of a power network is almost invariant to the size of the network.

2) In the Watts and Strogatz model, the author hypothesized that power networks possess the salient features of small-world graphs [116] i.e. while the vast majority of links are similar to that of a regular lattice, with limited

near neighbour connectivity, a few links connect across the network. From the study, small-world graphs are only partially able to capture the features of the power grid. While being similarly sparse, power grids have better connectivity scaling laws than small-world graphs.

5.3 Node Geographical Locations and Interconnections

The network topology must be based on specified node and link connections. In Chapter 4, Integer Linear Programming techniques were used to optimally locate PMUs across the UK national-wide area. The location of these distributed nodes and interconnections is the key to establishing a distributed set of WAMPAC applications. As stated in Chapter 4, PMUs are only required on 1/4 to 1/3 of network buses to ensure full observability. However, these locations are dispersed geographically at significant distances from each other.

Interconnections between nodes can be categorized based on applications and physical layer characteristics;

Dedicated versus Shared Communication: past research has suggested the use of dedicated channels in a fibre optic network as the main communication medium for PMU inter-connections [122, 123]. The network architecture would be composed of a main optical fibre backbone connected to a substation router. The PMU would be connected within the substation through a standard Local Area Network (LAN). A shared system is a wide area network based on TCP/IP protocol suite rather than a dedicated optical fibre network. The traffic from PMUs would be integrated with traffic from other applications such as Voice-over-IP. The TCP/IP protocol is an established protocol in utility networking, as it offers an open standard as well as enjoying wide adoption in industry [91]. The transmission medium in support may also include technologies such as microwave and radio [50].

Wired versus Wireless Communication; The backbone optical fibre network can be implemented through Optical Power Ground Wire (OPGW) [50] and All-Dielectric Self-Supporting (ADSS) [50] bound to the transmission line of power system. The wired technology, especially fibre optics, provides the highest bit rate and lowest interference. The drawback is the high cost of installation and maintenance, low scalability and flexibility in network configuration.

Wireless systems options include radio technology, microwave and satellite [50]. As one of the newest wireless technologies, WiMAX [59] can play the role of last-mile connections to PMU sites providing a high bit rate with wide coverage. It potentially fills the gaps between WLANs (which provide very high data rate but short range coverage) and cellular systems (which provide highly mobile, long range coverage but modest data rates).

5.4 Control-based Network Architecture

An extensive range of WAMPAC applications acquires measurements from multiple, appropriately located and distributed PMUs across a national area. The processing of the data can be executed either locally or managed by a Control Centre tens to hundreds of kilometres away. Here, three different control strategy dependent networks are proposed: centralized, decentralized and hybrid.

5.4.1 Centralized Control Strategy based Network Architecture

A typical implementation of a centralized architecture is the unified network where all phasor measurements are sent to a Central Control Centre (CCC). After processing the received data, appropriate decisions are made and related commands are transmitted to controllable remote devices. For example, the widely used Supervisory Control and Data Acquisition (SCADA) system [64] is designed as a tree topology where all data sources are scanned by the CCC every 2-5 seconds (Fig. 5.11). The advantage of such an approach is that no system synchronization is required since the entire network is managed through the same supervisory control system. However, major drawbacks include traffic congestion, measurements delays and single-node failure.

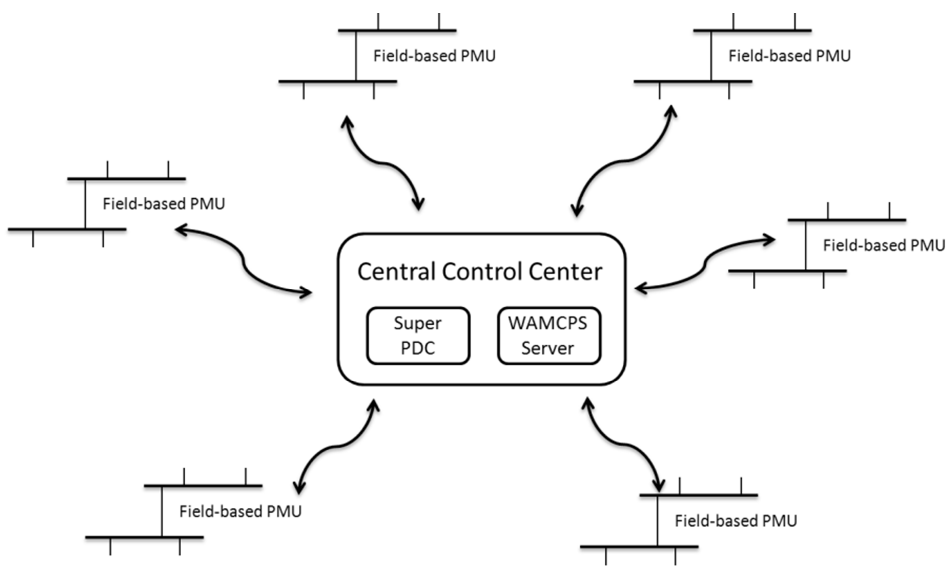


Figure 5.11 Representation of centralized control strategy.

5.4.2 Decentralized Control Strategy based Network Architecture

In a decentralized control strategy, the entire system is segmented into small clusters, each comprising its own Distributed Control Centre (DCC) (Fig. 5.12). Acquiring measurements via DCCs minimizes the time consumed in forwarding the data from information sources to the processing or controllable units. The segmentation of the network uses different clustering algorithms described in the latter Sections. In addition, the decentralized control scheme reduces the bottleneck at high data volumes and provides robustness to single node failure; however network complexity increases due to inter-networking between DCCs. The DCCs process the acquired data but unlike the CCC implementation, they share data to enable situational awareness throughout the system.

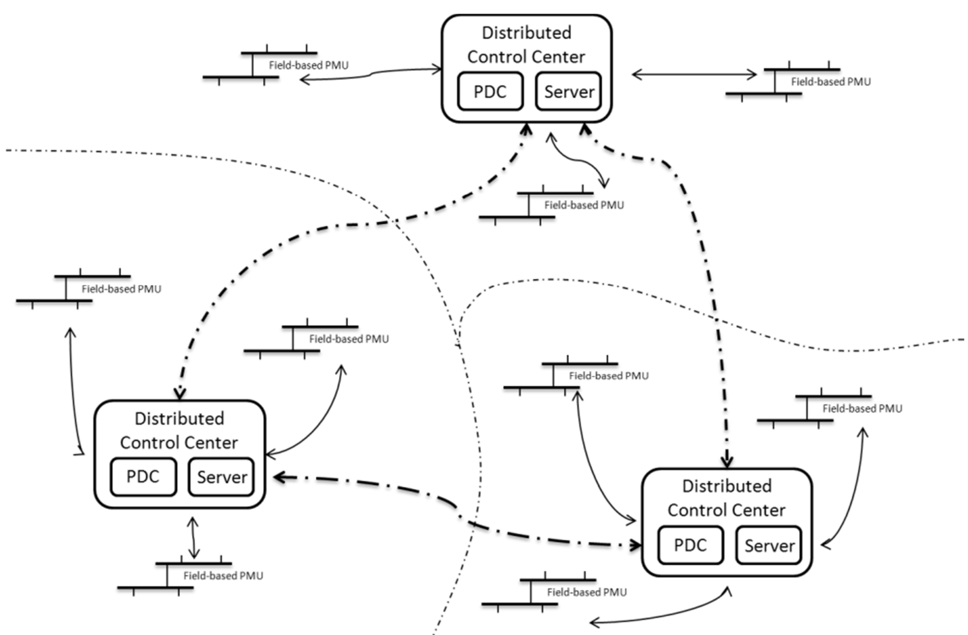


Figure 5.12 Representation of decentralized control strategy.

The advantages and disadvantages of centralized and decentralized based topologies are listed in Table 5.3. The centralized topology has lower complexity and lower cost of installation, since a single Control Centre processes all the data. However, large volumes of data will cause traffic congestion [114]. A single node failure also has a great impact on the operation of the entire system. A decentralized topology overcomes these drawbacks.

Table 5.3 Advantages and disadvantages of different network control topologies

	Centralized Topology	Decentralized topology
Advantages	Low complexity Low cost	Reduce high volume at bottlenecks Reduce impact of a single point failure High Scalability High Flexibility
Disadvantages	Limited Scalability Got a single point of failure	High Network Complexity

5.4.3 Hybrid Control Strategy Network Architecture

A hybrid control strategy combines elements drawn from both centralized and decentralized approaches to achieve a balance between the traffic bottleneck and network complexity (Fig. 5.13). Data flow is governed by the WAMPAC application, predominately categorized into either a distributed monitoring or a central control service. In the former, state estimation is invoked locally to limit the amount of data flow in the backbone network. However, some adaptive protection schemes require a more comprehensive understanding of the state of the entire network and this type of decision making can only be executed within the CCC. Moreover, it is essential for the entire system to operate holistically under fault conditions; thus protection applications, such as intelligent load shedding and islanding communicate directly with the CCC.

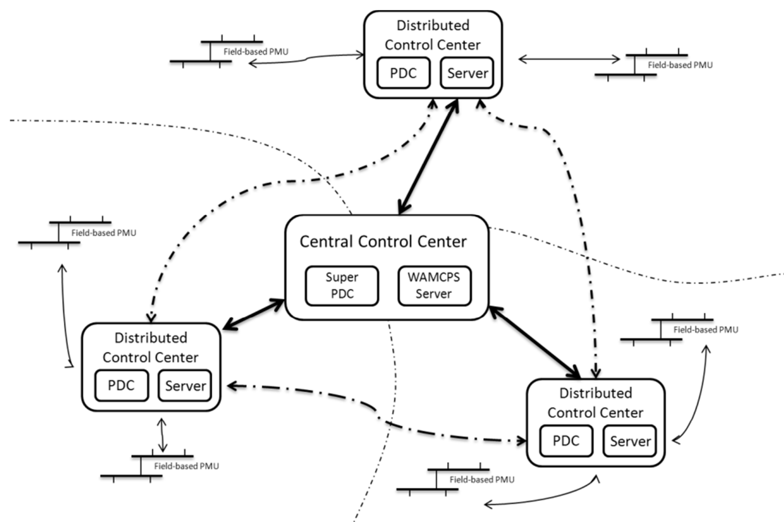


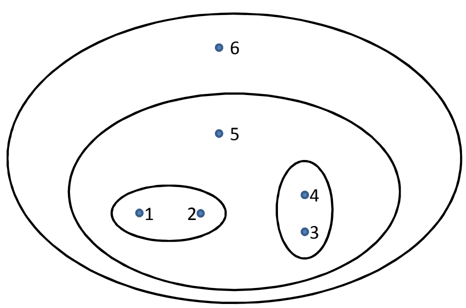
Figure 5.13 Representation of hybrid control strategy.

5.5 Network Clustering

Proper design of the network topology contributes to better network performance at lowest cost. Consequently in this research different clustering algorithms are verified for a UK WAMPAC system. These clustering methodologies include connectivity models such as link hierarchical clustering [124], centroid models such as K-means clustering [125], and density models such as Expectation maximisation algorithm [126].

5.5.1 Linkage Hierarchical Clustering

Hierarchical Clustering groups data over a variety of scales by creating a cluster tree or dendrogram [124]. The tree is not a single set of clusters, but rather a multilayer hierarchy, where clusters at one level are joined as clusters at the next level. In a dendrogram, the y-axis marks the distance at which the clusters merge, while the objects are placed along the x-axis such that the clusters don't mix. Referring to Fig. 5.14, the network topology is clustered with a multilayer tree diagram based on the distance between each other. The lowest layer is formed by nodes with the shortest distances between them; nodes which are further apart are added into the higher layers.



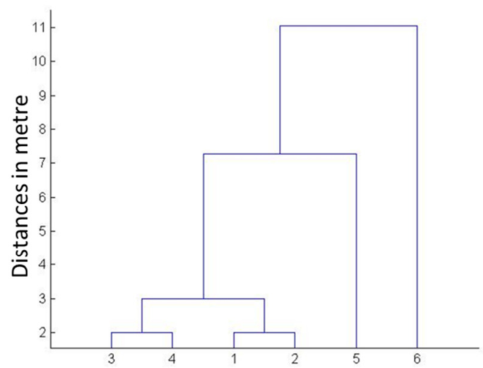


Figure 5.14 (a) Clustering based on the topology of the nodes (b) dendrogram for the clustering network.

With increasing network size, more layers in the tree appear and the dendrogram becomes more complicated, such as in Figure 5.15 where 50 nodes in the UK WAMPAC system are clustered based on the Euclidean distance between each other and a 14-layer tree layout is illustrated. The y-axis displays the distance in meters which will be used as a reference to cluster the network in a robust manner.

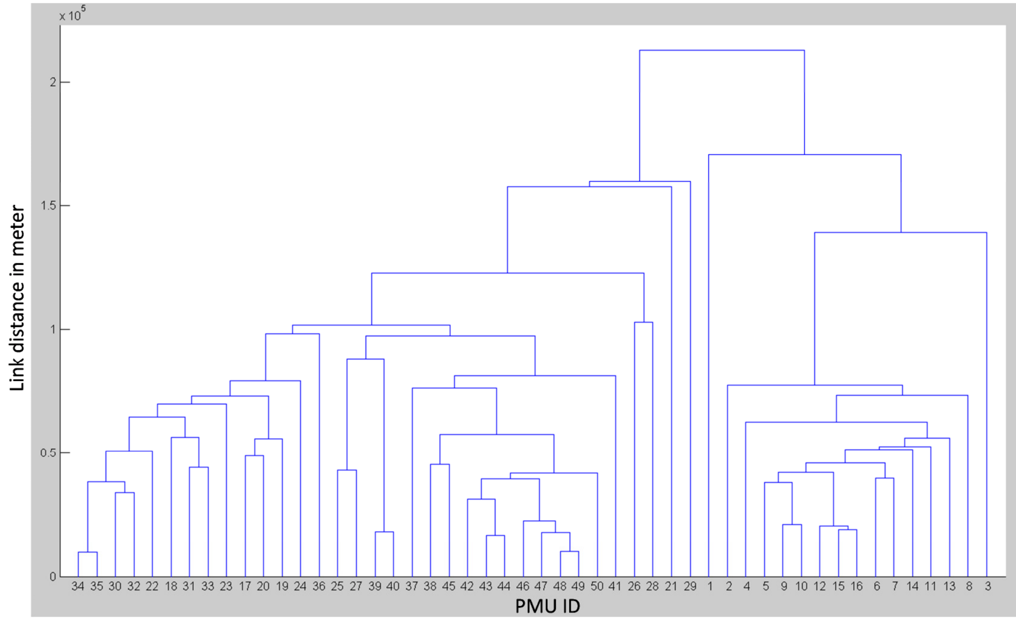


Figure 5.15 Dendrogram for 50 nodes in a UK WAMPAC network.

For a wired system, the clustering distance is based on the average link distance amongst the nodes. In a UK WAMPAC system, the mean value and variance of the distance are calculated in Table 5.4. A length of 82.75 km for the average link distances in UK WAMPAC system is a suitable starting point to verify the cluster size of the network i.e. the layer under 82.75 km in the dendrogram of Figure 5.15 is clustered. Further analysis is carried out in Section 5.7.

Table 5.4 Link characteristics in UK WAMPAC system

Link Type	Optical ground wire (OPGW)
Mean value	82.75 km
Variance	2882.62
Standard Deviation	53.69

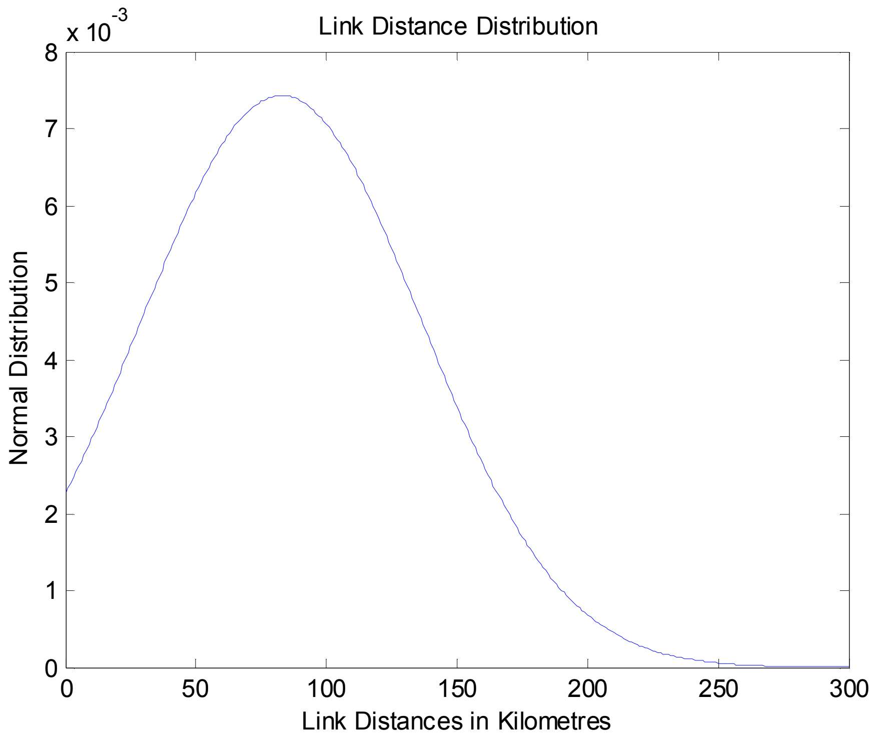


Figure 5.16 Link distance distribution in UK WAMPAC system.

For a wireless system, in addition to the geographical distance between nodes, constraints imposed by the wireless physical layer characteristics also have a major effect on the clustering design. For instance, WiMAX propagation distances range from 12 km in Line-of-sight (LOS) transmission to 2.5 km in Non-Line-of-sight (NLOS) transmission [52]. For a WiMAX base station installed in an open area, the propagation of the signal over long distances can be obtained accurately through the two-ray ground reflection path loss model [52];

$$P_L(d) = \frac{P_t G_t G_r h_t^{\,2} h_r^{\,2}}{d^4} \tag{5.7}$$

where h_t and h_r are the heights of the transmit and receive antennas respectively. G_t and G_r are the gains in these antennas.

Furthermore, referring to the Shannon-Hartley theorem [52], the capacity of the channel is calculated as;

$$C = B \cdot \log_2(1 + SNR) \tag{5.8}$$

where B is the bandwidth of the channel. SNR represents the Signal-to-Noise Ratio calculated as the fraction of receive power Pr over the sum of noise power P_0 and interference power Pi;

$$SNR = P_r / (P_0 + P_i) \tag{5.9}$$

Since the transmission boundary is of interest, the most robust modulation and coding scheme, Binary Phase Shift Keying (BPSK) 1/2 is commonly used [127, 128] as the basis to investigate the maximum propagation range that can be achieved in WiMAX deployments. The minimum receiver SNR requirement for BPSK ½, is 6.4 dB, taken from the 802.16 standard [127]. Further, in Europe, the maximum allowed

Equivalent Isotropic Radiated Power (EIRP) within the 5 GHz band is restricted to 1W or 30 dBm [128]. In Figure 5.17, the propagation distance for WiMAX is shown, the red line indicating the required received signal power to achieve a SNR of 6.4dB.

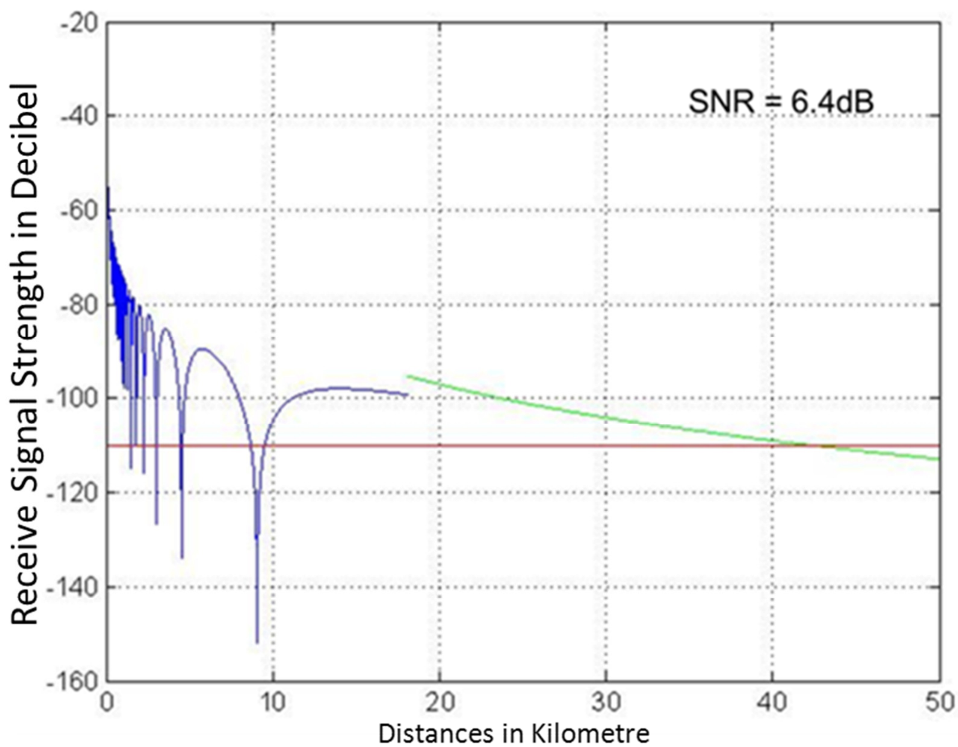


Figure 5.17 Propagation distance of WiMAX from the two ray model.

Therefore, for wireless communication links based on the WiMAX standard, the transmission range is restricted to less than 8 km. However in the dendrogram shown in Figure 5.15, that connection distance is insufficient to link neighbouring PMUs single hop. WiMAX is thus more suitable as a last-mile connection rather than a backbone segment of a nationwide WAMAPC system.

5.5.2 k-means Clustering

The function k-means partitions data into k mutually exclusive clusters, and returns the index of the cluster to which it has assigned each observation [125]. Unlike hierarchical clustering, k-means clustering operates on actual observations (rather than the larger set of dissimilarity measures), and creates a single level of clusters. It is known as a centroid-based clustering approach, whose clusters are represented by a central vector, which may not necessarily be a member of the data set. When the number of clusters is fixed to k, k-means clustering gives a formal definition as an optimization problem: find the cluster centres and assign the objects to the nearest cluster centre, such that the squared distances from the cluster are minimized.

In Table 5.5, different number of clusters using k-mean clustering is analysed. With increasing number of clusters, the interconnecting link distances and cluster sizes decrease. Figure 5.18 depicts the deployment of each cluster derived through 8-means clustering in a UK WAMPAC system.

Table 5.5 K-means clustering in a UK WAMPAC system (where k = 8, 9, and 10).

	Zone Number	Total Distance (km)	Number of Nodes	Average Distance (km)
8-means clustering	Zone 1	315.27	3	105.09
	Zone 2	320.22	4	80.05
	Zone 3	383.14	5	76.63
	Zone 4	950.11	11	86.37
	Zone 5	641.14	9	71.24
	Zone 6	619.99	5	124
	Zone 7	511.91	7	73.13
	Zone 8	256	6	42.67
	average	499.72	6.25	82.4
9-means clustering	Zone 1	383.14	5	76.63
	Zone 2	511.91	7	73.13
	Zone 3	501.18	8	62.65
	Zone 4	641.14	9	71.24
	Zone 5	367.74	3	122.58
	Zone 6	256	6	42.67
	Zone 7	298.83	5	59.77
	Zone 8	320.22	4	80.05
	Zone 9	315.27	3	105.09
	average	399.49	5.56	77.09
10-means clustering	Zone 1	383.14	5	76.63
	Zone 2	298.83	5	59.77
	Zone 3	256	6	42.67
	Zone 4	501.18	8	62.65
	Zone 5	220.66	5	44.13
	Zone 6	442.43	5	88.49
	Zone 7	186.95	3	62.32
	Zone 8	367.74	3	122.58
	Zone 9	449.71	7	64.24
	Zone 10	315.27	3	105.09
	average	342.19	5	72.86

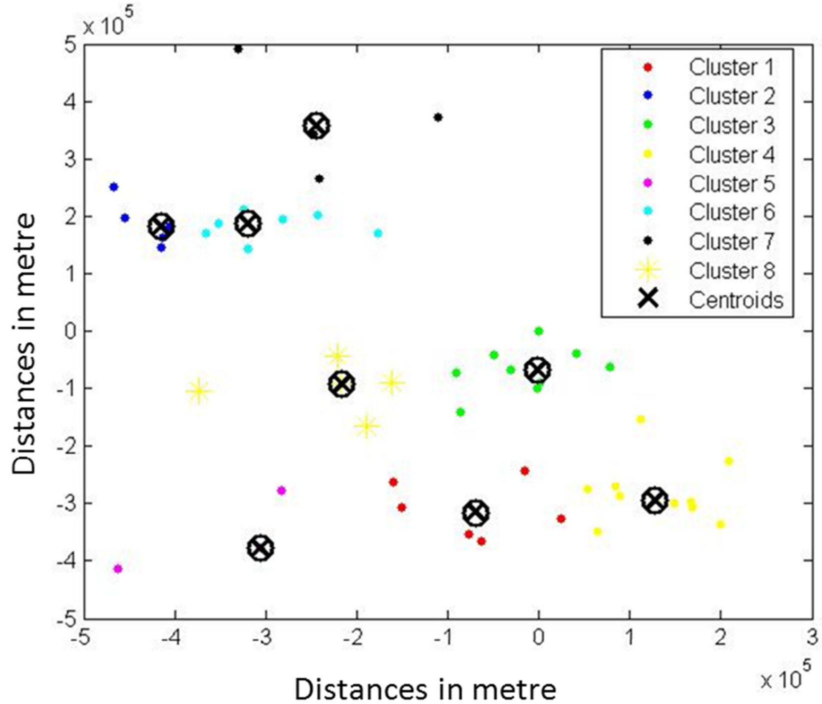


Figure 5.18 8-means clustering for a UK WAMPAC topology.

5.5.3 Expectation-Maximization Algorithm

An Expectation-Maximization (EM) algorithm is an iterative method for finding maximum likelihood or Maximum a Posteriori (MAP) estimates of parameters in statistical models, where the model depends on unobserved latent variables [129]. A mixture model can be described by assuming that each observed data point has a corresponding unobserved latent variable, specifying the mixture component that each data point belongs to. A Gaussian mixture model is formed by combining multivariate normal density components, which assign posterior probabilities to each component density with respect to each observation [129].

Figure 5.19 plots the counter lines based on the density of nodes inside a WAMPAC network whilst Figure 5.20 shows the map of network clusters based on the Gaussian mixture model.

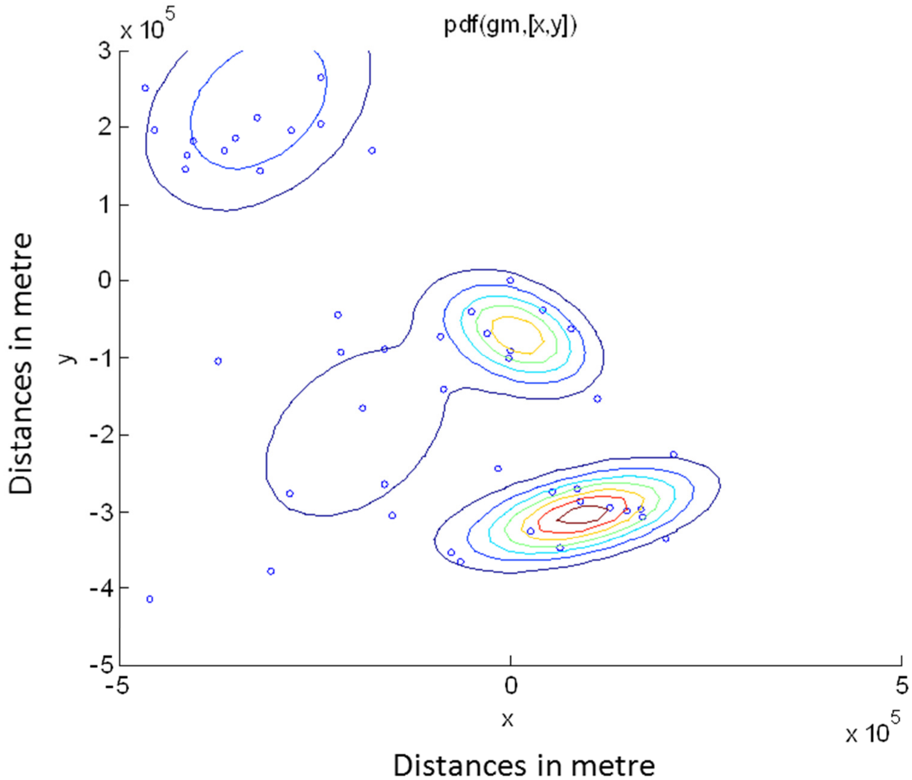


Figure 5.19 UK WAMPAC PMUs fit into a 4-component Gaussian Mixture Model.

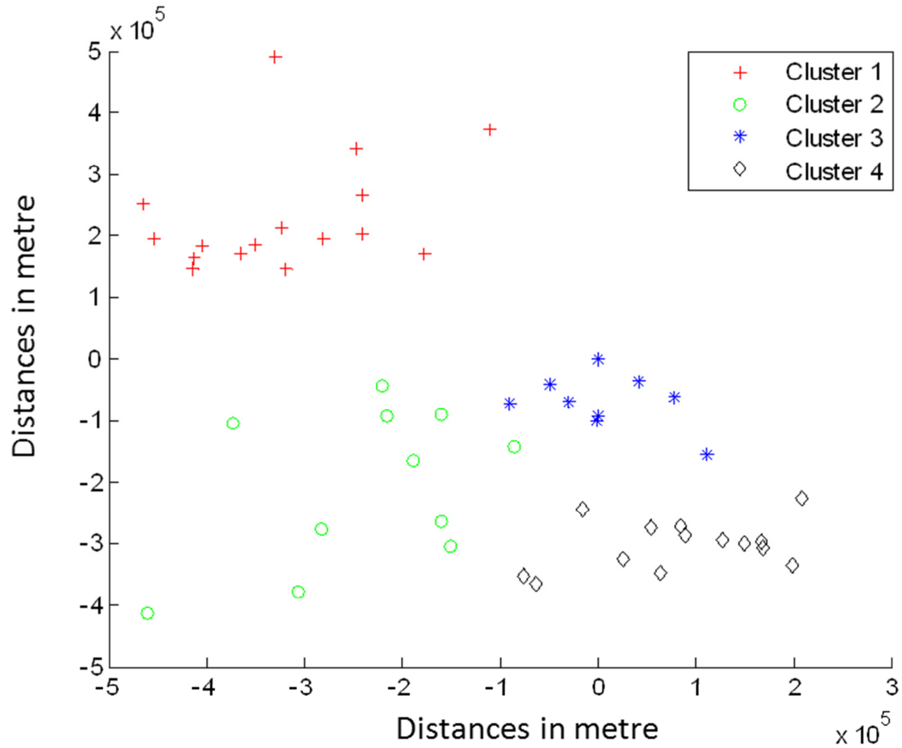


Figure 5.20 Cluster layout in a UK WAMPAC system using EM algorithm.

5.5.4 Discussion of Clustering Methods

Different clustering algorithms have been reviewed and analysed. The linkage hierarchical clustering utilizes the link characteristics (such as Euclidean distance) to establish a dendrogram of the network and together with the analysis of the physical communication medium, a design of the system with clusters can be derived.

A k-means algorithm is a centroid based approach which partitions data into k clusters. As a consequence, it is more suitable to be implemented through a wireless system where the coverage is a strong function of the limitations bounded by attainable propagation distances. Furthermore, no constrains can be added to the cluster, which limit its application.

The EM algorithm is more suitable for clusters of different sizes and correlations within them. It has been implemented in the case where there is an underlying linear regression model explaining the variation of some quantity, but also where the values actually observed are truncated versions of those represented in the model. However, in the case of a WAMPAC system, all locations and correlations between nodes are fixed, and where network density does not influence the final network clustering. Thus EM algorithm is not appropriate for WAMPAC applications. Consequently the linkage hierarchical clustering algorithm is selected to derive optimized node clusters.

5.6 Case Study: Clustering on a UK WAMPAC System

The following is further development of network clustering for a UK WAMPAC system combining the requirements in terms of communication networking with the capability of power transmission.

For the purpose of illustrating system performance (Appendix 2), 17 boundaries are considered as proposed in the National Grid Seven Year Statement [7]. These boundaries are used, amongst other things, to provide a clearer picture of the overall capability of the system to transmit power. In addition, 17 system zones are labelled across the power system in the UK with 4 zones in SHETL, 2 zones in SPT, and 11 zones in the NGET system.

It would be inefficient and unreliable from the communication performance point of view to determine the communication network clusters which reflects the existing power system zones. First of all, the power system zones are proposed based on generation and loads whereas a communication system must serve the needs of the measurement framework e.g. PMUs and relays. Secondly, the division of power system zones focus on power flows inside the UK regardless of the size of each zone whereas the size of each cluster influences greatly the performance of the communication network. However it is necessary to take into consideration the boundaries and power flows as references in the design of the system. The reasons include the deployment of ADSS and OPGW communication links which follow power line cables; some of the WAMPAC applications are referred to the power flows in the network such as tie-line PMU monitoring, intelligent islanding, and inter-area oscillation. Therefore, both aspects, i.e. power system operation and communication performance, are important in the design of the best communication network for power system applications.

Based on PMUs and link topologies described above, the communication network is segmented into cluster areas based on the dendrogram in Fig. 5.15. Figure 5.21 shows the solution for network clustering in a UK WAMPAC system; 7 clusters are established, 1 cluster for SHETL and SPT zones and 5 clusters in NGET.

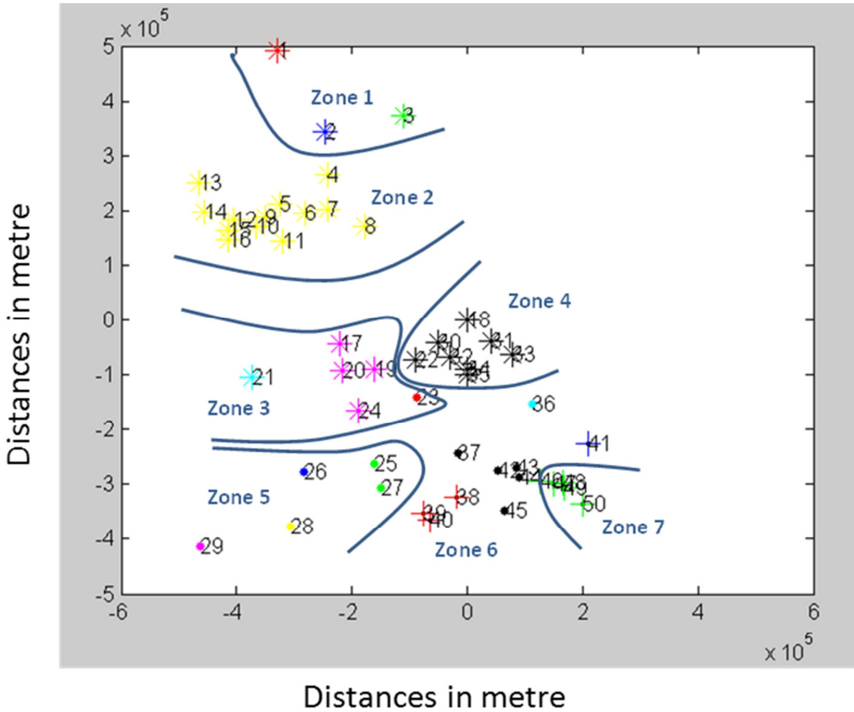


Figure 5.21 A network clustering solution of a UK WAMPAC system.

Zone 1 covers the north of Scotland, with 3 PMU sites and comprises a significant amount of existing hydro, thermal power and other new renewable generation. Demand in this area is significantly lower than the installed generation; consequently this zone is normally an exporting zone.

Zone 2 covers the middle belt of Scotland, the primary importing corridor from Scotland (SHETL Network) to England (NGET Network) in the UK. In this area, 13 PMU sites are clustered as a sub-network.

Zone 3 has 6 PMU sites covering the North West of the NGET network. This zone is characterized by relatively high generation capacity and demand levels which tend to complement each other, leading to a very low net transfer from this zone. As the bulk of the transfer travels South West to meet some of the localized demand in London, under a fault or outage condition some of the 400kV circuits within this area can be overloaded substantially due to a concentrated import from Scotland.

Zone 4 contains 9 PMU sites and covers the upper north of NGET, lying beneath the SPT network carrying the bulk of the flow from Scotland to England. As transfers from Scotland increase, and new generation connects to this zone, there is an essential need for further capacity growth in the area to meet future demand in England and Wales and to achieve renewable targets.

Zone 5 contains 5 PMU sites in the sub-network covering the west of central London.

Zone 6 covers the inner and outer London containing 10 PMU sites and characterised by high demand and low generation.

Zone 7 clusters 5 PMU sites in the sub-network and consists of a mixture of generation including nuclear and Combined Cycle Gas Turbine (CCGT) plants, as well as some offshore wind farms. Generation exceeds demand giving a surplus and a high planned transfer which slightly drops as older conventional plants close. Two interconnectors exist within this zone; the French and the BritNed links [7]. From Sellindge there is an existing HVDC which interconnects the NGET network to the French RTE network, while the BritNed HVDC link (based in the Isle of Grain) interconnects to the Dutch TenneT network. These interconnectors may have a large effect on transfers and flows by importing and exporting power in and out of the NGET network.

The site of the Control Centre in a centralized scenario is located at Norton, using the minimum spanning tree algorithm [21, 22]. In the de-centralized and hybrid scenarios, the location of the cluster headers, also referred to as Distributed Control Centres, are listed in Table 5.6.

Table 5.6 Decentralized cluster header deployments

Zone	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7
Sites	Tealing	Strathaven	Dalens	Thrope Marsh	Melksham	Grain	Bramley

5.7 Conclusions

This Chapter focuses on the design of the communications network architecture, key to enabling the de-centralized control of WAMAPC applications. The Chapter starts with introducing two representative network models viz. small world and scale-free network. The mechanisms for their evolution are explained and comparisons are made between these models, the power standard model and a UK WAMPAC network topology. Results show that both of the small world and scale-free network models fall short of fully representing real world network operation, but their properties can be used as key indicators that inform successful network design. Two features are highlighted through the comparison of the characteristics of the communication network based on IEEE standard models and the UK transmission real power system models. Power grids are sparsely connected; the average nodal degree does not scale as network size increases; grids have better connectivity scaling laws than small-world models.

Proper design of the network architecture contributes to better network performance at lowest cost. Consequently, three different control strategy dependent network architectures are proposed: centralized, de-centralized and hybrid. Compared to the centralized based network architecture, decentralized control reduces network bottlenecks at high data volumes and provides robustness to single node failure. A hybrid control strategy combines elements drawn from both centralized and decentralized approaches to achieve a balance between the acceptable level of traffic bottleneck and network complexity.

In order to establish a distributed system, different clustering algorithms are verified for a UK WAMPAC system. These clustering methodologies include connectivity models such as Link hierarchical clustering, Centroid models such as k-means clustering, and density models such as Expectation Maximization algorithm. The Linkage hierarchical clustering is selected as the most suitable candidate to derive optimized node clusters. Further refinements of network clustering for a UK WAMPAC system are proposed combining the requirements in terms of communication networking with the power transmission capability existing in the system. A working solution for network clustering for a UK WAMPAC system is proposed with 7 clusters, 1 cluster for SHETL and SPT zones and 5 clusters in the NGET zone.

Chapter 6

Traffic Flow Assignments for WAMPAC

6.1 Introduction

The performance of the WAMPAC applications is characterized by throughput, latency and reliability. Throughput represents the aggregation of all data flows to be delivered to all terminals in a network. The data volume of various applications range from a few hundred bytes to a few mega-bytes every second e.g. visualization requires a large volume of data from all PMUs whereas adaptive protection information requires less than 100 bytes directed to a specific controllable device.

Latency indicates the maximum End-to-End (ETE) delay that can be tolerated. Monitoring applications refer to a system of data acquisition and a communications infrastructure that transports data to a central location. Therefore, the ETE delay from the measurement device to the Control Centre can be represented as:

$$T_{monitor} = T_{sens} + T_{trans} + T_{prop} + T_{queue} + T_{cc} \tag{6.1}$$

where T_{sens} and T_{cc} represent the processing time at the sensor node and Control Centre respectively; T_{trans} is the transmission time governed by the data rate of the link; T_{prop} is the propagation time between transmitter and receiver, which can be calculated by using Length of Medium (*LoM*) [61] divided by *v*, the velocity of electromagnetic wave in a specific medium:

$$T_{prop} = \frac{LoM}{v} \tag{6.2}$$

T_{queue} is the storage time experienced by each packet and forwarded in a queue on a total Number of Routers (*NoR*) which can be expressed as:

$$T_{queue} = \sum_{i=1}^{NoR} T_{i^{th}Router} \tag{6.3}$$

To simplify the latency calculation, assuming that the delay on each router has the same latency value, Equation (6.1) can be developed as [61]:

$$T = Const + \frac{LoM}{v} + NoR \times T_{Router} \tag{6.4}$$

From Equation (6.4), the latency increases as *LoM* and *NoR* increase.

In terms of system protection applications, data delivery to a central location should be sufficient to fulfil requirements. Thus the delay owing to the control of relays can be presented as:

$$T_{control} = T_{monitor} + T_{des} + T_{trans'} + T_{prop'} + T_{queue'} + T_{op} \tag{6.5}$$

where T_{des} and T_{op} are the execution time at the Control Centre and end control (or protection) device. Furthermore, the delay associated with the transmission of a control signal directly to controllable devices is also taken into consideration.

The data propagation delays (Fig. 6.1) are relatively small due to the high speed of transmission (nearly equals to the speed of light [52]) and as is bound to the volume of transmission data (compared to the link capacity). Thus these two parameters are omitted in the analysis. The main focus is on evaluating the queuing delay, representing the most limiting delay within the whole system.

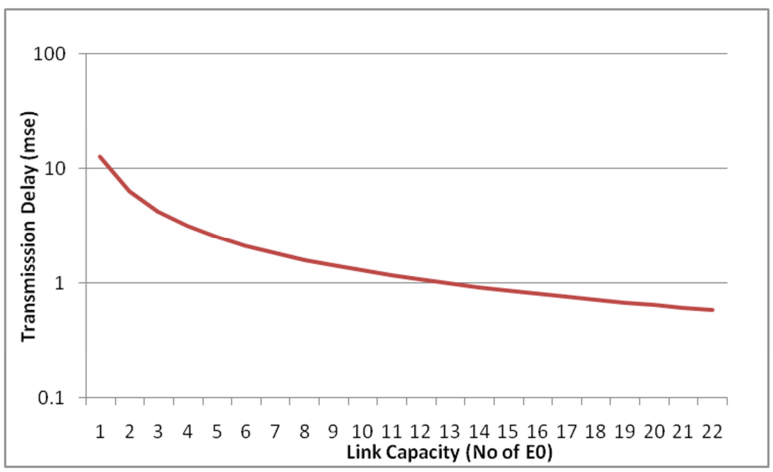


Figure 6.1 Transmission delay for 3-phase PMU data as a function of link capacity.

6.2 Traffic Flow Assignments

The determination of data traffic flows in WAMPAC networks draws on the knowledge of the defined network topology (Chapter 5) and potential power system applications (Chapter 3). These network topologies are categorized into centralized, decentralized and hybrid scenarios.

A. Power System Monitoring

As one of the most important applications of WAMPAC, power system monitoring needs all PMUs installed in substations to upload their measured data to the PDC located at the Control Centre. Three monitoring applications are state estimation, seams between state estimates, and instrument transformer calibration for all PMU estimators.

Although these three monitoring applications are different and independent, their communication characteristics are very similar. State estimation functions supervise the system by uploading all-PMUs measurements and seam between state estimation collects measurements data from boundary reference buses so that the Control Centre can identify the difference in reference angles. Since instrument transformer calibration utilizes the same data, no additional traffic flow is required to achieve the task.

Therefore, in the centralized scenario, PMU measurements will be aggregated at a super PDC located in the Control Centre; in the decentralized and hybrid scenarios, these data will be transported to the closest cluster head. Only data required for further analysis is forwarded to the high-level Control Centre (Table 6.1).

B. Power System Protection

In this category, the communication network architecture assumes charge of delivering real-time control commands. Typical protection applications include adaptive dependability and security (ADS), adaptive out of step (AOS), supervision of back-up zone (SBUZ), adaptive loss of field (ALF), intelligent load shedding (ILS) and intelligent islanding (II) [94]. Depending upon the communication latency needs, applications are categorized into non-critical which can tolerate up to one second delay, and time-critical with a maximum acceptable delay of below 50 milliseconds.

In the ADS application, the system Control Centre decides the current state of the system and then broadcasts voting messages to distributed set of critical relays. In the AOS applications, PMUs installed outside the generator, upload measurements and track rotor angles, and to determine coherent groups they send the information to the PDC in the Control Centre with no acknowledgement. In the SBUZ application, PMUs which fall inside the back-up zones can monitor the apparent impedance and transmit decisions to back-up relays with acknowledgements, and ultimately prevent mis-operations which could lead to cascading failures and blackouts. In the ALF application, in order to revise some drift data introduced by long time usage or unexpected environmental changes, the system Control Centre will transmit adjustment orders to the loss-of-field relays with acknowledgements. In the ILS application, PMUs used to monitor the tie-line power flows take charge of the supervisory control and send measurement data to the PDC in the Control Centre. In the II application, since instability is inevitable, the system Control Centre has to make decisions to trip or block the related circuit breakers with acknowledgements.

C. Power System Control

Using PMUs to damp low frequency inter-area oscillations is one of the most attractive WAMPAC applications. This application involves wide area communication where measurement data might be transported over long distances in excess of hundreds of miles. Wide Area Awareness (WAA) enables the global view of control and protection applications in modern power system via exchanging information between control centres.

Table 6.1 Traffic flows for WAMPAC applications as a function of different control strategies.

Applications	Centralized Network	De-centralized Network	Hybrid Network
SE	Distributed PMU → Centralized Control Centre	Distributed PMU → Distributed Control Centre	Distributed PMU → Distributed Control Centre
SSE	None	Zone Boundary PMU → Distributed Control Centre	Zone Boundary PMU → Distributed Control Centre
ADS	Centralized Control Centre → Distributed Relay	Distributed Control Centre → Distributed Relay	Centralized Control Centre → Distributed Relay
AOS	Distributed Generator → Centralized Control Centre	Distributed Generator → Distributed Control Centre	Distributed Generator → Distributed Control Centre

SBUZ	PMU → Backup Relay	PMU → Backup Relay	PMU → Backup Relay
ALF	Centralized Control Centre → Loss-of-field Relay	Distributed Control Centre → Loss-of-field Relay	Centralized Control Centre → Loss-of-field Relay
ILS	ISO Boundary PMU → Centralized Control Centre	Zone Boundary PMU → Distributed Control Centre	Zone Boundary PMU → Centralized Control Centre
II	ISO Boundary PMU → Centralized Control Centre	ISO Boundary PMU → Distributed Control Centre	ISO Boundary PMU → Centralized Control Centre
COIO	25 remote PMUs → Centralized Control Centre	25 remote PMUs → Distributed Control Centre	25 remote PMUs → Centralized Control Centre
WAA		Information Exchange between all Distributed Control Centre	Distributed Control Centre → Centralized Control Centre

6.3 Quality of Service for WAMPAC

A queuing system can be described in relation to data networks where packets arrive, wait in various queues, receive service at various points, and exit after some time

[14]. A single queue system is classified as stable if the packet arrival rate is smaller than system transmission capacity. In a congested system, packets accumulate in the queue and some may get dropped. For congested systems with large buffers, packet delays may potentially become excessively long which in turn may compromise the application. Little's law [131] is a very powerful relationship that holds for many queuing systems; the average number waiting in the queuing system is equal to the average arrival rate of the inputs to the system multiplied by the average time spent in the queue expressed as:

$$L = \lambda W \tag{6.6}$$

where L is the expected number in the system, λ is the arrival rate of the inputs and W represents the expected time spent in the system. It is not influenced by the arrival process distribution, the service distribution or the service order.

For a single queue system, if arrival packets are regular or spaced apart (Figure 6.2), no queuing occurs. However, with bursty traffic [91], a continuous transfer of data results in queuing delay; a high arrival rate of traffic increases the delay period. Similarly, irregular packet size with insufficient time space between packets leads to congestion. Therefore, as the traffic arrival rate (packet arrival rate multiplied by packet length) increases, queuing delay increases.

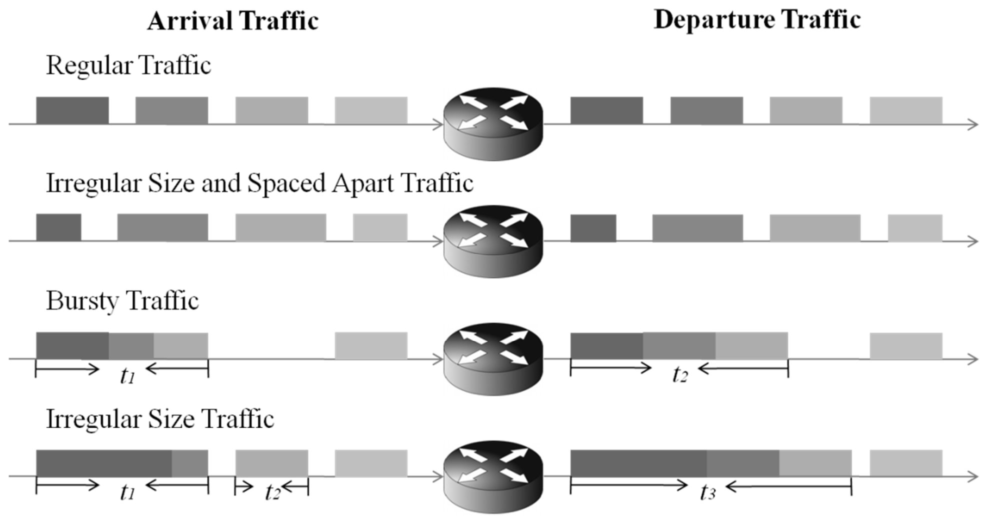


Figure 6.2 Traffic performance in a single queue system.

6.3.1 Performance Analysis of Queuing System

A. M/M/1 Model [91]

This type of queue is used to represent the flow of traffic in a single server or link system. The model is based on the assumption that the arrival distribution of the traffic is Poisson with rate of λ packets/sec [91]. The packet departure rates are exponentially distributed with mean $1/\mu$ [91]. In order to have a stable system, the utilization factor $\rho=\lambda/\mu$ must be less than 1; thus the expected total time in the system $T = 1/(\mu - \lambda)$.

The M/M/m model is an extension of M/M/1 model, but with m servers. The packet at the head of the queue is served when a server becomes empty. However, it is always better to have a single more powerful server whose service rate equals the sum of m servers than m servers with m queues [132].

In the case of a PMU generating 30 packets/sec of size 102 bytes in a dedicated network with channel capacities of 64 kbps, 1 Mbps and 2 Mbps, the departure rate μ

and queuing delay T can be calculated as:

$$\mu = \frac{64Kb/s}{102*8} = 78.43\ packets/s \tag{6.7}$$

$$T = \frac{1}{\mu - \lambda} = \frac{1}{78.43 - 30} = 20.65\ ms \tag{6.8}$$

Thus the queuing delays for link capacities of 64 kbps, 1 Mbps, 2 Mbps are 20.65ms, 0.84ms and 0.41 respectively (Fig. 6.3).

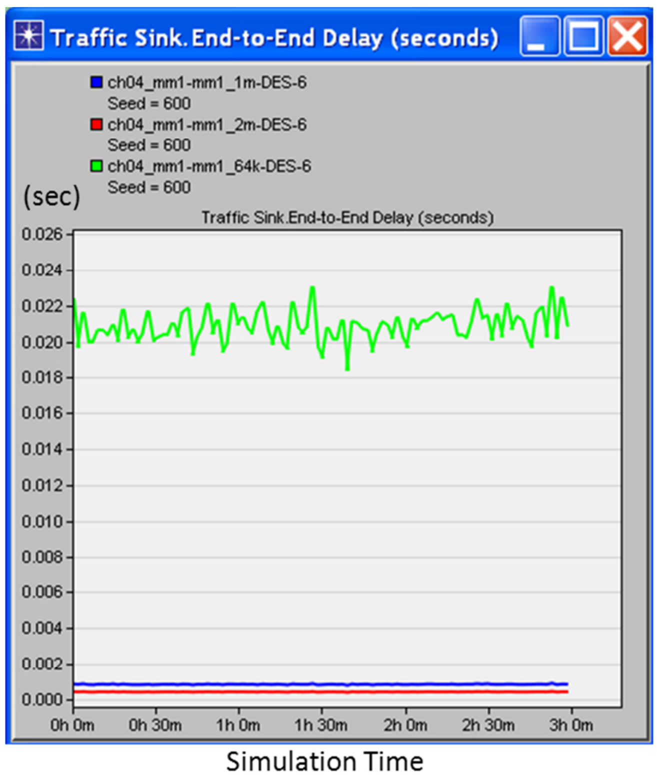


Figure 6.3 Queuing delay for the link capacities of 64 kbps, 1 Mbps and 2 Mbps.

B. M/G/1 Model [91]

In the M/M/1 model, all message lengths are assumed to be randomly and exponentially distributed. In the case of packet switched networks, this is no longer valid. Considering traffic with independent arrival rate, single server and the signal transmission time, in general, with mean $1/\mu$ and variance σ^2, then the queue can be modelled through the M/G/1 model. By using the Pollaczek–Khinchine formula [120], the average time in queue can be represented as;

$$T = \lambda(\sigma^2 + 1/\mu^2)/2(1- \rho) \tag{6.9}$$

Increasing σ^2, increases the queuing delay. The traffic delay with varying message lengths is considerably longer than with constant message lengths even though the average packet length is the same (Figure 6.4). This is an important result that demonstrates the fact that packet-switched networks are more efficient than networks that transmit messages of varying length.

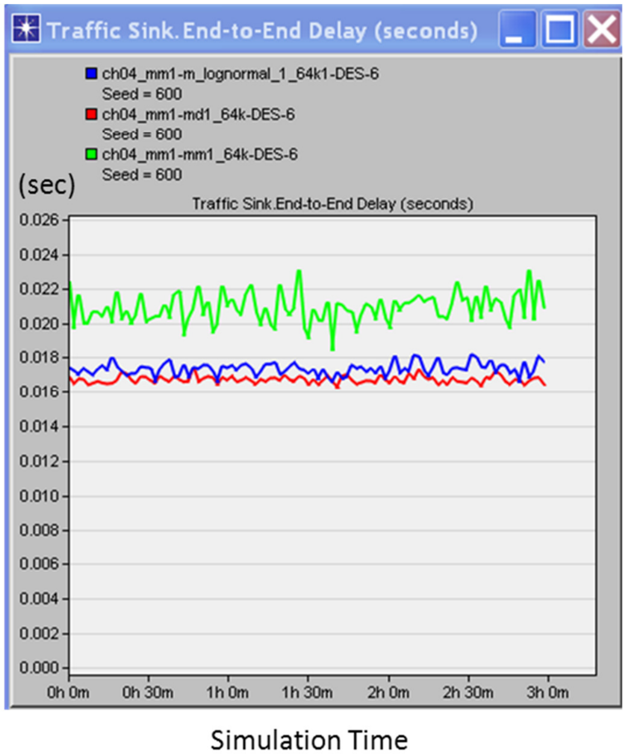


Figure 6.4 Queuing delay for a finite packet size in the constant, exponential and lognormal distributions with a link capacity of 64 kbps.

6.3.2 Quality-of-Service (QoS) Control

If a network is congested, different types of bottlenecks can be created at access points or at points within the core network. These bottlenecks can be further categorized into isolated or inter-related (bottlenecks are triggered in a chain) [14]. Bottlenecks result from congestion caused by high load sessions, or convergence of a sufficient number of moderate load sessions at the same queue. Different techniques can be used to reduce or eliminate the problem such as Quality-of-Service (QoS) enforcement [13], prioritization [14] and traffic flow control [13].

Traditional delivery in IP networks follow the 'best effort' principle, in which all traffic is treated equally without any guarantees. However, various WAMPAC applications acquire data at different rates, accuracy and timeliness. Differentiated Services (DiffServe) [13] can be used to deliver QoS by classifying packets with priorities whereas Integrated Services (IntServe) [13] allows the end system or application to request a QoS from the network (Table 6.2). Under DiffServe, all policing and classification is done at the boundaries between DiffServe domains. This means that in the core of the network, routers are unhindered by the complexities of collecting payment or enforcing agreements. That is, in contrast to IntServe, DiffServe requires no advance setup, no reservation, and no time-consuming end-to-end negotiation for each flow.

The communication requirements in WAMPAC are based on the types of applications which are more suitable to a DiffServe approach. For instance, applications that require a high level of reliability, such as ADS, ALF, need to be provided with higher priority in the forwarding and queuing of traffic data. As a consequence, DiffServe can be implemented to classify network traffic and provide QoS on modern packet networks.

Table 6.2 Comparison between different Quality of Service strategies.

	Best Effort	**IntServe**	**DiffServe**
Scalability	Poor	Poor	Good
Granularity	Fair to all	Per flow	Per class

Classification	None	At host/router	At the edge
Control	FIFO only	At host/router	Marking at the edge of core network
Complexity	Low	High	Medium

The Per-Hop Behaviour (PHB) in DiffServe is determined by the DiffServe field of the packet header, which contains a 6-bit Differentiated Services Code Point (DSCP) value [14]. The definition of Per-Hop Behaviour includes a default PHB representing typical best effort traffic; Expedited Forwarding (EF) PHB is dedicated to low loss, low latency traffic; and Assured Forwarding (AF) PHB provides assurance of delivery under prescribed conditions. Therefore, EF PHB is suitable for voice, video and other real-time services. EF traffic is often given strict priority queuing above all other traffic classes whereas AF PHB allows the operator to provide assurance of delivery as long as the traffic does not exceed a specified rate. Traffic that exceeds the subscription rate faces a higher probability of being dropped if congestion occurs. The AF behaviour group defines four separate AF classes with Class 4 having the highest priority. Within each class, packets are given a drop precedence (high, medium or low). The combination of classes and drop precedence yields twelve separate DSCP encodings from AF11 through AF43.

Referring to the communication requirements introduced in Chapter 3, WAMPAC control applications e.g. control of inter-area oscillation, demand higher bandwidth and lower latency, which are thus tagged as EF. The applications with higher throughput, e.g. AOS and SE, have a higher probability of experiencing traffic congestion, and consequently hence are tagged with group AF41-43. Time critical applications such as ILS and II, are more suitable to be labelled as priority classes AF 31-33 with low data loss, whereas those low QoS applications such as ADS and ALF can be classified as AF11 and AF21 (Fig. 6.5). Based on the classification of WAMPAC services, different priorities are assigned on each individual router.

Assured Forwarding (AF) Behavior Group

	Class 1	Class 2	Class 3	Class 4
Low Drop	AF11 (DSCP 10)	AF21 (DSCP 18)	AF31 (DSCP 26)	AF41 (DSCP 34)
Med Drop	AF12 (DSCP 12)	AF22 (DSCP 20)	AF32 (DSCP 28)	AF42 (DSCP 36)
High Drop	AF13 (DSCP 14)	AF23 (DSCP 22)	AF33 (DSCP 30)	AF43 (DSCP 38)

ADS (AF11)	ALF (AF21)		AOS (AF41)
		II (AF32)	SE (AF42)
		ILS (AF33)	
Inter-area Oscillation Control (EF)			

Figure 6.5 DSCP mapping of different WAMPAC applications.

6.3.3 Traffic Scheduling Algorithms

Various queuing disciplines can be used to control priorities in forwarding data. The commonly used queuing disciplines are: First-in-first-out (FIFO) [91], Priority Queuing (PQ) [14] and Weighted-fair Queuing (WFQ) [14].

FIFO follows the principle of a queue with first-come and first-serve behaviour (Fig. 6.6). In FIFO, all packets are treated equally by placing them into a single queue, then serving them in the same order as they were placed. Although a single FIFO queue seems to provide no QoS features at all, it actually does affect drop, delay, and jitter. The delay in the queue and average jitter are normally proportional to the length of the queue in the router.

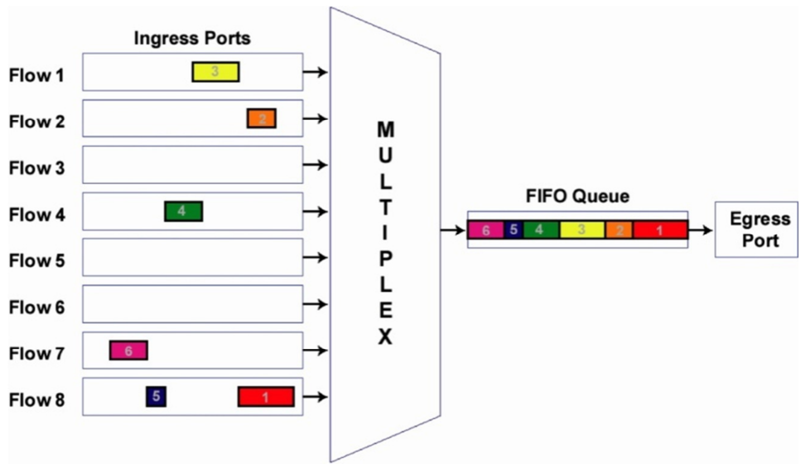


Figure 6.6 Traffic flow in FIFO queuing.

Priority Queuing (PQ) assigns multiple queues to a network interface, each queue being assigned a priority level; PQ has four pre-configured queues, high medium, normal and low priority [14]. Queues are serviced in strict order of queue priority, so the high priority queue always is serviced first, then the next-lower priority and so on (Fig. 6.7). If a new packet arrives at the time when a packet is being processed in a lower priority queue, the new packet will be processed immediately. Thus traffic with higher priority enjoys lower latency and jitter, whereas queue starvation is experienced by lower priority traffic. The principle of the Fair Queuing (FQ) discipline is to maintain a separate queue for each flow currently being handled by the router. The router then services these queues in a round robin manner.

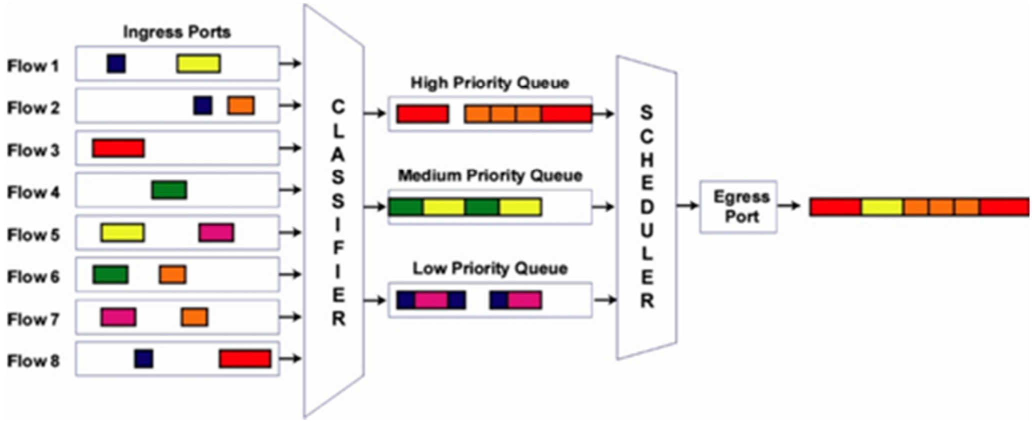


Figure 6.7 Traffic flow in Priority Queuing.

Weighted Fair Queuing (WFQ) [14] is a data packet scheduling technique allowing different priorities to be assigned to statistically multiplexed data flows (Fig. 6.8). At a link data rate of R, at any given time, the n active data flows are serviced simultaneously. If weights w_i are predefined, the data flow p will achieve an average data rate of:

$$R_p = \frac{R w_p}{\sum_{i=1}^{n} w_i} \tag{6.10}$$

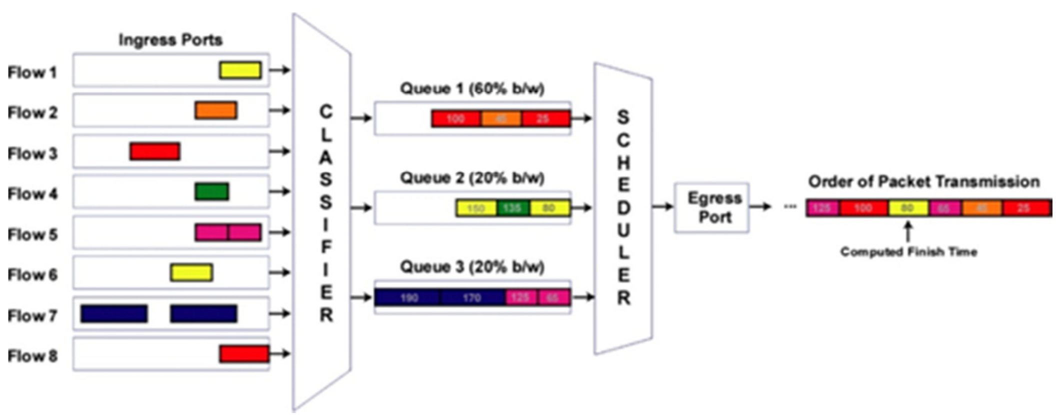


Figure 6.8 Traffic flow in Weighted Fair Queuing.

WFQ can be utilized for setting the QoS of different services so as to achieve a guaranteed data rate and packet loss. The weights w_i can be obtained from the Differentiated Services Code Point (DSCP) in each IP header.

Fig. 6.9 shows the end-to-end delay of FTP and Video Conference applications using the traffic scheduling mechanisms of FIFO, PQ and WFQ respectively. The profile of FTP and video conference traffic maps well to the WAMPAC applications characterised by periodic data transfer without acknowledgements such as state estimation and large amount of burst data transfer without acknowledgements as control of inter-area oscillation respectively [76]. In the example, the Video Conference service is labelled with AF 41 whereas the FTP application is tagged with AF 21. As a consequence, high priority and normal priority queues are assigned for video conference and FTP application respectively through a PQ mechanism. In WFQ scheme, a weight of 70 and 30 are attributed to the video and FTP applications, which represents the allocated bandwidth for each queue. Thus the video application with PQ experiences the lowest delay in sacrifice of a much higher delay in the FTP function. WFQ manages the delay of the two applications, ensuring priority in forwarding video conference data, but also keeping the time delay for FTP service under an acceptable level.

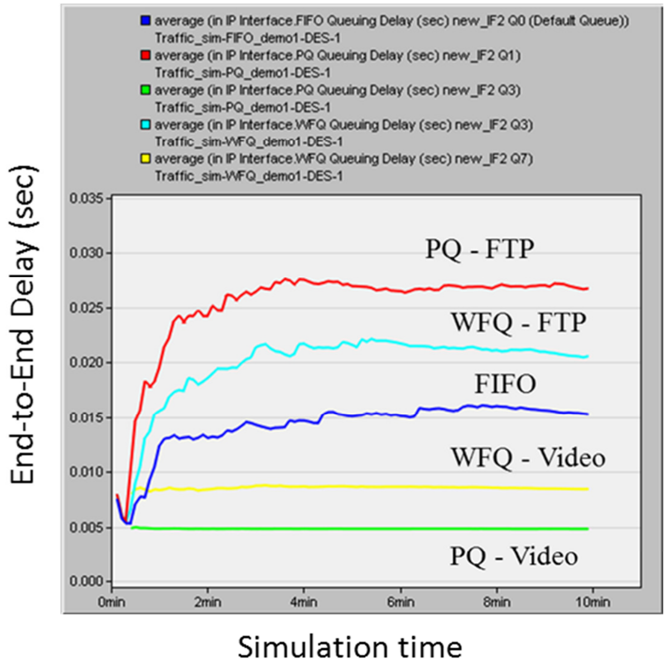


Figure 6.9 End-to-End delay based on FIFO, PQ and WFQ.

Combination of several queuing schemes is used to fulfil the requirements in scenarios with different traffic flows. Low Latency Queuing (LLQ) [133] is a feature that brings strict priority queuing to Class-Based Weighted Fair Queuing (CBWFQ) [133] (Fig. 6.10). It enables the use of a single, strict priority queue for delay-sensitive traffic. Traffic in this queue is assigned the highest priority, and only if this queue is empty, are other queues allowed to send traffic according to the traditional WFQ mechanism. A customized WFQ scheme can also be implemented to share the bandwidth of the channel more efficiently. Lowest priority, mostly used for traffic tolerant to latency and packet loss, can also be implemented for traffic scheduling.

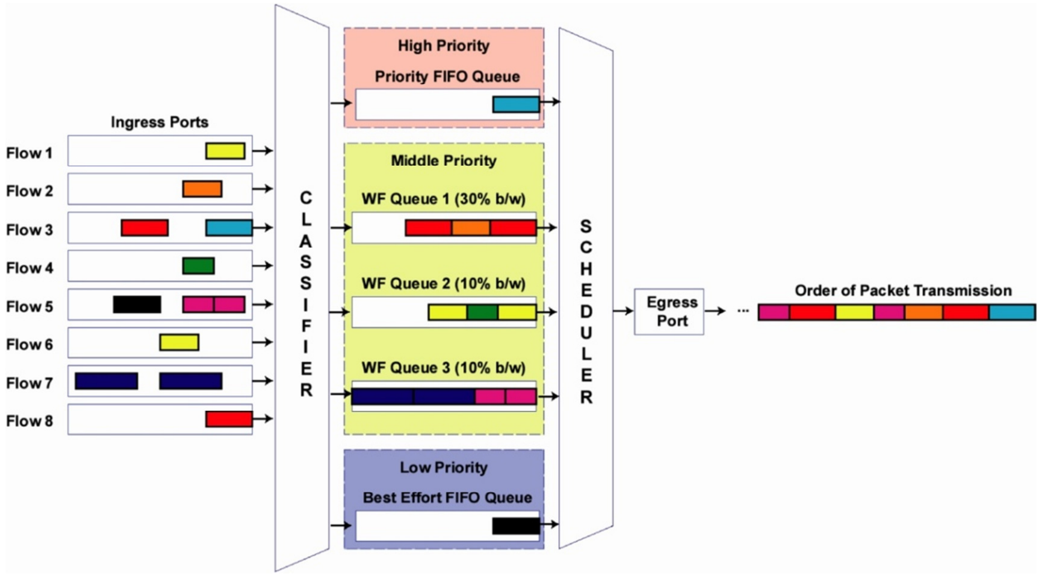


Figure 6.10 Traffic flow control with a combination of several queuing schemes.

6.3.4 MPLS Mechanism

Multiprotocol Label Switching (MPLS) is an Internet Engineering Task Force (IETF) specified framework that provides the designation, routing, forwarding and switching of traffic flows through the network [134]. In MPLS, data transmission occurs on Label-Switched Paths (LSPs). LSPs are a sequence of labels at each and every node along the path from the source to destination. LSPs are established either prior to data transmission (control driven) or upon detection of a certain flow of data (data-driven). MPLS is a versatile solution to address the problems faced by present-day networks; speed, scalability, QoS management, and traffic engineering.

MPLS and DiffServe can be applied together as they have some similar features that permit inter-operability. Both technologies perform packet classification only in the Ingress Edge Router (IER), considering aggregated classes of traffic: MPLS with Forward Error Controls (FECs) and DiffServe with PHBs. The IETF has proposed two ways in which MPLS and DiffServe inter-operate [6]. In one scheme, the DSCP in the packet header is copied onto the EXP field of the MPLS shim header and appropriated packet treatment is performed based on the value contained in the EXP field (E-LSP). In the other scheme, a MPLS signalling protocol like Label Distribution Protocol (LDP) [135] or Resource Reservation Protocol- Traffic Engineering (RSVP-TE) [136] is used to signal labels per class per packet source destination pair (L-LSP).

The RSVP protocol defines a session as a data flow with a particular destination and transport-layer protocol. However, when RSVP and MPLS are combined, a flow or session can be defined with greater flexibility and generality. The ingress node of an LSP uses a number of methods to determine which packets are assigned a particular label. Once a label is assigned to a set of packets, the label effectively defines the flow through the LSP. This kind of LSP is referred as LSP Tunnel because the traffic is opaque to intermediate nodes along the label switched path. In some applications it is useful to associate sets of LSP tunnels such as traffic engineering and fast re-route [137].

Therefore if a link fails, packets can be re-routed to circumvent the failed link ensuring communication is uninterrupted. This feature of a data switched network is called resilience because it hides network failures from end users.

The benefits of MPLS include:

- Can cooperate with other protocols by utilizing a simple label switching mechanism, which is where its versatility in application exists, e.g., MPLS over Ethernet [91], ATM [132], and frame relay (FR) [132].
- With techniques such as classification, queuing priority scheduling and

traffic-engineering, MPLS is capable of providing controllable QoS features [141].

- Provides a solution to scalability and enables significant flexibility in routing.
- The connection oriented architecture and QoS reliability features easily enable high quality end-to-end service features that are necessary in applications such as Virtual Private Networks (VPN) [142].

6.4 Simulation Framework

6.4.1 Geographical Topology

Figure 6.11 depicts the PMU locations derived from the optimization described in Chapter 4. In total, 50 PMUs are deployed to achieve full-observability of the network across the UK. All the geographical locations of PMUs are listed in Appendix 1.

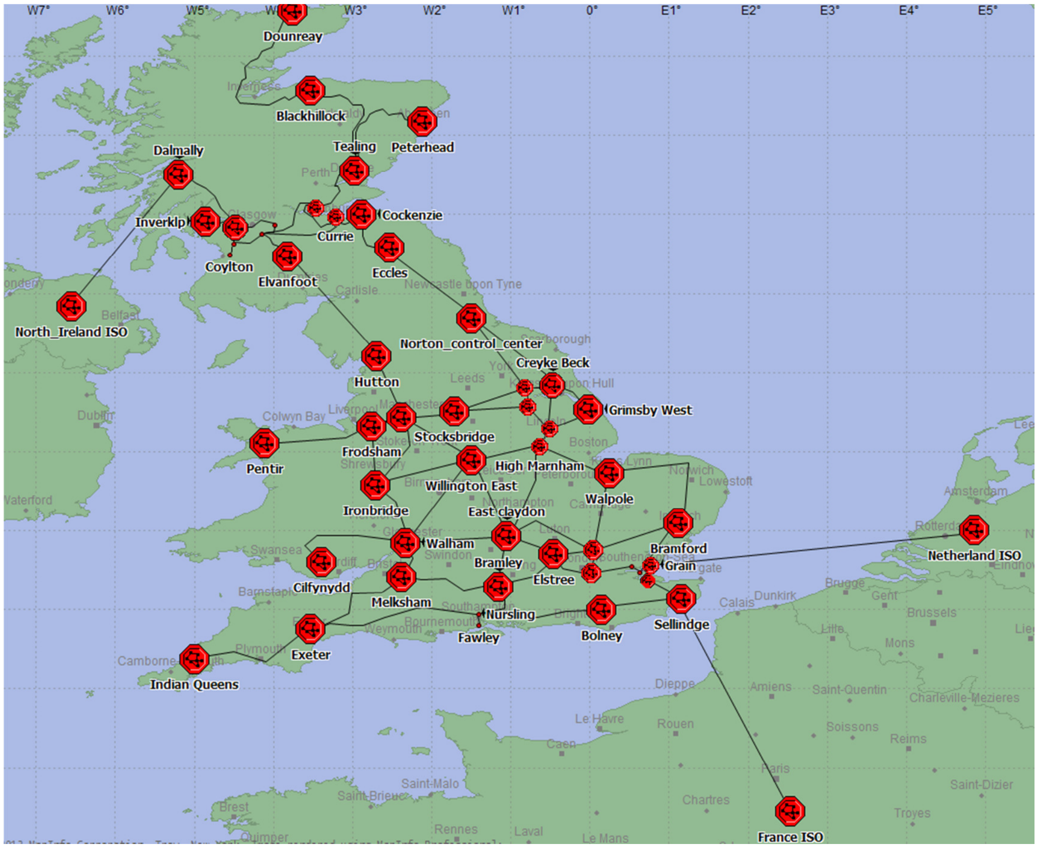


Figure 6.11 Optimized PMU locations across the United Kingdom.

Since WAMPAC includes functions for monitoring, protection and control purposes, large generators and critical paths will be under constant supervision and specific relays/ circuit breakers will be responsible for certain contingencies. The locations of generators and relays/circuit breakers are specified through the National Grid Seven Years Statement, and are listed in the Table 6.3.

Table 6.3 Sites of generators and critical relays/circuit breakers.

	Geographical Sites	Support functionalities
Generators	Blackhillock; Cockenzie; Cottam Dalmally; Fawley; Frodsham; Grain; Grimsby West; Hutton; Indian Queens; Ironbridge; KingsNorth; Norton; Nursling; Pentir; Peterhead; Thorpe Marsh; Walpole	Adaptive Out-of-Step
Relays	Blackhillock; Clifynydd; Exeter; Indian Queens; Kilmarnock South; Norton; Stocksbridge; Strathaven; Tealing; West Ham	Adaptive Dependability and Security; Supervision of Back-up Zones; Adaptive Loss-of-Field
Tie-line PMUs	High Marnham; Hutton; Ironbridge; Norton; Tealing; Tilbury; Walham	Intelligent Load Shedding; Seams State Estimation
Circuit Breakers	Dalmally; Frodsham; Sellindge; Strathaven; Tealing; West Ham; Bramford	Intelligent Islanding; Large Oscillation Control
Remote PMUs	North Ireland ISO; France ISO; Netherland ISO	Inter-area Control; Large Oscillation Control

6.4.2 OPNET Overview

It is difficult to capture the details of WAMAPC network performance purely within an analytical framework. Therefore, the OPNET [8] simulator is used to implement all the functionalities of WMAPAC, evaluating the effect on performance of variations in network topology, link capacity and QoS.

Although there are several well-known simulators that can be used for the analysis of network performance such as Network Simulator 2 (NS-2) [143], Network Simulator 3 (NS-3) [144], OMNeT++ [145], this Thesis employs the OPNET as the platform for several reasons:

- Widely utilized in network performance analysis
- Open source
- License free (educational version)
- Many existing routing protocols and algorithms are available under OPNET, including MPLS
- Geographical location awareness with a real map interfacing

Detailed comparisons of OPNET and other simulators can be found in [146].

Thus OPNET is a powerful and comprehensive modelling and simulation software dedicated to communication network research and development. OPNET simulations are event driven which saves simulation time. It also adopts object-oriented analyses, provides graphic edit interfaces, large amount of models and network technologies and has location awareness functionality. The structure of the simulation is normally composed of a process model, node model and network model, and their inter-relationships are shown in Figure 6.13.

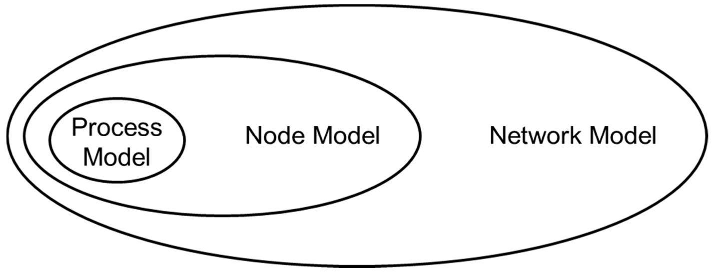


Figure 6.12 Structure of the OPNET simulation framework.

Process models are used to specify the behaviour of processing and queuing modules which exist in the node domain. Process models can be used to implement a wide variety of hardware and software subsystems, including communication protocols, algorithms, shared resources such as disks or memory, operating systems, queuing disciplines, specialized traffic generators and custom statistic collectors (Fig. 6.13).

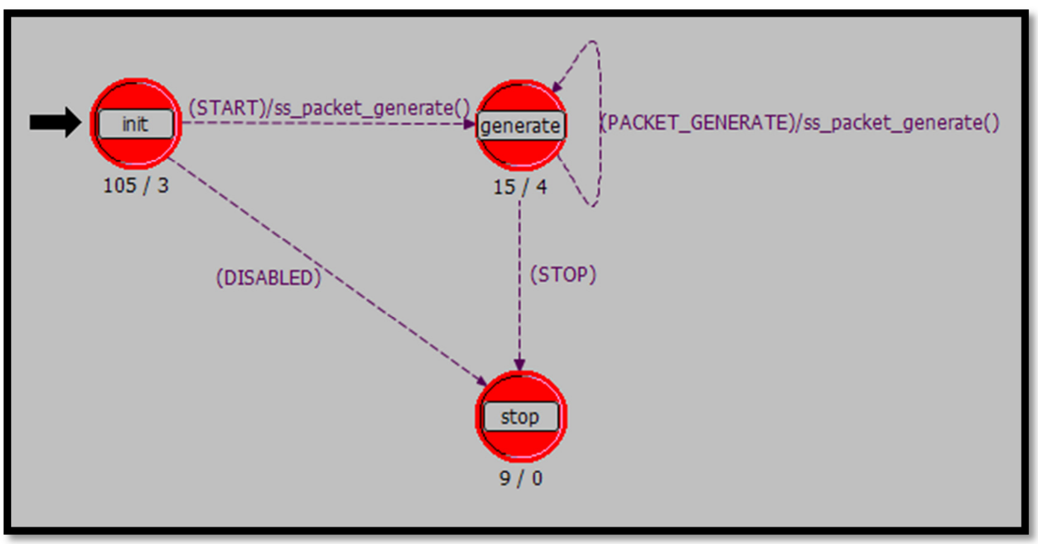


Figure 6.13 OPNET process model.

A node model is composed of a series of connected blocks called modules. Each module contains a set of inputs and outputs, state memory, and a method for computing the module outputs from its inputs and state memory. The manner in which this computation takes place depends upon the type of module. Figure 6.14 represents the node model for a single transceiver.

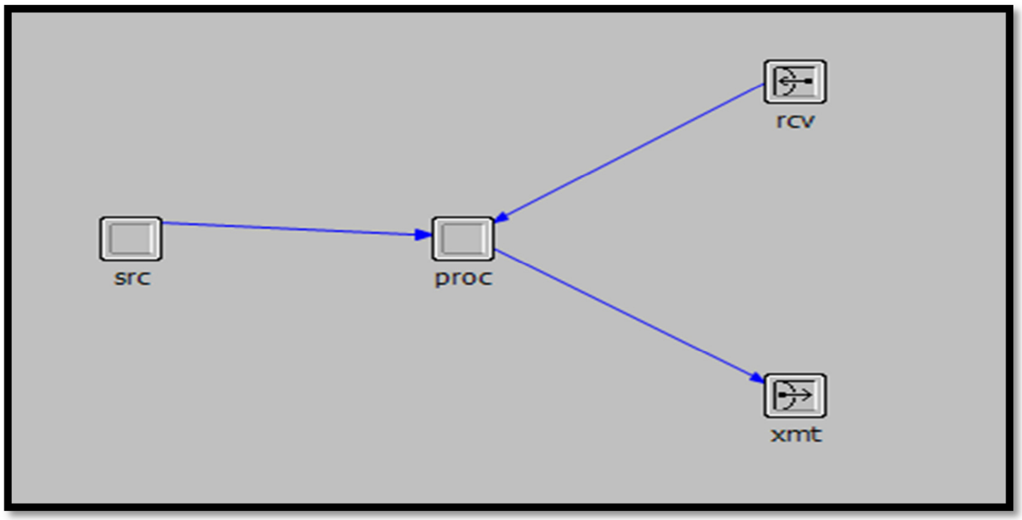


Figure 6.14 OPNET node model.

A network model defines the overall scope of a system to be simulated and is a high-level description of the objects contained in the system. The network model specifies the objects in the system, as well as their physical locations, interconnections and configurations (Fig. 6.15)

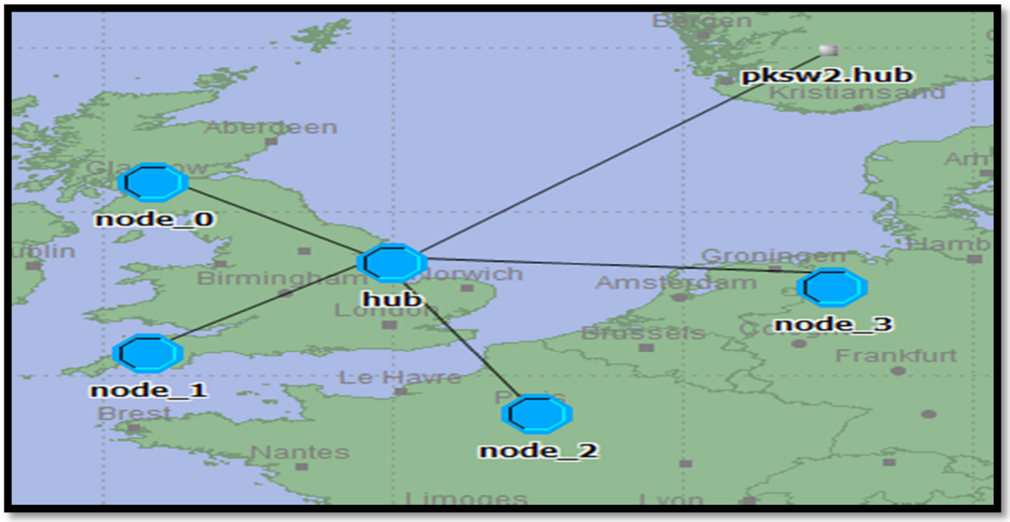


Figure 6.15 OPNET network model.

The node model in Figure 6.16 represents a generic model for an Ethernet workstation. Based on the Open Systems Interconnection (OSI) standard [91], the workstation model can be categorized into 6 layers. On top is the application layer where the definition of packet size, transmission rate, source and destination preferences are executed. An application issues a request to 'tpal' to initiate a session, to send data through an established session, or to end the session. The Transport Layer defines end-to-end services such as connection-oriented protocol TCP and connectionless protocol UDP. The Network Layer is a group of protocols (e.g. Internet Protocol) and specifications which forward data across the network. The Address Resolution Protocol (ARP) and Medium Access Control (MAC) are in the Data Link Layer which takes charge of protocols operation on the host's links. The Physical Layer is represented in Figure 6.16 by a transmitter and a receiver which sends and receives packets respectively. Ethernet communication is basically between PMUs and substation switch and between PDC, WAMPAC server and

Control Centre Ethernet switch. The generation of the WAMPAC traffic starts at the top ‘application’ module in PMUs or WAMPAC server node. The traffic then is passed to the Transport layer modules and thereafter to the network layer and so on.

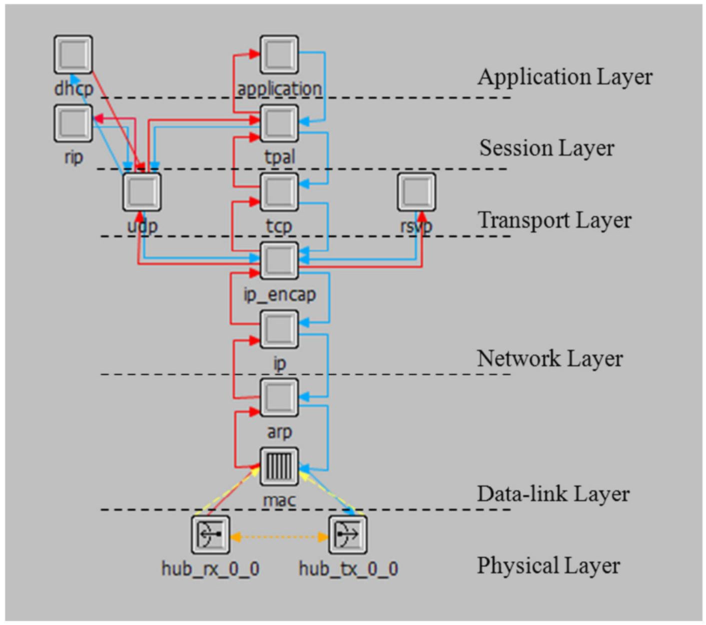


Figure 6.16 Model for an Ethernet workstation.

A generic substation model supporting WAMPAC applications is represented in Figure 6.17. As described in Section 6.2, a range of WAMAPC applications are simulated in detail. The substation model acts as a LAN composed of measurement devices, actuators and routers. The substation router operates as an edge router which interconnects the LAN with the backbone network and forwards the data across the whole system.

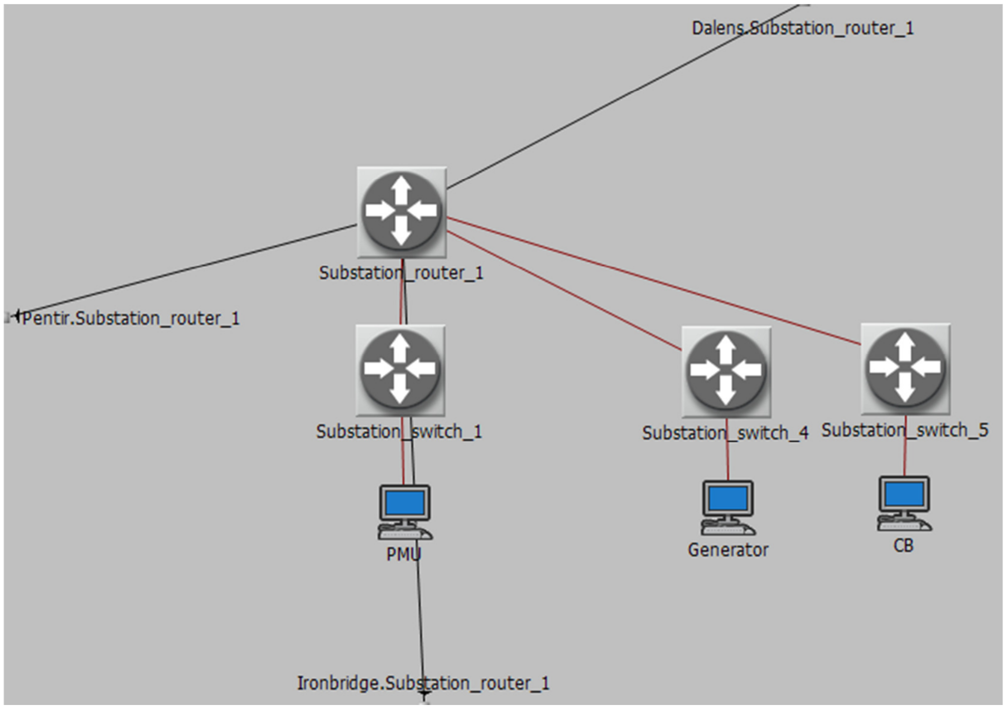


Figure 6.17 WAMPAC substation model (located in Frodsham).

In Figure 6.18, the 'WAMPAC' server in the Control Centre model fetches the information from distributed monitoring devices and also sends control and protection signals to the specific destinations based on the analysis of data received.

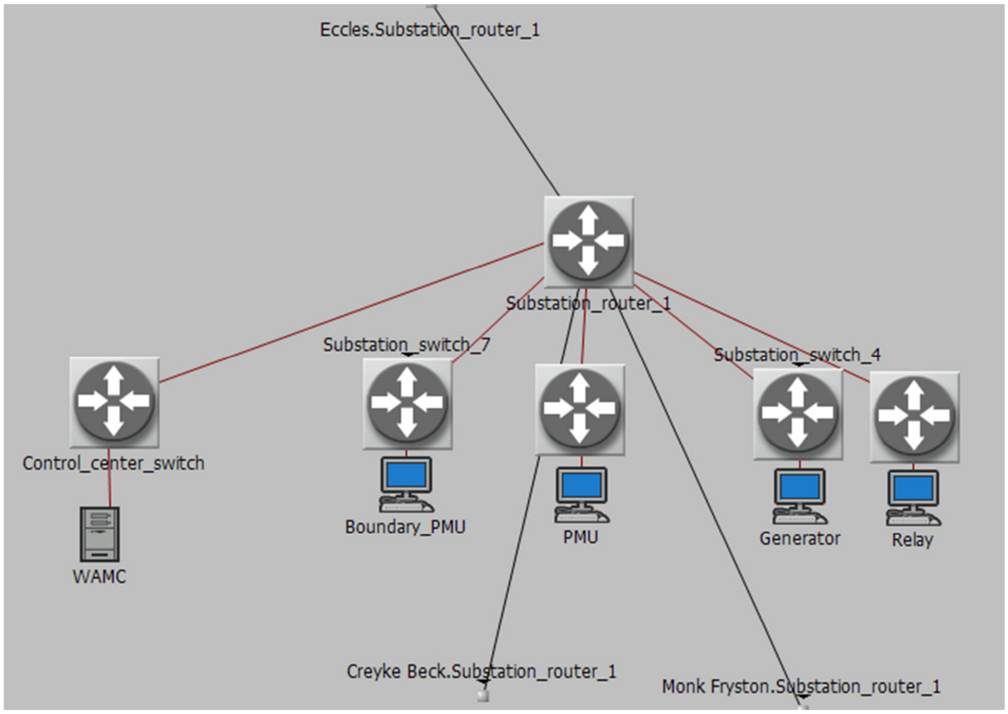


Figure 6.18 WAMPAC Control Centre model.

6.4.3 Network Settings and Configuration

According to the IEEE 37.118 standard, each Phasor is represented by a maximum of 54 bytes (3-phase in float format). Each data frame also comprises a 48 bytes header and trailer, broken down into 16 bytes for the C37.118 header and trailer and 32 bytes for the packet header. An example of a packet based on C37.118 is shown in Table 6.4.

Table 6.4 Packet structure based on the C37.118 standard [39].

Field	**Example entry**	**Size (Bytes)**
SYNC	Data Frame, Version number	2
FRAMESIZE	70 bytes in this frame	2
IDCODE	ID Number, 16-bit integer	2
SOC	Second count	4
FRACSEC	Time of phasor measurement in microseconds with Time Quality	4
STAT	Bitmapped flags: ‘00 00’ for Data valid; no PMU error; PMU sync; data sorted by time stamp; no PMU trigger; best time quality	2
PHASORS	For 3-phase value in float format, 4 phasor measurements are taken for VA, VB, VC and I1	32 Phasors
FREQ	Frequency deviation from nominal in millihertz. E.g. +2500 mHz (Nominal 50Hz with measured 52.5 Hz)	4
DFREQ	Rate of Change of Frequency	4
ANALOG	2 Analogue values in 32-bit float format	8 Analogue
DIGITAL	2 Digital values in 18-bit float format	4 Digital
CHK	CRC-CCITT	2

Communication links interconnect all substations where PMUs are located and establish a backbone network. All backbone links use E1 links at 2.048 Mbps and E3 links at 34 Mbps. Links internal to each substation interconnect PMUs, PDCs and other controllable devices.

6.4.4 Traffic Link Property

The WAMPAC communication network is segmented into 3 parts: the Core network operating as a backbone network interconnecting all distributed network sites and forwarding information over long distances; Access network acting as a bridge which links the Local Area Network (LAN) with the core network; and LANs connecting the sites where the measurements are taken and actuation is carried out, e.g. relays, circuit breakers executing control and protection functions (Fig. 6.19).

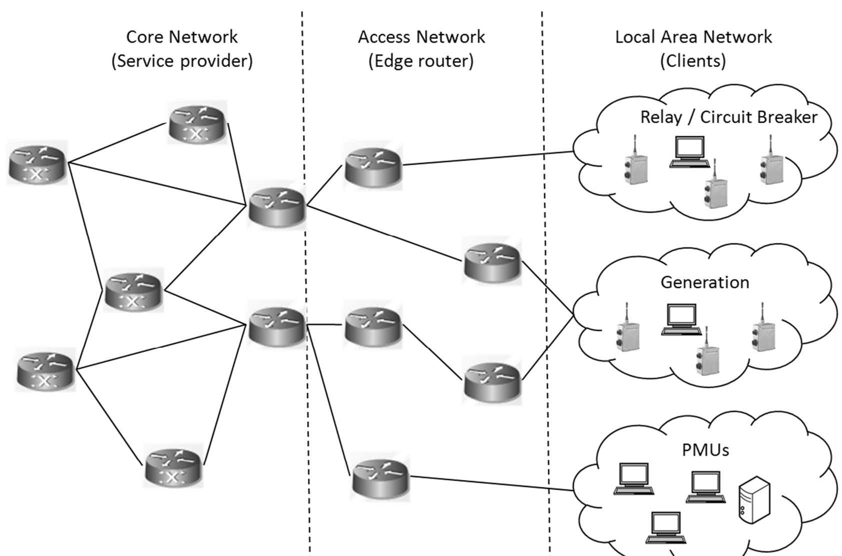


Figure 6.19 WAMPAC network model.

The focus of the analysis is on the performance of the interconnections in the core segment of the network - identified as backbone links - and the linkages beneath the edge router, identified as branch links; the bandwidth of the communication network can therefore be categorized into backbone and branch links respectively. For backbone links, the physical connections are selected as E1 - 2.048 Mbps - and E3 - 34.368 Mbps - respectively. In branch links, the bandwidth is constrained to 64 kbps, 1 Mbps and 2 Mbps.

6.5 Simulation Analysis

As mentioned in Section 6.4.4, the analysis through simulation will consider the bandwidth requirements in both backbone and branch links. Solutions must fulfil the requirements of a range of WAMPAC applications as well as minimise the cost of the communication infrastructure. Different design of network topology as described in Chapter 5 are evaluated and recommendations on the optimum solution drawn. The operational characteristics of the optimal solution are also verified through simulation (Fig. 6.20).

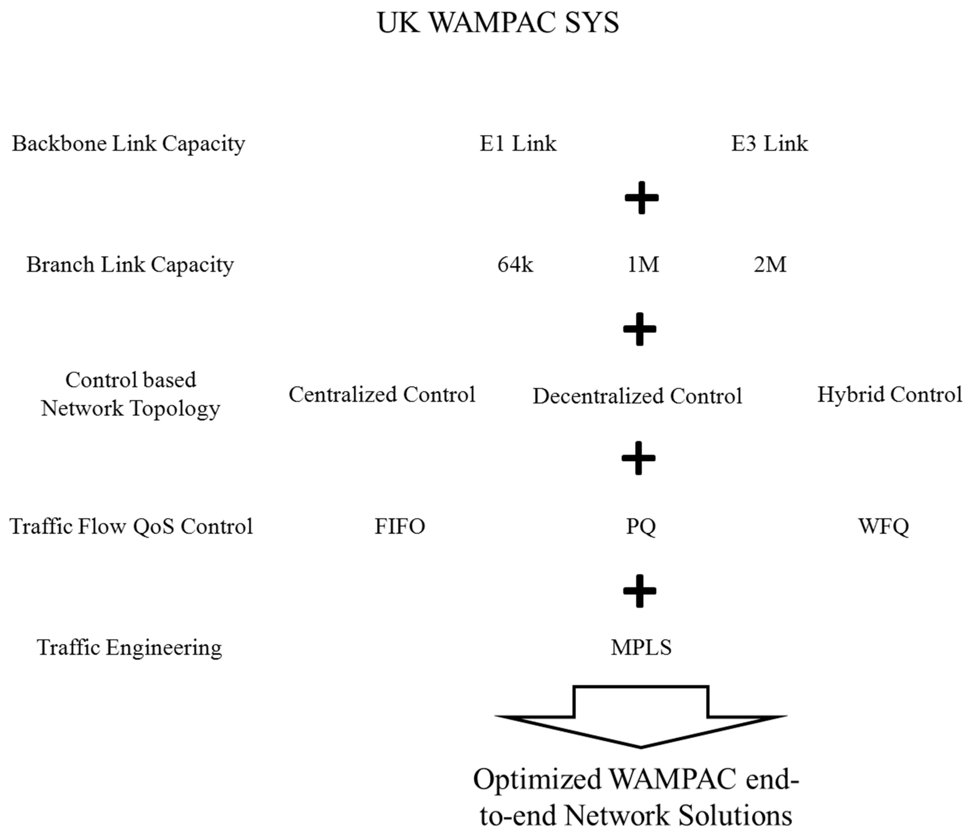


Figure 6.20 Simulation methodology for the UK WAMPAC system.

6.5.1 E1 Backbone and FIFO

A comparison of the End-to-End (ETE) delay as a function of different time-critical applications in a communication network with centralized control is shown in Figure 6.21. The ETE delay represents the time taken for a packet to reach its destination. In other words, it is the difference between the time a packet arrives at its destination and the time when the packet was created. The Control of Inter-area Oscillation (COIO) experiences the longest delay attributed to the relatively long transmission distances between adjoining ISOs. State Estimation (SE) and Adaptive out of Step (AOS) both request large amount of information transmitted across the system, which also causes burstiness in traffic flows across the network. In contrast, since the traffic flows in Adaptive Dependability and Security (ADS), Supervision of Back-up Zone (SBUZ) and Adaptive Loss of Field (ALF) have a lower bandwidth requirement, less queuing delay does not compromise the total ETE delay time

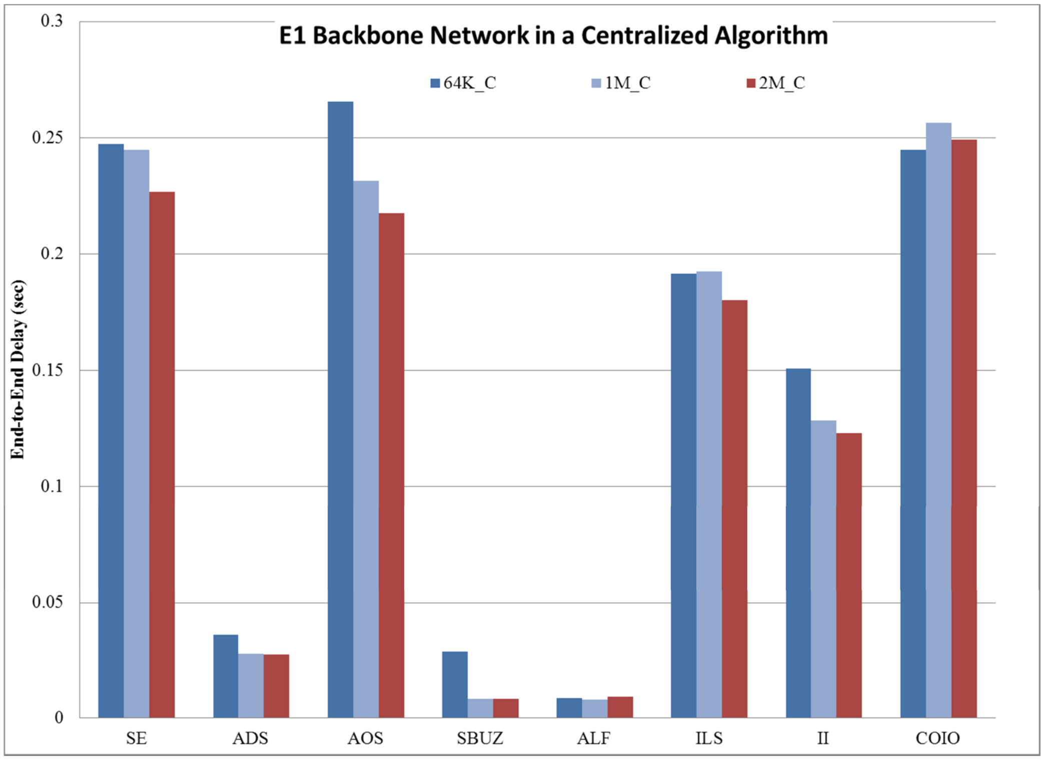


Figure 6.21 End-to-End delay for E1 backbone network with centralized control for a range of WAMPAC inspired applications.

Figure 6.22 illustrates End-to-End delay as a function of different network topology with increasing link capacity for the E1 Backbone Network. In the figure, '_C', '_D' and '_H' represent for the network topology of Centralized based, Decentralized based and Hybrid network topologies based respectively. The significant ETE delay for all centralized control based schemes does not meet the requirements of

WAMPAC applications. However, both the decentralized and hybrid control based systems have acceptable performance for most applications, the hybrid scheme having the added feature of lower network complexity.

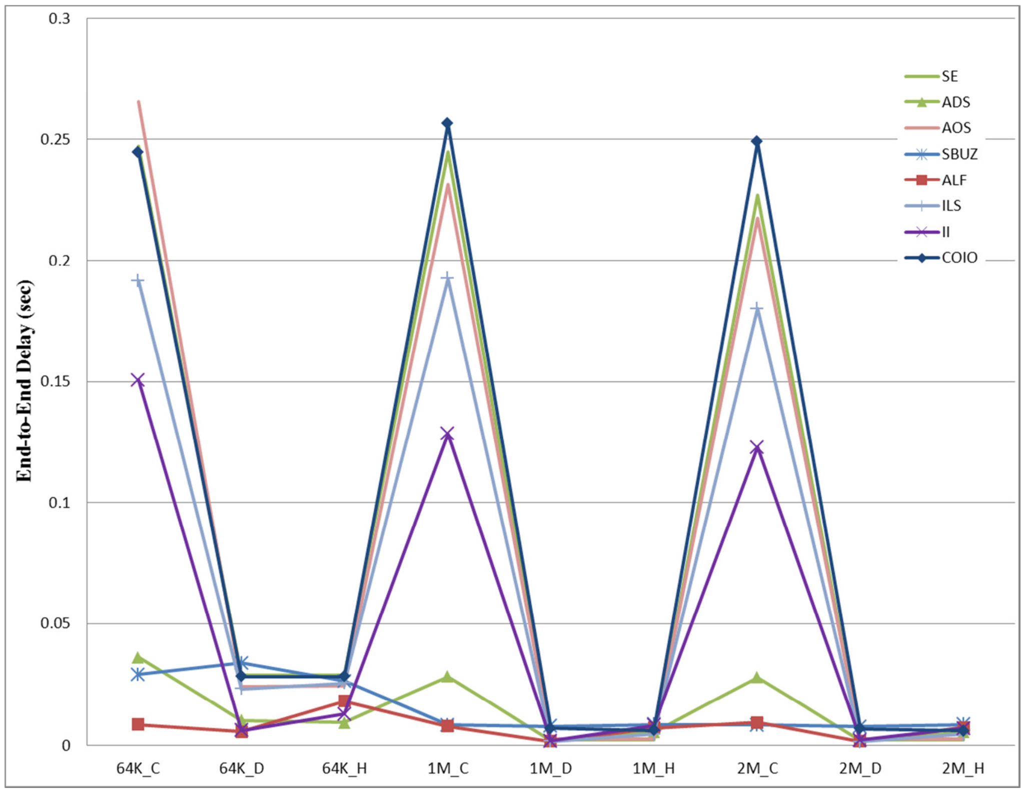


Figure 6.22 Comparison of End-to-End delay for the E1 backbone network as a function of topology for a range of WAMPAC inspired applications.

Figure 6.23 depicts the impact of link capacity and network control topology. Distributed and hybrid control designs decrease the influence of limited branch link bandwidth significantly. Although higher E2E delays result for a link capacity of 64kbps (green colour and purple bars) compared to the delays for link capacity of 1Mbps and 2Mbps respectively, the latter still do not satisfy the delay criteria for all WAMAPC applications. The major constrain on network performance in respect of latency originates from the centralized control topology (Fig. 6.23).

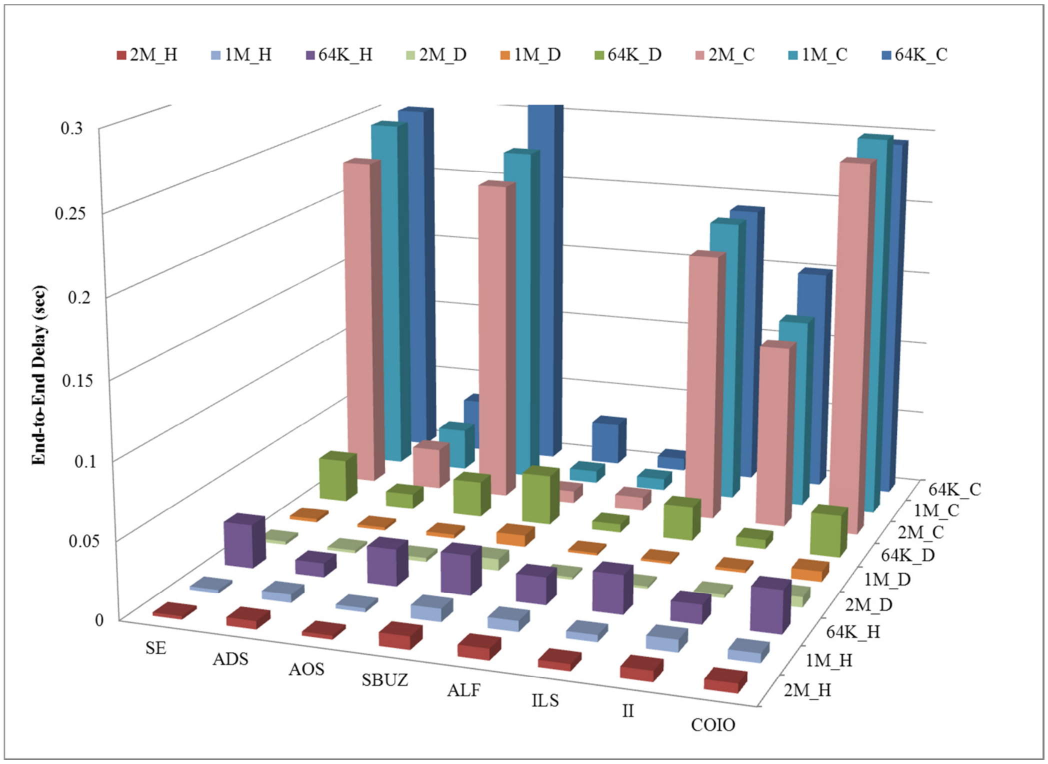


Figure 6.23 A comparison of E2E delay for different branch link capacities and network control topologies for E1 backbone links.

According to Equation (6.3) and Equation (6.4), the delay of a service is determined by a combination of the physical length of the connection path, link capacity and Number of Routers forwarding the data. Any design of the system must optimize these factors so as to meet the criteria for different WAMPAC applications (Chapter 3). Since different control scenarios have been proposed, a complete design of the communication network needs to be simulated to validate the feasibility and performance of WAMPAC applications.

An analytical comparison between latency for different control scenarios can be performed utilising normal distribution functions of the number of hops and link utilization based on their distribution histograms (Table 6.5, Fig. 6.24 and Figure 6.25).

Table 6.5 Number of hops and link utilization for WAMPAC inspired applications for different network control topologies.

Strategy	Characteristics	Mean	Variance
Centralized	Number of Hops	8.68	3.69
	Link Utilizations	0.53	1.29
Decentralized	Number of Hops	5.71	0.47
	Link Utilizations	0.35	0.35
Hybrid	Number of Hops	6.32	1.57
	Link Utilizations	0.26	0.32

Fig. 6.24 illustrates the influence of different control scenarios on the Number of Routers (NoRs) involved in forwarding the data. In comparison with the other schemes, the decentralized network exhibits the least number of hops and lowest variance since all PDCs are deployed near information sources. Conversely, the centralized approach suffers the highest mean value and the variance is largest. In another words, latency in centralized service scenarios is location sensitive with closer information sources providing the lowest delay. The hybrid network classifies the applications based on demand; thus the performance lies in between the other two.

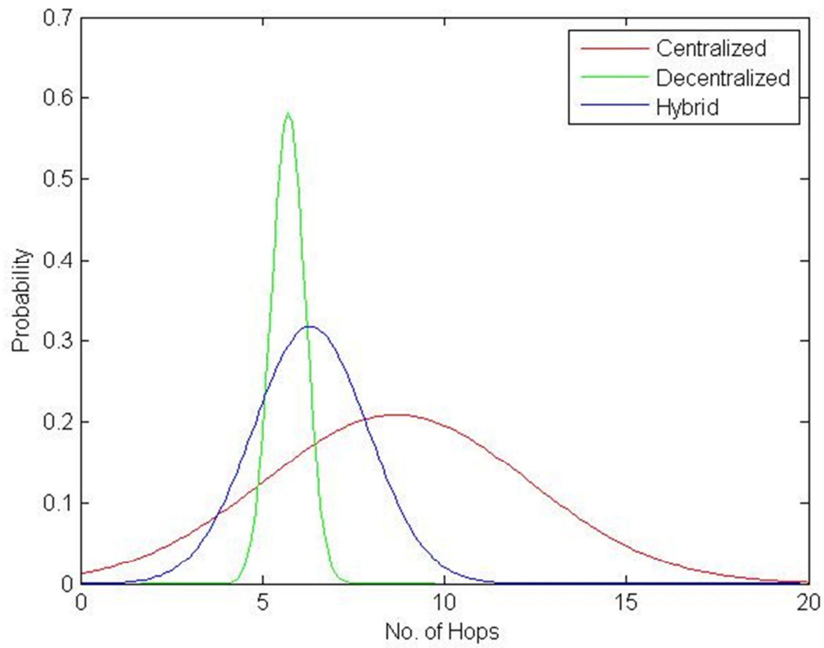


Figure 6.24 Distributions of number of hops in different network topologies.

Figure 6.25 shows the utilization of the interface throughput on each node. The centralized topology exhibits the worst performance since a large amount of data is forwarded across long transmission paths. However, both decentralized and hybrid strategies exhibit lower throughput since most tasks are accomplished within distributed PDCs. However, synchronization is required in order for the DCCs to achieve the necessary wide area awareness of the system.

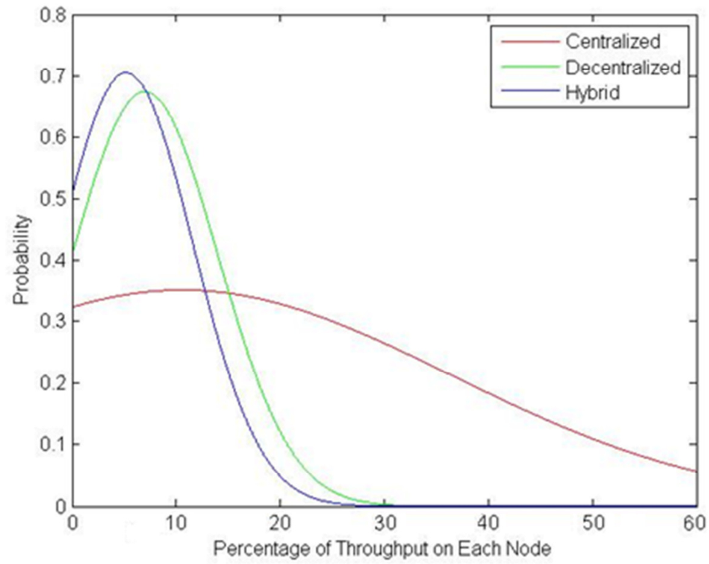


Figure 6.25 Distributions of link utilization for different network control topologies.

6.5.2 E3 Backbone and FIFO

For fast E3 backbone connections (34.368 Mbps), the E2E delay is reduced significantly compared to E1 links (2.048 Mbps). In Figure 6.26, the E2E delays for all applications are below 30 milliseconds, meeting the criteria for all WAMPAC applications. Among these applications, ADS, II and ALF have the lower latency compared to others because of their reduced bandwidth requirements. A peak can be identified for a branch link capacity of 64 kbps for all network topologies. Figure 6.27 illustrates a comparison of branch link capacity and network control topology for an E3 backbone network. The bandwidth limit on the branch links is identified as a major constrain on network performance in terms of latency.

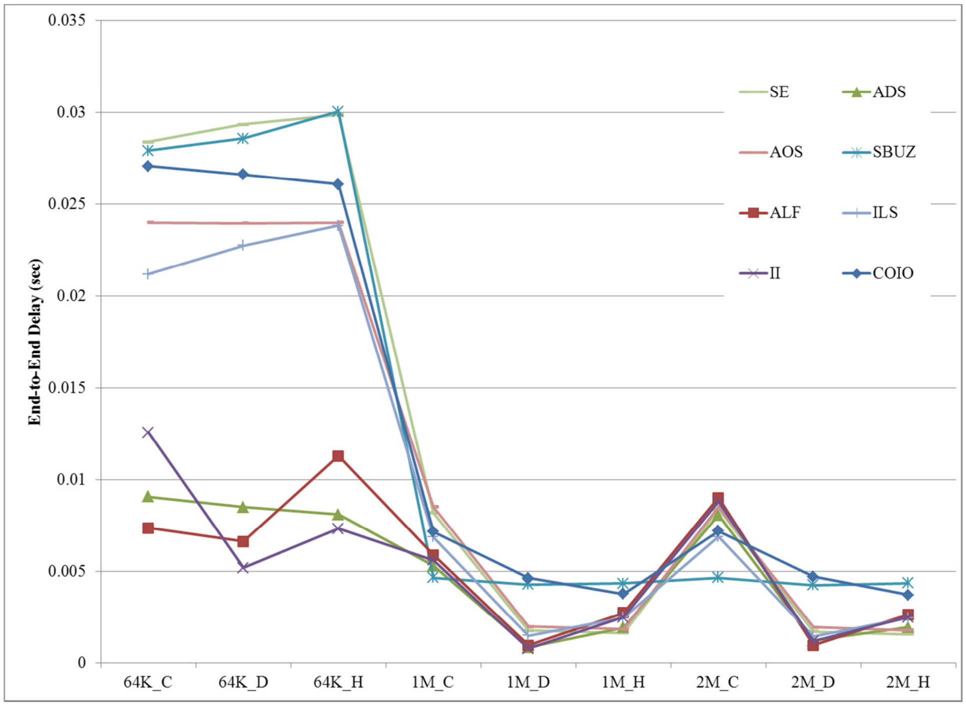


Figure 6.26 Comparison of End-to-End delay for an E3 backbone network as a function of network control topology.

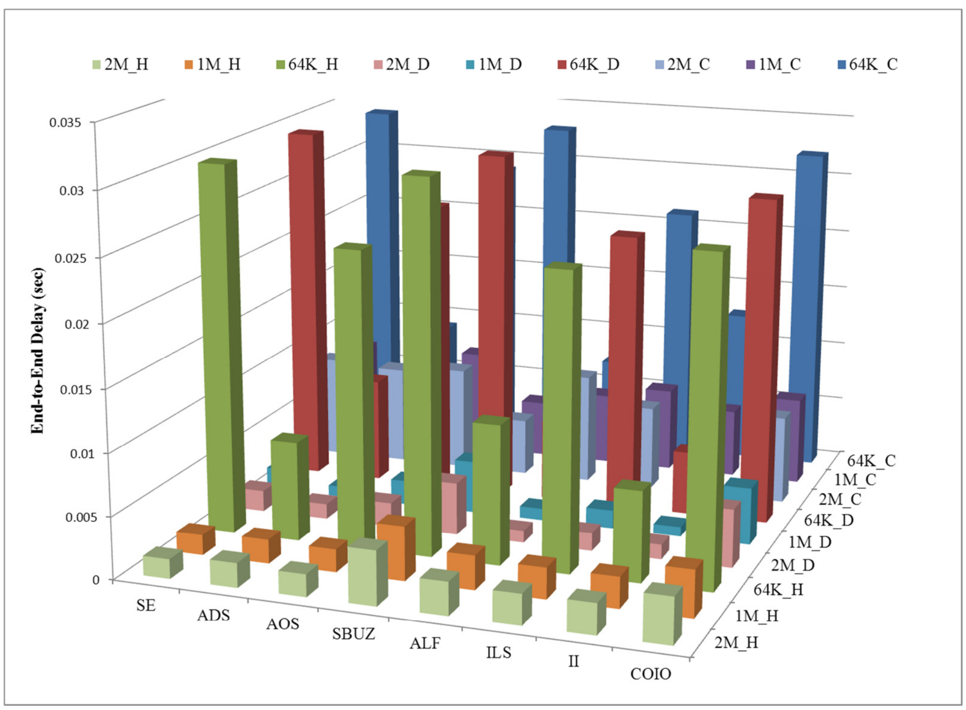


Figure 6.27 A comparison of End-to-End Delay for different branch link capacities and network control topologies for E3 backbone links.

Based on the results in Section 6.5.2 and Section 6.5.3, several compromise solutions can be identified. In a centralized network control, a minimum of E3 backbone is required to fulfil latency requirements. For decentralized and hybrid control, although a limit on the capacity of branch links causes a higher delay, the delay still remains under the acceptable level thereby meeting the requirements of WAMPAC applications. Furthermore, the latter two control strategies provide a higher level of reliability, able to better manage single node failure and network congestion.

6.5.3 QoS Traffic Flow Control

Centralized control is in common use in existing systems, since a migration to decentralized and hybrid alternatives will have a significant impact through a redesign of the whole system. Thus a study of enhancements on the performance of centralized network control systems by using priority queuing options is presented.

For E1 backbone links in a centralized control environment, the latency requirement is not met for several WAMPAC applications, especially those with a high demand on link bandwidth such as SE, AOS and COIO. Thus, customized queuing (CWFQ) is implemented to improve performance. Table 6.6 lists the scenarios with different weight of PHBs. As discussed in Section 6.3.2, ADS (AF11), ALF (AF21), II (AF32), ILS (AF33), AOS (AF41), SE (AF42) and COIO (EF) are assigned to the appropriate PHB level. The remaining applications are managed in a FIFO fashion and as such, are assigned the lowest priority. In Table 6.6, Scenario 3 refers to standard weighted fair queuing whereas Scenario 2 reverses the weight inputs for AF41-43 categories with EF. Scenario 1 and Scenario 4 assign LLQ to the two most demanding applications, SE with AOS and COIO respectively.

Table 6.6 Customized DSCP weights and the simulation scenarios.

	AF11-13 (ADS)	AF21-23 (ALF)	AF31-33 (II/ILS)	AF41-43 (AOS/SE)	EF (COIO)
Scenario 1	5	5	30	LLQ	60
Scenario 2	5	10	15	40	30
Scenario 3	5	10	15	20	50
Scenario 4	5	5	30	60	LLQ

Results shown in Figure 6.28 indicate that for Scenario 1 and Scenario 2 a significant reduction in the delay for applications such as SE, AOS but at the expense of a much higher latency for COIO far in excess of the acceptable level. The same trend is observed for Scenario 3 and Scenario 4, with a lower delay for COIO, ILS, and II, but the latency for SE and AOS is significantly higher than the criteria required by WAMPAC.

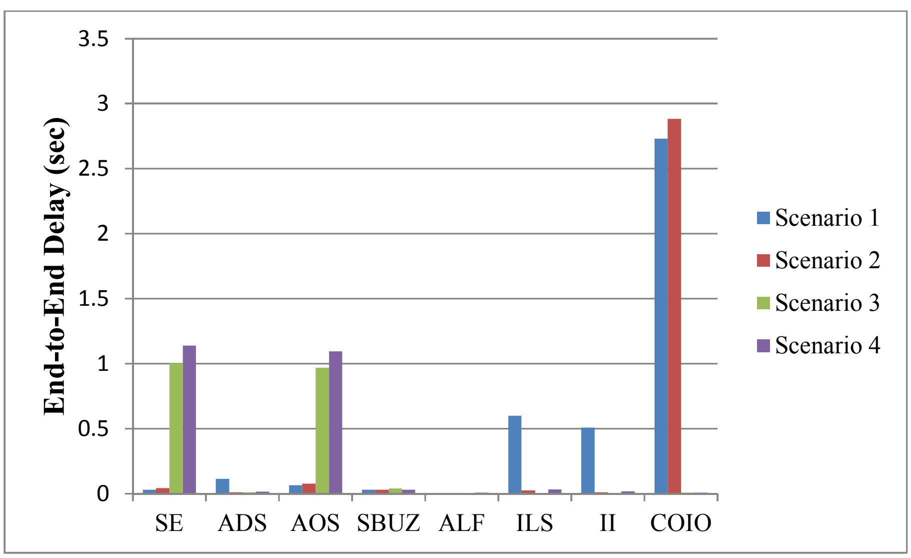


Figure 6.28 End-to-End delay under different QoS controls for a range of WAMPAC inspired applications.

Figure 6.29 shows the variance of the latency for AOS and SE applications with and without WFQ. Results support the conclusion derived from Figure 6.28 that both the AOS and SE application experience a longer delay in Scenario 3 and Scenario 4. An important feature is that the variance for applications with WFQ is much higher than without QoS control. In another words, the latency in applications with WFQ is distributed unequally, creating congestion in certain areas or links.

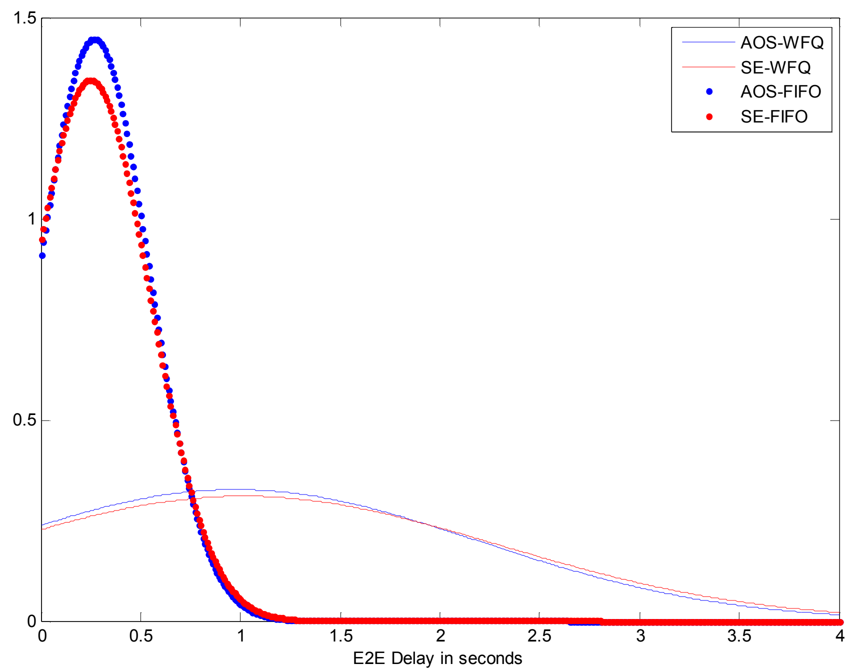


Figure 6.29 Possibility Density Function (PDF) of End-to-End delays for WAMPAC inspired applications with Priority Queuing.

6.5.4 MPLS Traffic Engineering

In order to understand the impact of traffic engineering on the performance for a given network, an Interior Gateway Protocol (IGP) analysis [91] has been carried out. If the IGP analysis shows that one or more links are highly utilized while others remain virtually unused, the network can benefit from traffic engineering. In this case, the next step is to create LSPs in the network that will drive traffic from the over-utilized to the less utilized links.

Figure 6.30 illustrates the link utilization following IGP analysis through the network. Different colours labelled on the link indicate the utilization level. The path “Bramley- East Claydon- High Marnham – Cottam – Creyke Beck – Norton” has a much higher utilization compared to others; the percentage of link utilization between High Cottam and Creyke Beck, Creyke Beck and Norton sit at greater than 60.

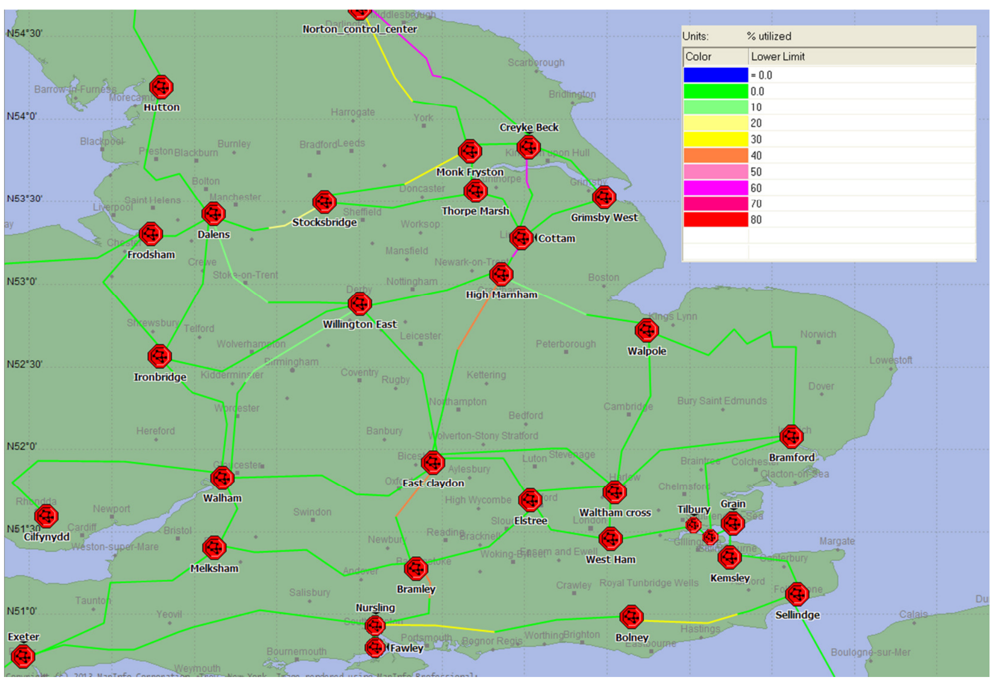


Figure 6.30 WAMPAC communication network link utilization in the UK.

In order to manage congestion on certain links, a LSP tunnel using MPLS is established as shown in Figure 6.31. All the source IP address from neighbouring France ISO will be accommodated into the tunnel and forwarded following a pre-defined path.

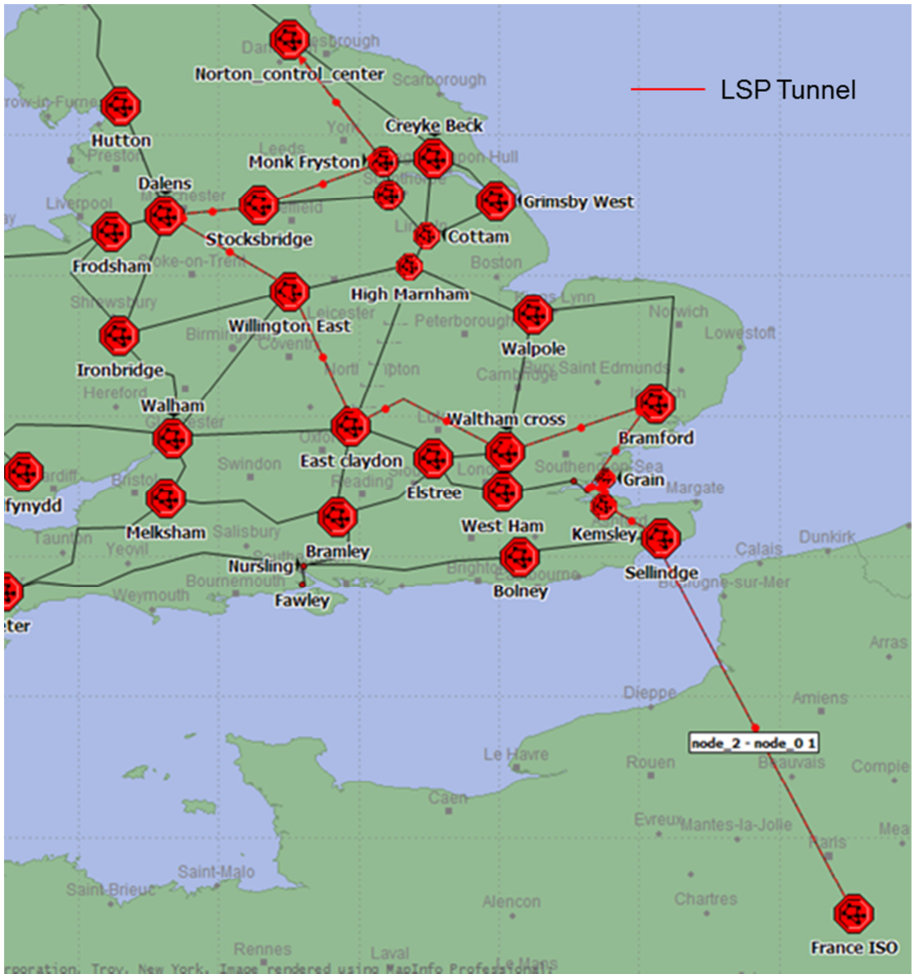


Figure 6.31 MPLS LSP assignments.

Figure 6.32 shows the E2E delay for all WAMPAC applications with WFQ with MPLS traffic engineering. The delay is reduced significantly for those applications with higher bandwidth needs, most noteworthy for COIO, where the LSP tunnel delay is reduced to fewer than 20 milliseconds. The delay for ALF, SBUZ and ADS has however increased owing to changes in traffic flows, but all still meet the delay criteria for each application. Figure 6.33 illustrates the comparisons of Various Weighted Fair Queuing options with or without MPLS Traffic Engineering.

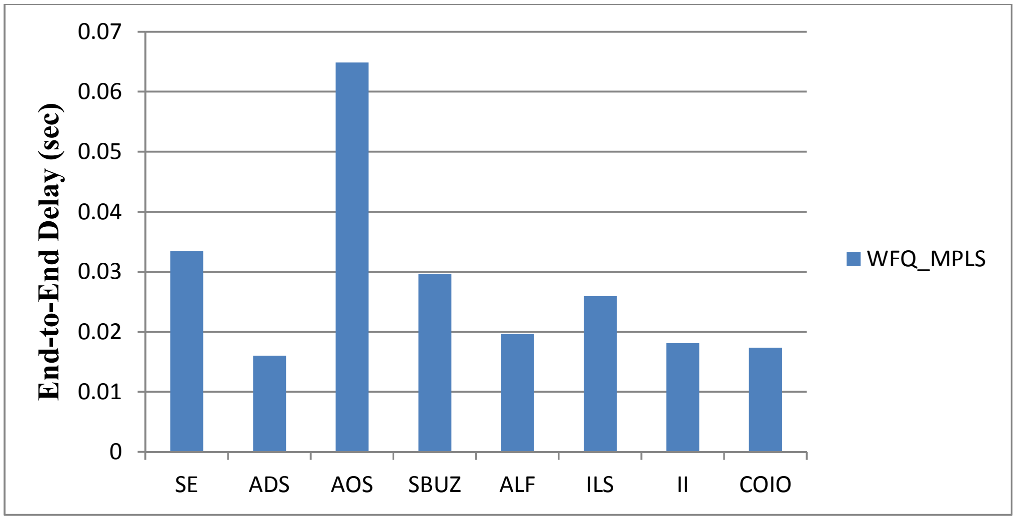


Figure 6.32 ETE delay for a range of WAMPAC inspired applications with MPLS.

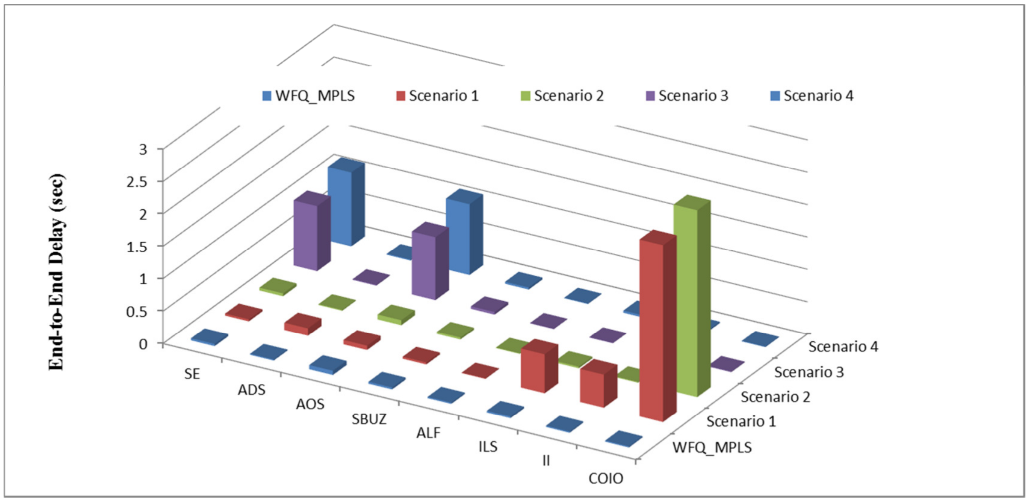


Figure 6.33 Comparison of the End-to-End delay for number of Weighted Fair Queuing options with or without Traffic Engineering for a range of WAMPAC inspired applications.

The fast re-route capability enabled by MPLS enhances the reliability of communication network even under centralized network control. The delay for re-direction to a back-up LSP is no more than 50 milliseconds rendering the system resilient to any single node failure. Figure 6.34 shows the ETE delay after link failure triggers the re-routing of packets to the back-up LSPs at a time between 500 seconds to 1000 seconds. Although the delay is much higher due to congestion on the links, the information is re-directed to the Control Centre successfully.

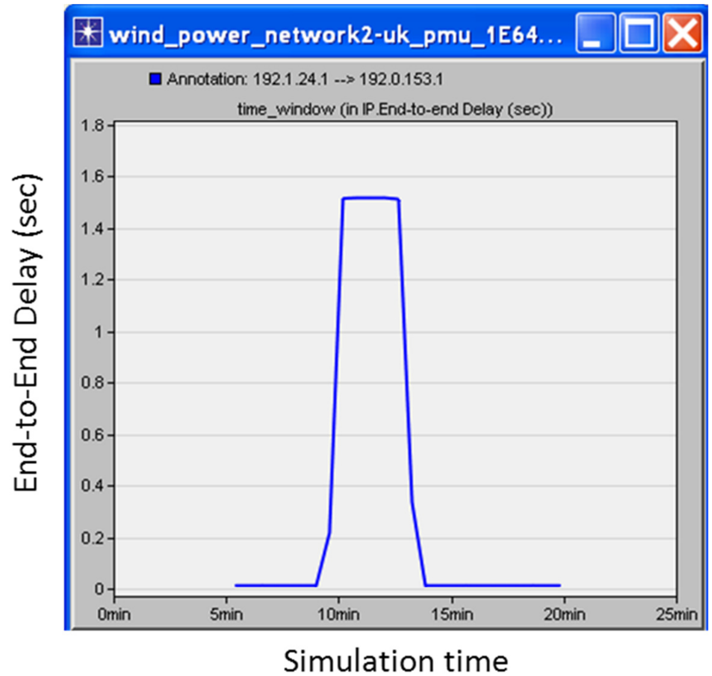


Figure 6.34 End-to-End delay for the WAMPAC inspired SE application after link failure.

6.6 Conclusions

WAMPAC inspired functionalities represent core elements facilitating the efficient implementation of smart grids. The deployment of WAMPAC applications is enabled by a flexible, scalable networking platform inter-connecting widely distributed PMUs, the core components of WAMPAC. Large volumes of data exchanges between measurement devices, Control Centres and controllable remote devices make the design of the network infrastructure challenging. The Chapter presents potential network solutions that meet the requirements of WAMPAC applications. Data sources, governed primarily by the locations of the PMUs and the resultant data flows are influenced by the control strategy, impact greatly on the design of the network.

Proposed network solutions are evaluated in terms of delay through simulation for the case of the UK power transmission system. The performance of PMU-based WAMPAC applications are analysed in terms of latency and reliability. The network with E3 backbone links fulfils the latency requirements regardless of network topology whereas E1 backbone links result in a higher level of network congestion. For centralized control under E1 backbone links, delay is beyond the latencies criteria defined for a range of WAMPAC applications introduced in Chapter 3. Further, the reliability of centralized network control is lower than for decentralized and hybrid control mechanisms. In addition, several queuing schemes - with the aim of enhanced control of a rich mix of data flows and services - have been evaluated and surprisingly the throughput performance within congested network scenarios indicates degraded performance for a certain class of application. WFQ/CWFQ provides traffic scheduling functions to ensure the performance of applications with high priority. The drawbacks are however significant in that applications assigned with lower priority experience much higher delay due to the limited channel capacity. MPLS traffic engineering promotes co-operation with differentiated service principles resulting in the significant reduction in the latency. In addition, the fast re-route capability improves network reliability even in centralized network control scenarios.

As a conclusion, the link capacity in the backbone network is an important factor in network performance. The restricted bandwidth in branch links cause bottlenecks, but the needs of the applications are nevertheless met if sufficient backbone link capacity is provided. Further the selection of network architecture is a factor that influences the impact of insufficient link capacity. Both decentralized and hybrid network control improves the latency and reliability of the system.

Under centralized network control with limited link capacities, and as a consequence of the high utilization of these links, implementing WFQ/ CWFQ has a significant impact; although the performance of high priority applications is guaranteed, those assigned the lower priority are at the same time, degraded. MPLS-based traffic engineering which utilise links which are virtually unused through re-routing improves application performance significantly.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

The Thesis centres on the development of a roadmap to the successful deployment and operation of WAMAPC inspired applications and proposes several flexible and reliable network solutions to meet the requirements of advanced monitoring, protection and control applications.

The dissertation starts with the background to the evolution of existing power system, containing the drive for Smart Grid functionality and the supporting communication requirements. The case is then developed for WAMPAC principles, identified as one key route to enabling smart monitoring and control in the power transmission network. Far superior in performance to the conventional widely deployed SCADA systems, WAMPAC benefits from high data rate transmission of time-stamped data from distributed PMUs, the basis for dynamic state estimation and many other advanced protection and control applications

Due to the high cost of a single PMU and corresponding communication infrastructure, a major design effort have been devoted to maximise the observability of the network for a minimum number of deployed PMUs. The methodology of determining the optimized placement of PMUs is implemented based on existing research and a case is made for Integer Linear Programming (ILP), one of the most efficient and accurate methods. The functionality of the algorithm is validated based through the IEEE bus model and utilised to determine the locations of PMU sites for the UK power system. Results show that 50 PMUs in total are required to achieve full-observability of the system and in doing so provide the necessary data that seed a range of applications, a linear estimate of the status of the whole system.

Compatibility is another key issue in designing a reliable and cost-effective system. Power systems have traditionally used fibre optic cables within the earth conductor in the transmission level. These existing communication infrastructures provide reliability through years of practical tests and conveniences in deploying a new system. Therefore, the proposed network architecture makes use of these existing communication infrastructures to interconnect the PMUs in WAMPAC system.

Current approaches to the implementation of WAMPAC principles are all based on centralized network control, which suffers from issues of single link failure and restricted scalability. Distributed network control is preferred as a way to manage these limitations.

The design and analysis of a distributed network supporting a range of WAMPAC applications has been decomposed into;

- developing network topology;
- assigning representative traffic flows over network links;
- assigning and sizing line capacity.

Thus different network topologies and their corresponding features have been investigated and the salient difference between a power system communication network and small-world/free-scale model are highlighted. Taking into consideration the features of the model and the existing system characteristics, three control based network architectures are proposed and analysed: centralized, decentralized and hybrid. Clustering algorithms are applied to determine the optimum network cluster size and the locations of distributed cluster-heads. These clustering methodologies include connectivity models such as link hierarchical clustering [124], centroid models such as k-means clustering [125], and density models such as Expectation Maximisation[126]. Linkage hierarchical clustering is selected to determine optimal node placements. The goal is to segment the UK power network combining the requirements in terms of communication networking with the capability of power transmission; 7 clusters are established, 1 cluster for SHETL and SPT zones and 5 clusters in NGET, summarised in Table 7.1.

Table 7.1 Network clustering for a UK WAMPAC system.

	Cluster Head	No. of PMU	Geographical Location	SYS Study Zone [7]
Cluster 1	Tealing	3	North of Scotland	Z1, Z2 and Z4
Cluster 2	Strathaven	12	Middle belt of Scotland	Z3, Z5 and Z6
Cluster 3	Dalens	6	North West of NGET Network	Z9 and Z11
Cluster 4	Thrope Marsh	9	Upper North of NGET	Z7, Z8 and Z10
Cluster 5	Melksham	5	West of Central London	Z13 and Z17

Cluster 6	Grain	10	Inner and outer London	Z12, Z13, Z14 and Z16
Cluster 7	Bramley	5	East of Central London	Z15

Furthermore, traffic flows across the network representative of WAMPAC applications are defined and form the basis for the evaluation of network performance. The mix of preferred sources and destinations are categorized based on network topology. QoS control technologies are considered and compared to improve network performance in the aspects of latency and reliability. FIFO, widely used in packet networks, has limited ability to control the latency and reliability of the application, whereas WFQ/CWFQ provides traffic scheduling functions that ensure the performance of the applications with high priority. The drawback is that applications with lower priority experience much higher delays due to the limited channel capacity. Thus MPLS based traffic engineering is applied to re-route traffic flows through the links with less utilizations.

The work concludes with extensive simulation based analysis of a mix of scenarios which capture the effect on network performance of link capacity, network topology and QoS. Results are summarised in Table 7.2.

Table 7.2 Network performance analysis in terms of various link capacities, network architectures and QoS mechanisms.

	Link Capacity	Network Topology	QoS Control	Performance
Scenario 1 ~ Scenario 3	Backbone E1 Branch 64 kbps/ 1 Mbps/ 2 Mbps	Centralized	FIFO	Low Reliability High Latency
Scenario 4	Backbone E1 Branch 64 kbps	Decentralized	FIFO	High Reliability Medium Latency
Scenario 5 ~ Scenario 6	Backbone E1 Branch 1 Mbps / 2 Mbps	Decentralized	FIFO	High Reliability Low Latency
	Link Capacity	Network Topology	QoS Control	Performance
Scenario 7	Backbone E1 Branch 64 kbps	Hybrid	FIFO	High Reliability Medium Latency
Scenario 8 ~ Scenario 9	Backbone E1 Branch 1 Mbps / 2 Mbps	Hybrid	FIFO	High Reliability Low Latency

Scenario 10 ~Scenario 19	Backbone E3 Branch 64 kbps/ 1 Mbps/ 2 Mbps	Centralized/ Decentralized/ Hybrid	FIFO	Low Reliability in Centralized case High Reliability for Decentralized and Hybrid mechanisms Low Latency
Scenario 20 ~Scenario 24	Backbone E1 Branch 64 kbps	Centralized	WFQ/ CWFQ	Low Reliability High Latency for lower priority applications
Scenario 25	Backbone E1 Branch 64 kbps	Centralized	WFQ/ MPLS	High Reliability Low Latency

The network with E3 backbone links (Scenario 10 - 19) fulfils the latency requirements regardless of network topology whereas with E1 backbone links (Scenario 1 - 9) a higher level of network congestion is evident. For the centralized control under E1 backbone links (Scenario 1 - 3), delay is beyond the limit of the latencies defined for a range of WAMPAC applications. Further, the reliability of centralized network control is lower than for the decentralized and hybrid alternatives.

In addition, several queuing schemes (Scenario 20 - 24) have been evaluated. WFQ/CWFQ provides traffic scheduling functions to ensure the performance of the applications with high priority at the expense of compromised latencies experienced by those applications assigned a lower priority. Thus under congested network scenarios the performance of low priority applications degrades. In order to solve this limitation, MPLS traffic engineering (Scenario 25) is implemented harnessing co-operation with differentiated service principles and resulting in a significant reduction in the latency of all applications. In addition, the fast re-route capability improves network reliability even in centralized network control scenarios.

As shown in Table 7.3, link capacity in the backbone network is an important factor in network performances. The restricted bandwidth in branch links cause bottlenecks, but the needs of the applications are nevertheless met if sufficient backbone link capacity is provided. Further the selection of network architecture is a factor that influences the impact of insufficient link capacity. Both the decentralized and hybrid network control improve the latency and reliability of the system.

Under centralized network with limited link capacities, and as a consequence of the high utilization of the links, implementing WFQ/ CWFQ has a significant impact; although the performance of high priority applications is guaranteed, those assigned the lower priority are at the same time, degraded. MPLS-based traffic engineering which utilise links which are virtually unused through re-routing improves application performance significantly.

Table 7.3 Applications' criteria analysis in terms of various link capacities, network architectures and QoS mechanisms.

Backbone Link Capacity	Branch Link Capacity	Network Topology	QoS Mechanisms	Meet Applications' Requirements?
E1	64 kbps/ 1 Mbps/ 2 Mbps	Centralized	FIFO	No for the applications with high volume and long transmission distances
E1	64 kbps/ 1 Mbps/ 2 Mbps	Decentralized/ Hybrid	FIFO	Yes for all
E3	64 kbps/ 1 Mbps/ 2 Mbps	Centralized/ Decentralized/ Hybrid	FIFO	Yes for all
E1	64 kbps/ 1 Mbps/ 2 Mbps	Centralized	WFQ	No for the applications with low communication traffic priority
E1	64 kbps/ 1 Mbps/ 2 Mbps	Centralized	WFQ_MPLS	Yes for all

7.2 Future Work

The development of WAMPAC inspired solutions are still early stage and many research challenges remain. In respect of power systems, more advanced applications will be explored and exciting functionalities can be developed owing to the richness of real-time data generated by an extensive network of PMUs. In tandem, research on the communication platform that supports these new applications is a major key to supporting fully-functional WAMPAC, but also to ensure robustness, flexibility and security of the resulting applications. Any future development of the WAMPAC communication platform should consider the following:

Security: always a major concern in developing a reliable system. In order to prevent cyber-attacks, a complete data security methodology is needed.

Wireless: a range of mature communication infrastructures are core options in deploying a complete WAMPAC solution e.g. satellite communication may be essential for the acquisition of measurements in rural areas. The performance for these communications technologies must be further assessed driven by cost/performance criteria of an extensive integrated system.

The establishment of WAMPAC inspired solutions cannot be accomplished without experimental trailing where developing technologies and hardware infrastructures are tested across significant test areas operating in real/emulated environments.

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APPENDIX I

Geographical Locations of PMUs

Location	Latitude (Degree)	Longitude (Degree)	Latitude (Meter)	Longitude (Meter)	Delta-Latitude*	Delta-Longitude*	Euclidean Distance
Dounreay	58.58	-3.75	6477272.66	-417188.88	491595.20	-329990.37	592080.64
Blackhillock	57.23	-3.00	6328117.18	-334322.13	342439.72	-247123.62	422297.34
Peterhead	57.51	-1.78	6358903.19	-198600.44	373225.73	-111401.93	389496.90
Tealing	56.53	-2.96	6251161.32	-329146.91	265483.86	-241948.40	359194.53
Longannet	56.05	-3.69	6197996.13	-410890.79	212318.67	-323692.28	387112.26
Currie	55.90	-3.31	6180760.08	-368387.86	195082.61	-281189.35	342234.82
Cockenzle	55.97	-2.96	6188783.88	-329504.24	203106.41	-242305.73	316171.29
Eccles	55.67	-2.37	6155346.30	-264357.24	169668.84	-177158.73	245301.31
Newarthill	55.82	-3.94	6171857.87	-438354.41	186180.41	-351155.90	397458.94
Strathaven	55.68	-4.06	6156276.78	-452436.37	170599.32	-365237.86	403116.39
Elvanfoot	55.44	-3.66	6129799.39	-407049.50	144121.93	-319850.99	350821.59
Neilston	55.79	-4.42	6168425.32	-492573.66	182747.86	-405375.15	444663.69
Dalmally	56.40	-4.97	6236632.34	-553497.99	250954.88	-466299.48	529540.90
Inverklp	55.91	-4.87	6181864.16	-542161.27	196186.69	-454962.76	495459.71

Kilmarnock South	55.61	-4.50	6149541.94	-500801.03	163864.48	-413602.52	444880.44
Coylton	55.44	-4.52	6130633.34	-502607.51	144955.88	-415409.00	439973.69
Hutton	53.73	-2.77	5941662.60	-308095.15	-44014.87	-220896.64	225239.06
Norton	54.13	-0.78	5985677.46	-87198.51	0.00	0.00	0.00
Daines	53.33	-2.23	5896690.27	-248175.58	-88987.19	-160977.07	183935.69
Frodsham	53.30	-2.73	5893271.66	-303841.09	-92405.81	-216642.58	235526.73
Pentir	53.18	-4.14	5880418.98	-460837.06	-105258.49	-373638.55	388181.81
Stocksbridge	53.48	-1.59	5913803.70	-177411.21	-71873.76	-90212.69	115343.70
Willington east	52.85	-1.56	5844208.20	-173617.68	-141469.26	-86419.17	165776.43
Ironbridge	52.63	-2.48	5819331.04	-276218.51	-166346.42	-189020.00	251792.95
Walham	51.75	-2.23	5721847.79	-247772.27	-263829.67	-160573.76	308852.76
Cilfynydd	51.62	-3.32	5707976.17	-369465.31	-277701.29	-282266.80	395970.40
Melksham	51.37	-2.14	5680235.81	-237958.72	-305441.66	-150760.21	340621.85
Exeter	50.72	-3.53	5608137.69	-393390.10	-377539.77	-306191.59	486096.26
Indian Queens	50.39	-4.93	5572264.06	-549019.85	-413413.41	-461821.34	619830.30
Monk Fryston	53.76	-1.23	5944642.90	-136951.76	-41034.56	-49753.25	64492.02
Creyke Beck	53.79	-0.41	5947899.52	-45320.64	-37777.94	41877.87	56399.72
Thorpe Marsh	53.51	-1.05	5917143.26	-117353.05	-68534.21	-30154.54	74874.79
Grimsby West	53.57	-0.08	5923169.54	-8992.79	-62507.92	78205.72	100116.81
Cottam	53.31	-0.78	5894568.47	-86470.04	-91109.00	728.47	91111.91
High Marnham	53.22	-0.79	5885019.41	-88266.73	-100658.06	-1068.22	100663.72
Walpole	52.74	0.22	5831262.97	24991.23	-154414.49	112189.74	190867.42
East claydon	51.92	-0.92	5741551.74	-102735.53	-244125.72	-15537.02	244619.63
Bramley	51.19	-0.56	5660814.92	-62230.66	-324862.54	24967.85	325820.60
Nursling	50.94	-1.47	5632981.01	-163632.58	-352696.45	-76434.07	360883.57
Famley	50.83	-1.35	5620341.52	-150640.43	-365335.94	-63441.92	370803.49
Bramford	52.08	1.10	5758404.77	121935.72	-227272.69	209134.23	308852.72

Elstree	51.64	-0.30	5710499.36	-33194.55	-275178.11	54003.96	280427.21
Waltham cross	51.68	-0.02	5715001.38	-2253.21	-270676.08	84945.30	283692.17
West ham	51.54	0.01	5698792.11	1616.91	-286885.35	88815.42	300318.80
Bolney	51.00	-0.20	5638818.55	-22639.84	-346858.92	64558.67	352815.72
Tilbury	51.46	0.36	5690472.42	40130.28	-295205.05	127328.79	321494.39
Kingsnorth	51.42	0.56	5686079.97	62149.40	-299597.49	149347.91	334758.80
Grain	51.45	0.72	5689407.48	79616.46	-296269.99	166814.97	340004.62
Kemsley	51.36	0.74	5679489.65	81865.66	-306187.81	169064.17	349762.30
Sellindge	51.10	1.01	5650846.34	112226.25	-334831.12	199424.76	389720.56

* ‘Delta-’ represents the geographical location based on the reference latitude and longitude in Norton.

APPENDIX II

National Electricity Transmission System

(NETS) Seven Year Statement

- Figure II-1: Substation and circuits layout in UK transmission system as in 2011.
- Figure II-2: Boundaries and SYS study zones in UK transmission system as in 2011.
- Figure II-3: SHETL existing transmission system as in 2011.
- Figure II-4: SPT existing transmission system as in 2011.
- Figure II-5: NGET existing transmission system as in 2011.

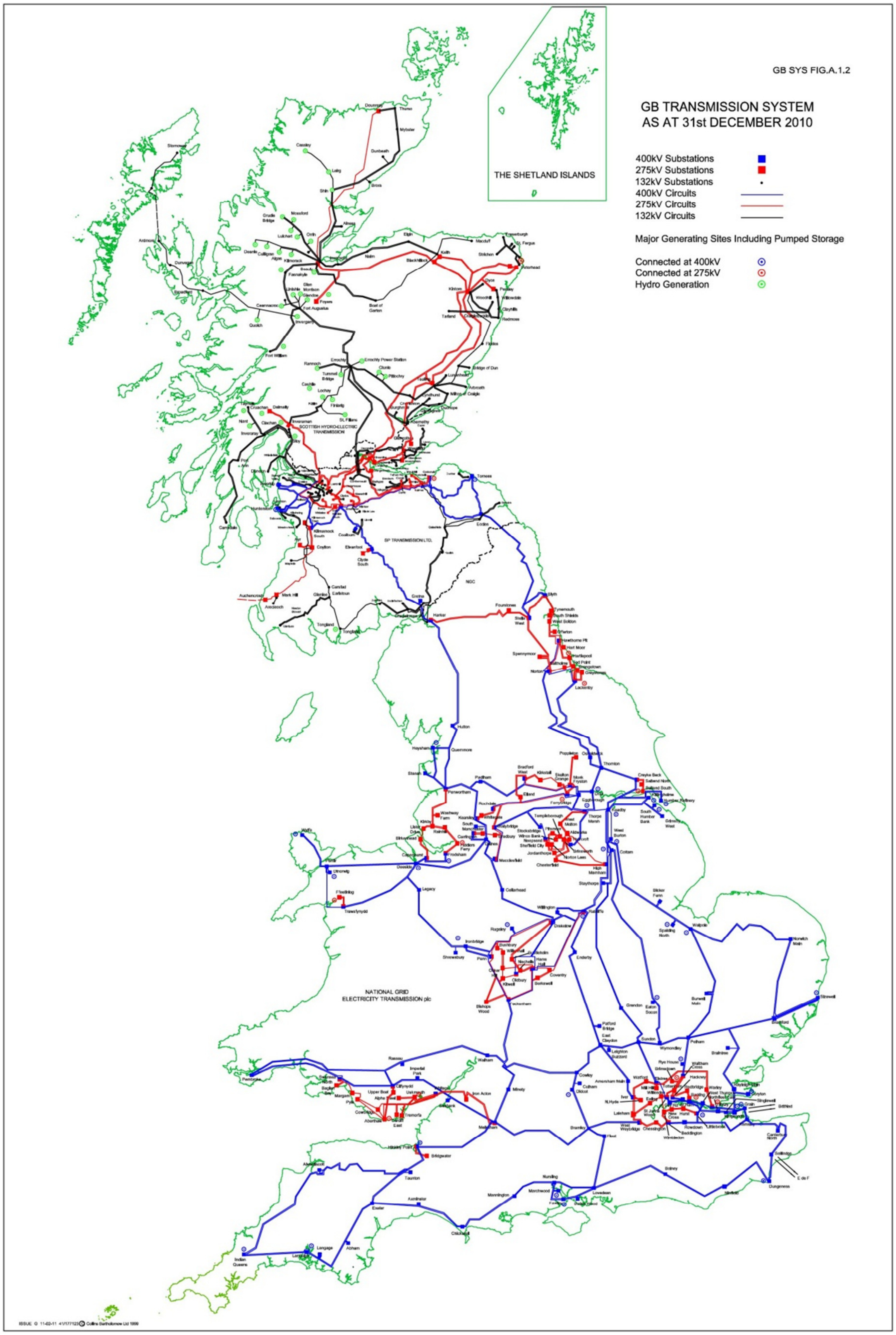


Figure II-1: Substation and circuits layout in the UK transmission system as in 2011.

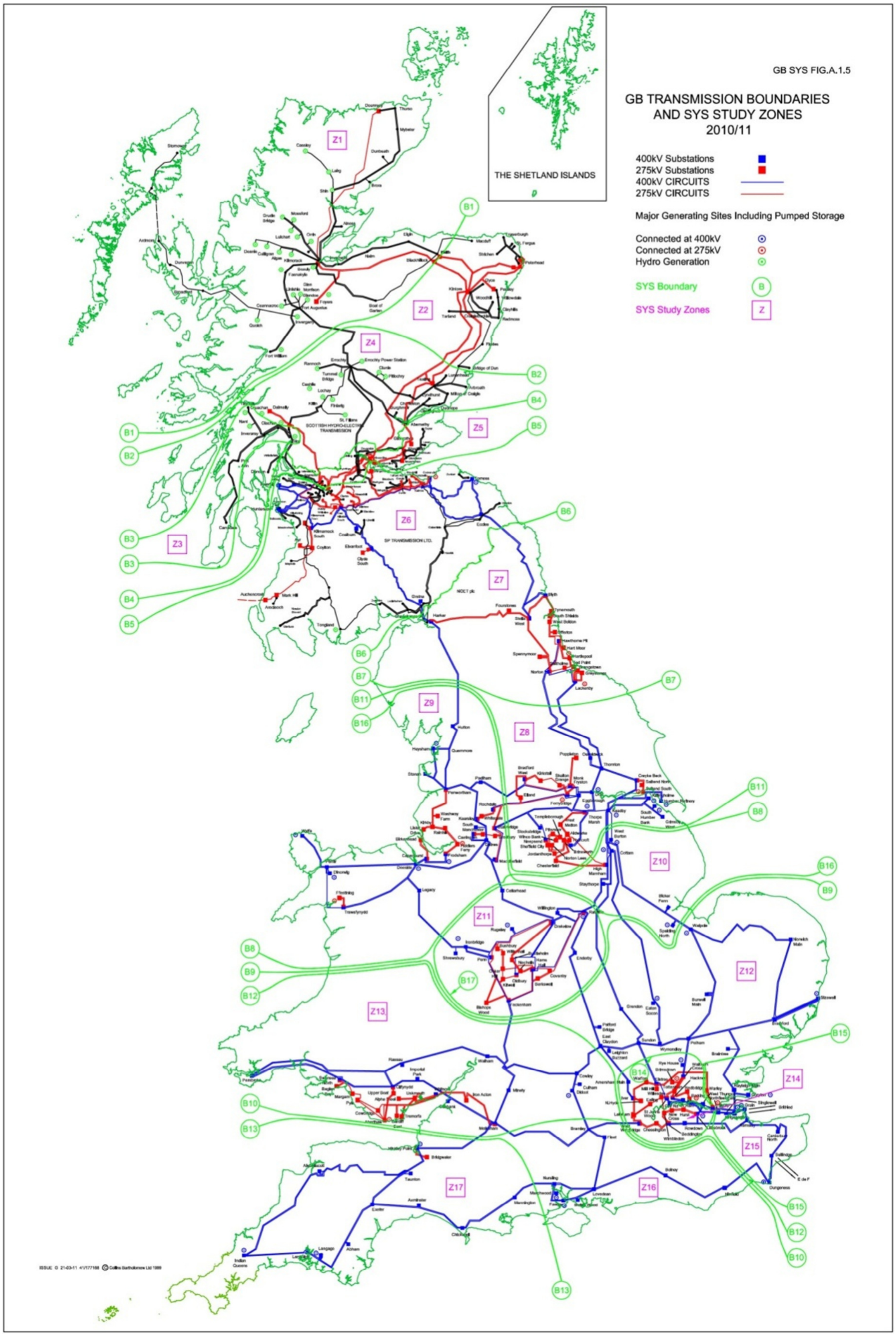


Figure II-2: Boundaries and SYS study zones in the UK transmission system as in 2011.

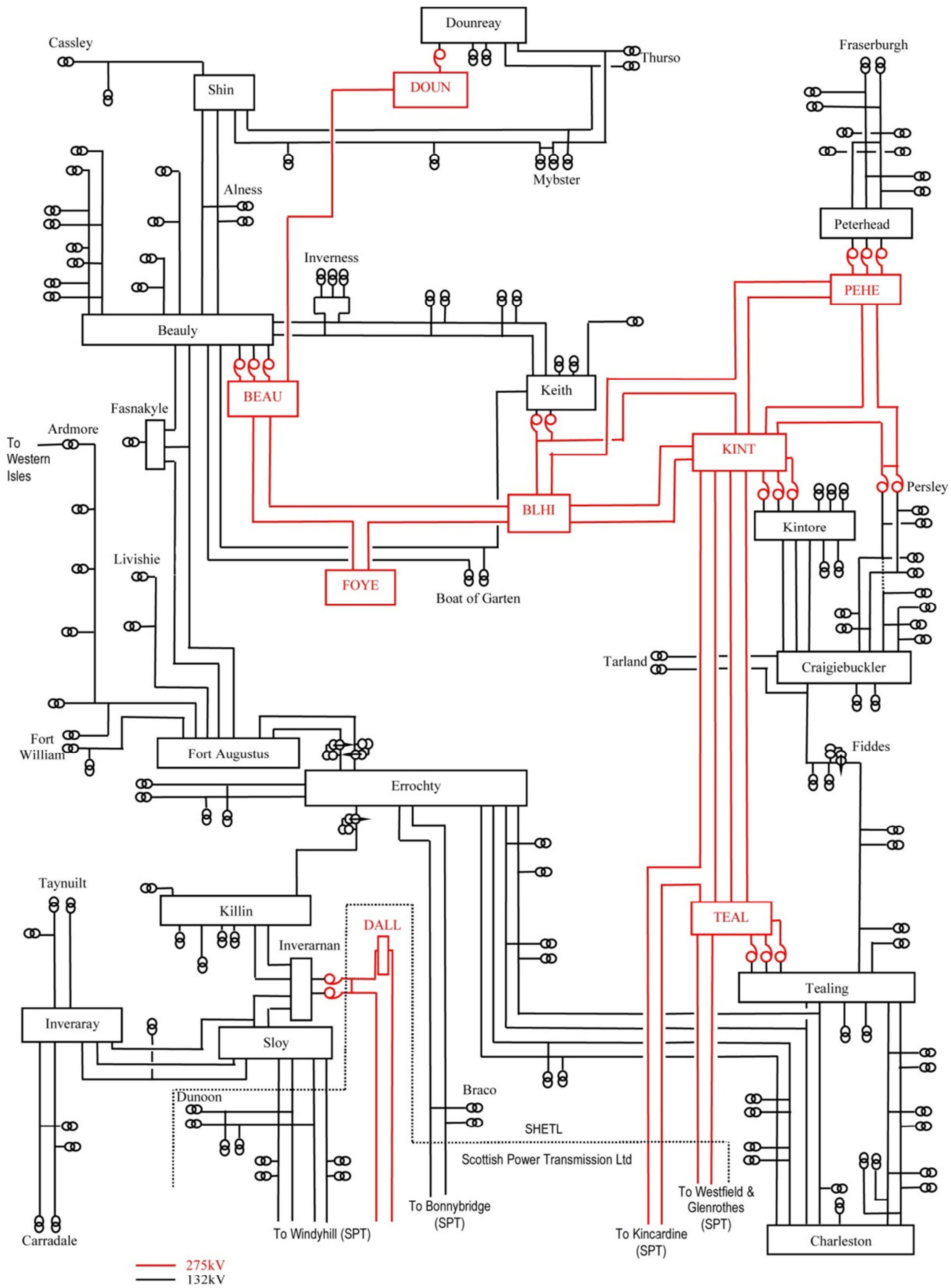
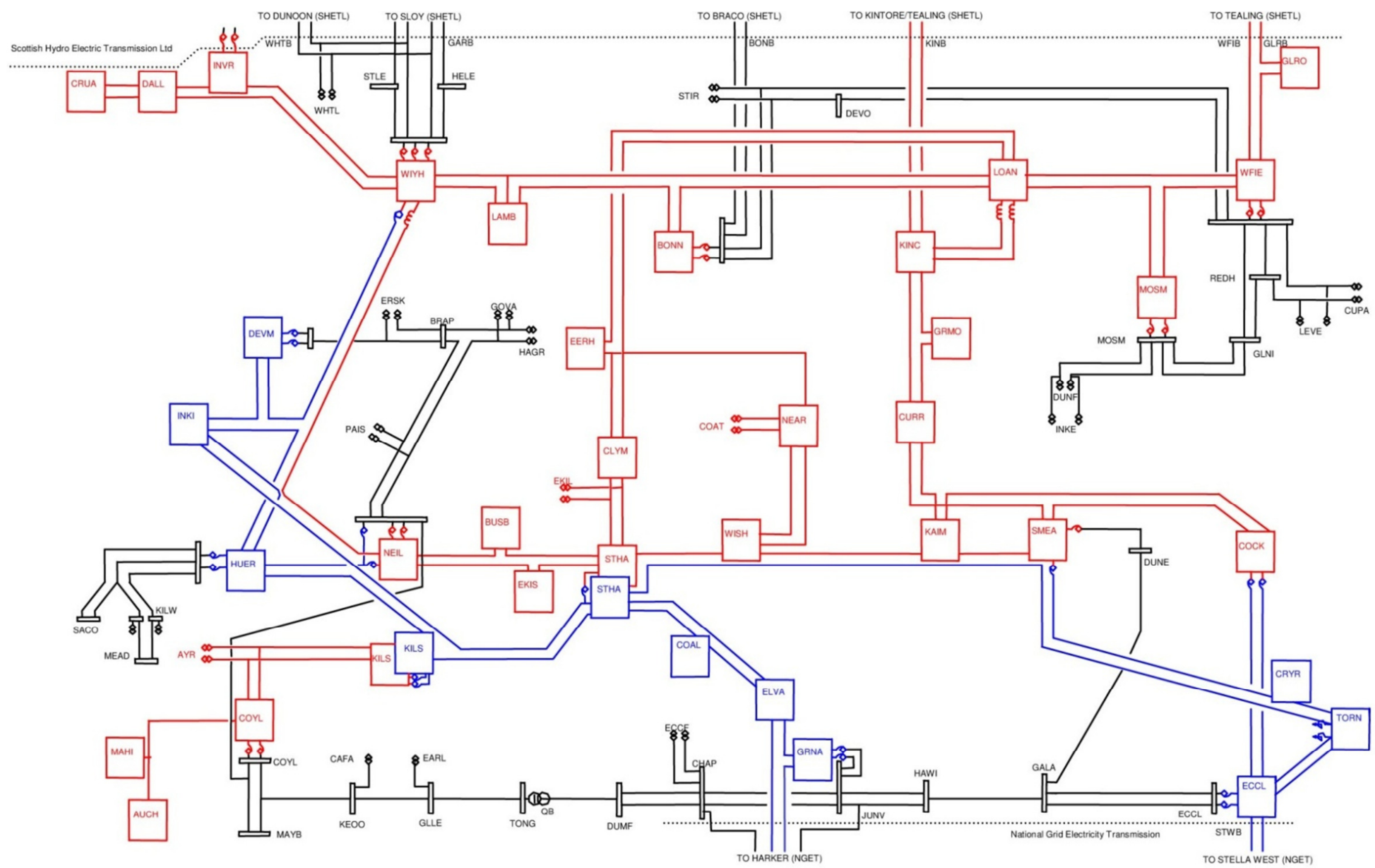


Figure A.2.1 SHETL Existing Transmission System – Year 0 (May 2011)

Figure II-3: The SHETL transmission system as in 2011.



400kV BLUE
275kV RED
132kV BLACK

INTERCONNECTED TRANSMISSION SYSTEM
SPT Existing Transmission System, April 2011

Figure A.3.1

Figure II-4: The SPT transmission system as in 2011.

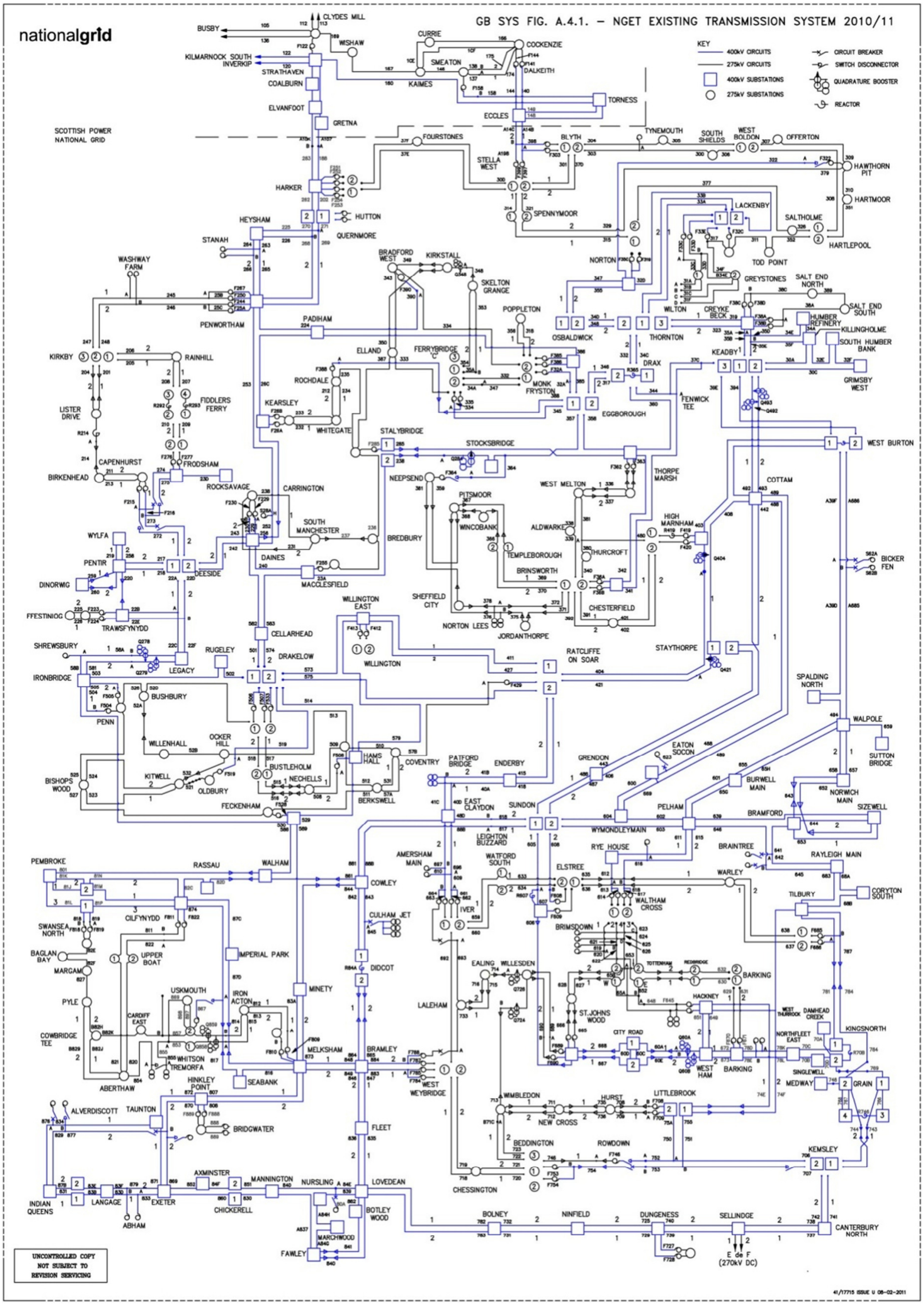


Figure II-5: The NGET transmission system as in 2011.

APPENDIX III

Phasor Measurement Unit (PMU) Packet Structure

Table 1: Data frame organisation.

No.	Field	Size (bytes)	Comment
1	SYNC	2	Sync byte followed by frame type and version number.
2	FRAMESIZE	2	Number of bytes in frame, defined in 6.2.
3	IDCODE	2	PMU/DC ID number, 16-bit integer, defined in 6.2.
4	SOC	4	SOC time stamp, defined in 6.2, for all measurements in frame.
5	FRACSEC	4	Fraction of Second and Time Quality, defined in 6.2, for all measurements in frame.
6	STAT	2	Bitmapped flags.
7	PHASORS	4 × PHNMR or 8 × PHNMR	Phasor estimates as defined in Clause 5. May be single-phase or 3-phase positive, negative, or zero sequence. Values are 4 or 8 bytes each depending on the fixed 16-bit or floating-point format used, as indicated by the configuration frame.
8	FREQ	2 / 4	Frequency (fixed or floating point).
9	DFREQ	2 / 4	Rate of change of frequency (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 used, as indicated by the configuration frame.
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

Table 2: Configuration frame organisation.

No.	Field	Size (bytes)	Short Description
1	SYNC	2	Sync byte followed by frame type and version number.
2	FRAMESIZE	2	Number of bytes in frame, defined in 6.2.
3	IDCODE	2	PMU/DC ID number, 16-bit integer, defined in 6.2.
4	SOC	4	SOC time stamp, defined in 6.2.
5	FRACSEC	4	Fraction of Second and Time Quality, defined in 6.2.
6	TIME_BASE	4	Resolution of fraction-of-second time stamp.
7	NUM_PMU	2	The number of PMUs included in the data frame.
8	STN	16	Station Name—16 bytes in ASCII format.
9	IDCODE	2	PMU ID number as above, identifies source of each data block.
10	FORMAT	2	Data format within the data frame.
11	PHNMR	2	Number of phasors—2-byte integer (0 to 32 767).
12	ANNMR	2	Number of analog values—2-byte integer.
13	DGNMR	2	Number of digital status words—2-byte integer.
14	CHNAM	16 × (PHNMR + ANNMR + 16 × DGNMR)	Phasor and channel names—16 bytes for each phasor, analog, and each digital channel (16 channels in each digital word) in ASCII format in the same order as they are transmitted. For digital channels, the channel name order will be from the least significant to the most significant. (The first name is for Bit 0 of the first 16-bit status word, the second is for Bit 1, etc., up to Bit 15. If there is more than 1 digital status, the next name will apply to Bit 0 of the 2nd word and so on).
15	PHUNIT	4 × PHNMR	Conversion factor for phasor channels.
16	ANUNIT	4 × ANNMR	Conversion factor for analog channels.
17	DIGUNIT	4 × DGNMR	Mask words for digital status words.
18	FNOM	2	Nominal line frequency code and flags.
19	CFGCNT	2	Configuration change count.
	Repeat 8–19		Fields 8–18, repeated for as many PMUs as in field 7 (NUM_PMU).
20+	DATA_RATE	2	Rate of data transmissions.
21+	CHK	2	CRC-CCITT

Table 3: Header frame organisation.

No.	Field	Size	Comment
1	SYNC	2	Sync byte followed by frame type and version number.
2	FRAMESIZE	2	Number of bytes in frame, defined in 6.2.
3	IDCODE	2	PMU/DC ID number, 16-bit integer, defined in 6.2
4	SOC	4	SOC time stamp, defined in 6.2.
5	FRACSEC	4	Fraction of Second and Time Quality, defined in 6.2.
6	DATA 1	1	ASCII character, 1st byte
K+6	DATA k	1	ASCII character, Kth byte, K>0 is an integer.
K+7	CHK	2	CRC-CCITT check

Table 4: Command frame organisation.

No.	Field	Size	Comment
1	SYNC	2	Sync byte followed by frame type and version number.
2	FRAMESIZE	2	Number of bytes in frame, defined in 6.2.
3	IDCODE	2	PMU/DC ID number, 16-bit integer, defined in 6.2.
4	SOC	4	SOC time stamp, defined in 6.2.
5	FRACSEC	4	Fraction of Second and Time Quality, defined in 6.2.
6	CMD	2	Command being sent to the PMU/DC.
7	EXTFRAME	0–65518	Extended frame data, 16-bit words, 0 to 65 518 bytes as indicated by frame size, data user defined.
8	CHK	2	CRC-CCITT check