Performance Evaluation of Information and Communications Technology Infrastructure for Smart Distribution Network Applications

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Abstract

Current electrical networks require secure, scalable and cost-effective Information and Communications Technology (ICT) solutions to facilitate the novel functionalities required by Smart Grids. Countries around the globe are investigating alternative energy sources to mitigate the current energy crisis and environmental issues experienced by many countries due to global warming, rapid growth of population, inefficient energy management, dwindling fossil fuel resources, etc. Therefore, alternative or renewable energy sources, such as wind, solar, hydro, combined heat and power, etc., are required to mitigate such a crisis and such sources will also need to be integrated in to the power grid in a distributed manner. Such distributed energy sources are mainly connected to the distribution networks and introduce huge challenges to the distribution network operator (DNO). Many of these challenges cannot be dealt with effectively using existing network operation mechanisms therefore the research and development of novel ICT solutions to support smart distribution network operation is required.

This research investigated suitable ICT solutions to enable the Smart Grid to tackle these challenges and proposes ICT infrastructure models that can be used for simulation studies in order to investigate cost-effective, scalable and secure solutions for the DNOs. Initially, a Quality of Service (QoS) monitoring test-bed was proposed to evaluate the performance of bandwidth intensive applications, such as smart meter data transmission. Simulation studies for different communication technologies, cellular and Power Line Communication (PLC), were also carried out and the simulation models were verified using experimental test results. Finally, the modelling and analysis of smart metering infrastructure was carried out using simulation and extensive studies were performed to evaluate the data transmission rate performance for different configurations of smart meters and concentrators.

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Financial and motivational support from my family members is priceless and would like to dedicate this thesis to them.

Declaration

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

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Abbreviations

3GPP	3rd Generation Partnership Program
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
BER	Bit Error Rate
BPL	Broadband over Power Line
CBA	Cost Benefit Analysis
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CEN	European Committee for standardisation
CENELEC	European Committee for Electrotechnical Standardisation
CIT	Conventional Instrument Transformer
CM	Condition Monitoring
CML	Customer Minute Lost
CSMA	Carrier Sense Multiple Access
DER	Distributed Energy Resource
DiffServ	Differentiated Service
DLC	Distribution Line Communication
DM	Data Mining
DMS	Distribution Management System
DNO	Distribution Network Operator
DNP3	Distribution Network Protocol
DSE	Distributed State Estimation
DSM	Demand Side Management
ETSI	European Telecommunications Standards Institute
ENA	Energy Network Association
ESYS	External System
FLOP	Floating-point Operations per second
FSM	Finite State Machine
GGSN	Gateway GPRS Support Node
GOOSE	Generic Object Oriented Substation Event
GPRS	General Packet Radio Services
GSM	Global System for Mobile communication
GUI	Graphical User Interface
HMI	Human Machine Interface
HPC	High Performance Computing
HTTP	Hyper-text Transport Protocol
ICT	Information and Communication Technologies
IEC	International Electro technical Commission
IED	Intelligent Electronic Device
IETF	International Engineering Task Force
IP	Internet Protocol
ISO	International Organisation for Standardisation

IT	Information and Technology
ITU	International Telecommunication Unit
LAN	Local Area Network
LTE	Long Term Evolution
LV	Low Voltage
MAC	Media Access Control
MAN	Metropolitan Area Network
MB	Megabyte
MOM	Message Oriented Middleware
MPLS	Multi Protocol Label Switching
MU	Merging Unit
MV	Medium Voltage
NCC	Network Control Centre
NS-2	Network Simulator 2
OSI	Open System Interconnection
PDF	Probability Distribution Function
PER	Packet Error Rate
PLC	Power Line Communication
Profibus	Process field bus
QoS	Quality of Service
RNC	Radio Network Controller
RRA	Round Robin Archive
RRD	Round Robin Database
RSVP	Resource Reservation Protocol
RTCP	Real-time Transport Control Protocol
RTP	Real-time Transport Protocol
RTRM	Real Time Rich Media
RTSP	Real Time Streaming Protocol
RTT	Round Trip Time
RTU	Remote Terminal Unit
SA	Substation Automation
SCADA	Supervisory Control and Data Acquisition
SE	State Estimation
SGSN	Serving GPRS Support Node
SLA	Service Level Agreement
SMS	Short Message Service
SNMP	Simple Network Management Protocol
STR	Successful Transmission Time
TB	Terabytes
TCP	Transport Control Protocol
TFLOP	Tera FLOP
UCA	Utility Communication Architecture
UDP	User Datagram Protocol
UKERC	UK Energy Research Council
UMTS	Universal Mobile Telecommunication Systems
VLAN	Virtual Local Area Network

VT	Voltage Transformer
WAN	Wide Area Network
WiMax	Worldwide Interoperability for Microwave Access

Chapter 1 Introduction

1.1 Overview of the Research

Integration of ICT into the existing power grid has become an active and ongoing research area around the world [1]. Several research projects have been carried out and completed to address solutions for many challenges endured during the integration phase [2] [3]. ICT and power system related international standards and protocols were proposed by these projects and are currently used in many other ICT and energy projects [4] [5].

Monitoring and control of distribution networks has been a challenge for decades due to lack of visibility of devices within the distribution networks. This is mainly due to reduced network management and infrequent update about newly connected or disconnected network devices. Automatic detection and configuration of devices within a particular distribution network can be easily achieved by utilising the existing or future communication infrastructure. It is also anticipated that the suitable integration of ICT infrastructure into the traditional power grid will help to implement novel Distribution Management System (DMS) functionalities and to make the Smart Grid vision a reality.

Two main aspects, high performance computing and high speed communication, of ICT infrastructure have been researched as part of the EU-funded FP7 High Performance computing technologies for smart Distribution Network Operation (HiPerDNO) project [2]. Millions of devices will be connected to the future Smart Grid hence there will be huge demand for local/central storage and short/long distance data transmission between different types of communication networks, such as local area network (LAN), wide area network (WAN) and metropolitan area network (MAN). This complex communication architecture demands sophisticated performance monitoring mechanisms to evaluate the overall QoS. These QoS guarantees highly depend on the requirements specified by different DNOs or any relevant body who is responsible for the overall management of the communication network within distribution networks. DNOs require low-cost and secure ICT infrastructure to support novel DMS functionalities in near to real-time so that the control and monitoring of the overall distribution network can be managed conveniently.

The following sections detail the main aims, objectives and motivation of this research to develop communication solutions such as General Packet Radio Services (GPRS), Universal Mobile Telecommunication Systems (UMTS), PLC, etc. based on experimental, simulation and case studies.

1.2 Aims and Objectives of the Project

The main objective of the research was to investigate and evaluate communication systems for distribution network operation in the Smart Grid. Initial research included investigation and development of a Java based QoS monitoring tool for bandwidth intensive applications. Specific objectives of the research project can be listed as below:

- Investigate about available wired and wireless communication media such as GPRS, UMTS and PLC, for the distribution network operation and evaluate their performance using simulation models
- Investigate and develop a QoS monitoring tool for bandwidth intensive applications and evaluate the performance based on different parameters such as end-to-end delay, throughput, QoS, etc.
- Investigate low-cost, scalable and suitable communication solutions for the required DMS functionalities in distribution network operation
- Investigate the scalability and performance of smart metering infrastructure by using different number of smart meters and concentrators in simulation environment

These objectives were achieved through number of steps carried out as part of the research and are discussed below.

The initial investigation about the available communication technologies for the Smart Grid was carried out through a number of means such as by reading conference and journal publications, by attending Smart Grid related conferences and symposiums and by accessing online information from different UK and rest of the world energy related organisations such as energy network association (ENA), Ofgem, IEEE, etc. Once this investigation was completed the OPNET 16.0 simulation tool was selected for testing different communication technologies and the selection criteria for this simulation tool is provided under Section 5.2. Some experimental tests were carried out as part of the HiPerDNO project (see Section 2.1.4) for different communication media such as GPRS, UMTS and PLC. The results from these experimental tests were used to validate the simulation models in OPNET. A number of case studies were derived from the ENA document [6] to perform simulation tests and to evaluate the performance of different communication media in distribution networks. A Java based QoS monitoring tool for bandwidth intensive applications was developed; its performance was evaluated and compared against the benchmark Wireshark (formerly Ethereal) monitoring tool [7].

1.3 Research Motivation

Global environmental and economical changes introduce new and demanding challenges and they require short or long term solutions. The emergence of the Smart Grid brings more opportunities and challenges to the academic and industrial researchers, and requires novel, low-cost, scalable, secure and efficient ICT solutions to enable several functionalities in the existing electricity networks. This research studied the possibilities to tackle some of these challenges by using simulation environment and to contribute enhanced ICT solutions to different stakeholders. This research project took different approaches such as modelling and analysing the performance of different communication media, studying bandwidth intensive applications performance using emulation and evaluating the scalability and performance of smart metering infrastructure using simulation.

Distribution networks have undergone revolutionary changes in the recent years to meet the energy and CO_2 related targets set by governments or continents around the world. Limited energy resources pose huge economical and environmental challenges because the world population may not be supported to perform their day-to-day activities without these valuable energy sources. Therefore low-cost, novel, secure and sustainable solutions are required for the global market to balance the supply and consumption mechanism for longer existence of human life on earth. Many projects have already investigated about novel or enhanced solutions to support governments and continents to meet their energy targets and to provide sustainable mechanisms to ensure all possible ways are utilised for efficient power generation and consumption.

Lack of visibility of medium voltage (MV)/ low voltage (LV) distribution network devices is a challenge for DNOs to minimise energy losses and to increase reliable power supply for the end users. DNOs will be using novel DMS functionalities to meet the demand in future once the Smart Grid is fully functional. However, it requires the use of ICT infrastructure in an efficient manner to help achieve this huge objective. It has been widely acknowledged that the research and development of low-cost, reliable, secure and scalable computing and communication solutions are inevitable to accomplish the vision of the Smart Grid perceived by different stakeholders. Smart meters are expected to generate massive amount of data that have to be processed and stored locally or centrally by the DNOs. Therefore, monitoring and evaluating the performance of the communication network in distribution networks is important and beneficial for the DNOs.

Video, audio and web conferencing tools have revolutionised the methods of communication in the modern era and are alternate solutions for conducting conferences and meetings from one part of the globe to the other within minutes if not in seconds. Current financial crisis and global warming issues have further added extra burden on industries to look for low-cost and convenient solutions to substitute the long journeys (using air or land) across the globe. Governments have placed additional CO_2 emission targets for companies and this has forced the companies to use the available alternate conference and meeting solutions to cut the cost and time involved with many long journeys. This has resulted in two main benefits to the companies and the environmentalists around the world. A) Significant savings on travel costs for the companies, and B) substantial reduction in CO_2 emission (hence reduced amount of global warming effects). Providing the required tools with guaranteed QoS is a research challenge and many tools have been developed by several companies and academic researchers to overcome diverse challenges encountered by the users. These tools are capable of evaluating the performance of bandwidth intensive applications and they can also be used in the distribution network operation for streaming large volume of data once the millions of smart meters are installed. These bandwidth intensive monitoring tools can be adopted within distribution networks to enhance or support the functionalities required by the Smart Grid.

These challenges motivated this research project to investigate and to propose novel ICT solutions to Smart Grid applications which have been discussed in detail throughput this thesis.

1.4 Structure of the Thesis

This thesis is organised in the following manner and high-level introduction is provided below to highlight the main areas covered within each chapter of this thesis.

Chapter 1: This chapter provides general background and introduction about the project and it highlights the research aims, objectives, motivation and contribution towards knowledge. A list of publications resulted through this research project is also provided.

Chapter 2: This chapter investigates the state-of-the-art ICT solutions for the power systems. Communication media (GPRS, UMTS and PLC), emerging standards (IEC 61850, Utility communication architecture (UCA), etc.) and the middleware architectures (client/server and publisher/subscriber) are discussed in detail. A brief introduction to the HiPerDNO project and the challenges when integrating the ICT into the electricity networks are also discussed briefly.

Chapter 3: Data communication and processing requirements for the distribution networks are studied using two case studies from UK and Belgium. Use case scenarios from the ENA document were used to identify the required communication solutions for various DNO applications. The requirements for and challenges from the high performance computing are briefly discussed and the power consumption between different high performance computing systems are discussed.

Chapter 4: Detailed information about the QoS monitoring tool designed and developed for bandwidth intensive applications is presented with contribution from a conference paper resulted from this development. This chapter discusses about the design and implementation stages involved during the development, testing and evaluation of the proposed Java based test-bed. Comparison of results using a benchmark tool (Wireshark) to validate the developed tool and the integration of this test-bed with the 'LiveGraph' tool are discussed in detail.

Chapter 5: Experimental and simulation tests were carried out as part of the HiPerDNO project to evaluate the throughput and latency performance of different communication media (GPRS, UMTS and PLC) and to suggest a suitable solution for different DMS functionalities. The experimental tests were carried out using a real office network environment and a similar test-bed was set-up in OPNET simulation tool. Simulation results were validated using the experimental results and a conference paper for UPEC 2011 was published through this work. The experimental and simulation test results are discussed in detail and suggestions for improvement of the models are also provided.

Chapter 6: This final chapter discusses about the main conclusions arrived from the project and future work that can be carried out to investigate further about the research area. Several suggestions for future work based on this research are highlighted.

1.5 Summary of the Research Contribution

Following sections highlight the knowledge contribution resulted through the work carried out as part of this research project.

A. Literature review about communication media and technologies for distribution network operation

Investigation about high performance computing and communication solutions were carried out and the requirements from ICT systems were highlighted with the vision of integrating millions of smart meters in near future, part of it being conducted within the HiPerDNO project. The requirements in terms of vast amount of data transmission and storage are discussed in detail using case studies to forecast approximate data transmission and storage and this will eventually help the DNOs during the planning and design stages of their ICT infrastructure. The challenges encountered by the current distribution networks and the efficient integration of communication infrastructure to carry out critical network control and monitoring activities will be beneficial for the stakeholders to avoid any issues in future.

B. Performance evaluation of communication media using simulation

OPNET was used to simulate different communication media such as GPRS, UMTS and PLC. Simulation tests were carried out and the results were verified using the results from the experimental tests. Novel DMS functionalities require differentiated QoS provided by the underlying communication infrastructure under varying network conditions and they can conveniently be modelled and simulated using a simulation environment from small to large network topologies. This is the basis for the validation of OPNET simulation models using the experimental test results for a real network environment. The performance evaluation of different ICT solutions using a simulation environment is cost-effective and convenient for the DNOs before the field trials.

C. Smart meter data traffic analysis using case studies and simulation

The performance evaluation of smart metering infrastructure was carried out using the OPNET where several scenarios were used to study the data transmission time effects. Case studies were used to evaluate the performance of different communication media for several use cases provided in the ENA document for smart meter data traffic analysis. The required data rates and response times (estimated values) for different DMS functionalities were provided in that document and these estimate values were used during the OPNET simulation for smart metering infrastructure. Detailed performance analysis with discussion regarding the smart meter data transmission time, number of data concentrators, number of smart meters and successful transmission rate was carried out by simulating the smart metering infrastructure (Chapter 6). The results are useful for the DNOs to decide the required components in the smart metering infrastructure to achieve the expected performance.

D. Survey of QoS monitoring tools available for bandwidth intensive applications

An investigation regarding available commercial and open-source QoS monitoring tools for bandwidth intensive applications was carried out. This detailed information gathering and discussion resulted in identifying advantages and disadvantages between different monitoring tools highlighting any bottlenecks during their implementation or testing. This helped to produce a simple and easy to use QoS monitoring tool that was developed and evaluated in this project against a well know open-source Wireshark monitoring tool. A Java based Client-Server program was used to develop this test-bed. Different aspects of this monitoring tool were achieved by modifying the program to accommodate a more realistic network which consists of Client-Gateway1-Gateway2-Gateway3-Server. Calculating QoS parameters using equations, adding statistics collection, writing them into a file for off-line analysis, monitoring these statistics in real-time using the Java Graphical User Interface (GUI), performing the testing using one PC and two PCs, configuring the program to take input from the user and creating batch files for simple implementation of this test-bed, are some added features that are discussed under Chapter 4. The use of this tool in distribution networks will be beneficial for data streaming.

Chapter 2 Communication Solutions for the Smart Grid

It has been widely discussed and accepted that communication technology is a key enabler to the Smart Grid when integrating several devices (consumer appliances, electric vehicles, distributed generators, smart meters, etc.) in distribution networks. It will help to control and monitor the devices efficiently to facilitate novel DMS functionalities. These novel functionalities require the computing and communication systems to be operating in an efficient manner to accommodate the growing needs from the smart meters and the Intelligent Electronic Devices (IEDs). These devices will be a major contributor towards the data generation once the Smart Grid implementation is underway. Figure 2.1 [6] depicts the required integration of several components in the distribution network with the central service that include several central or local communication media [6].

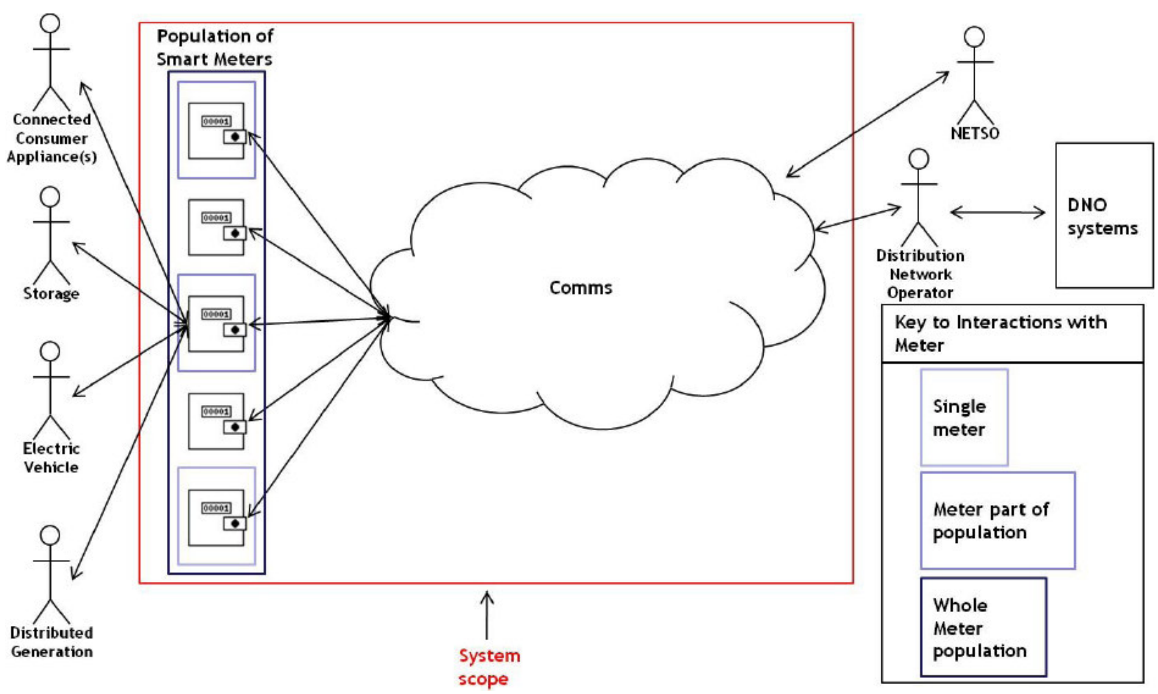

Figure 2.1: Electricity networks smart metering system scope [6]

There are a number of proposed ways to integrate ICT into energy systems to enable the Smart Grid and to provide assured QoS. Distribution network applications such as state estimation (SE) and condition monitoring (CM) require strict performance guarantees to support timely delivery of data. Thus, it is likely that more than one type of communication media will be necessary to provide resilience, low cost, scalability, and security for the emerging Smart Grid functionalities.

A survey on available communication solutions for substation automation is provided in [8] where the advantages and disadvantages for potential solutions were discussed. DNOs require dedicated and/or combination of communication technologies to facilitate the future surge of data from smart meters. This introduces new challenges in providing guaranteed throughput and latency performance for the communication medium and the storage of data for millions of smart meters. Some DNO applications require strict guarantees to support their timely and critical data delivery hence the performance analysis for various communication media should be studied at length. The main focus is on the integration of the ICT to the energy system to enable different levels of QoS using innovative solutions. Therefore, the realization of more than one type of communication medium is necessary to provide the resilience and the required level of support to scale well with the future demand.

Several communication technologies are investigated by DNOs to provide low-cost communication network infrastructure for the MV/LV distribution networks [2]. Cost benefit analysis of varying communication technologies for different DMS functionalities is important to justify the required solution. This requires a detailed performance analysis study of existing communications technologies with their performance metrics, such as throughput and latency, clearly highlighted.

2.1 Communication Media

There are several communication media available for the Smart Grid and they can be categorised into two main areas, wireless and wired, as discussed in the following sections.

2.1.1 Wireless Technology

It has been a perception for long that the wireless communication technologies are incapable of supporting faster data transmission compared to some wired communications. Over time, developments in wireless communication enabled it to be a suitable communication candidate for several band width intensive applications and it can nowadays support Gbps data rate that is comparable with the data rates supported by some wired technologies. These revolutionary improvements in bandwidth and security make wireless a suitable option for part or whole of the distribution networks. The security issues of wireless communication are beyond the scope of this study but further information about wireless 802.11e performance analysis can be found in [9].

It can be observed from Table 2.1 [10] that the developments in wireless technologies renders high data rate, for WiMax, with longer distance and it is superior to some wired-technologies (distribution line communication DLC)) [10]. The inherent flexibility and scalability of wireless technologies lead to lower installation costs than wired technologies. However, throughput, latency, and security are concerns over longer distance; hence strict QoS guarantees will be required. Wireless technologies currently support 10s of Gbps and it is sufficient for many DNO applications however it is inferior to some wired technologies data rates. Performance and cost benefit analysis of security issues and the wireless 802.11e standard are discussed in [9] [11]. WiMax is an IEEE 802.16m standard and currently provides about 1Gbps fixed data rate and is a candidate for the 'last-mile' communication to gather data from power network sensors [10].

Table 2.1: Potential Smart Grid applications for different wireless technologies [10]

Wireless Technology	**Data Rate**	**Approx. Coverage**	**Potential Smart Grid Applications**
Wireless LAN	1-54Mbps	100m	Distribution protection and Automation
WiMAX	70Mbps	48Km	Wireless Automatic Meter Reading (WMAR)
Cellular	60-240Kbps	10-50km	SCADA and monitoring for remote distribution
ZigBee	20-250Kbps	10-100m	Direct load control of home appliances
MobileFi	20Mbps	Vehicular Std.	Communication for PEVs and remote monitoring
Digital Microwave	155Mbps	60 km	Transfer trip (point-to-point)
Bluetooth	721Kbps	1-100m	Local online monitoring Applications

2.1.1.1 GSM/GPRS/UMTS

Mobile communication technologies have evolved with time and different standards, such as global system mobile communication (GSM) (18 Kbps, 2G), GPRS (56 Kbps, 2.5G), to UMTS (384 Kbps, 3G) etc., have emerged to support the growing demand for modern mobile applications. The advanced technology for 4G and long term evolution (LTE) is emerging. The improvement in data rates enabled the convenient use of bandwidth intensive applications, such as audio/video/data streaming and gaming over smart phones, in day-to-day activities. GSM is a popular circuit switched digital cellular technology (largely in Europe and Asia) and is the world's leading standard in digital wireless communications [12]. GPRS is packet switched network and was initially standardised by the European Telecommunications Standards Institute (ETSI) and later standardised by the Third Generation Partnership Program (3GPP). Main benefits from GPRS can be listed as follows [12]:

- efficient use of the radio spectrum (the radio bandwidth is used only when the packets are exchanged between end points)

- minimal upgrade effort is needed with the existing GSM network
- enhanced data rate compared to the GSM data service
- support for larger message lengths than short message service (SMS)
- wide range of access to data networks and services (virtual private network (VPN)/internet service provider (ISP) access and wireless application protocol (WAP) service)

UMTS is also packet switched network and is standardised by the 3GPP. It provides wideband code division multiple access (CDMA) that enables UMTS to offer the following services in addition to the services provided by GPRS [12]:

- higher throughput (144 kbps for satellite and rural outdoor, 384 kbps for urban outdoor and 2048 kbps for indoor and low-range outdoor)
- real-time services
- end-to-end QoS (connection-oriented radio access bearers with specified QoS)
- delivers pictures, graphics, voice, video and other multimedia services

Significant improvement in data rates from GPRS (56 kbps) to UMTS (384 kbps) enabled the latter to be efficient for the modern smart phones to utilize and experience bandwidth intensive applications (audio, video, etc.) on the move. This potential has also been noted in the Smart Grid environment and testing is underway to analyze their throughput and latency performance under extreme network conditions [13]. As part of the initial work in the HiPerDNO project, performance evaluation of GPRS/UMTS for different transport layer protocols, user datagram protocol (UDP)/transport control protocol (TCP), have shown that UMTS/UDP and UMTS/TCP combinations outperform the GPRS/UDP and GPRS/TCP respectively (see Chapter 5). These initial experimental tests have further been studied using the OPNET simulation for similar scenarios and the latter relatively matches the former [13].

2.1.1.2 WiMax

Worldwide interoperability for microwave access (WiMax) is an emerging IEEE standard for the 4th generation (4G) wireless communication, where the IEEE 802.16m (also referred to as WiMax 2) is expected to provide about 1Gbps fixed data rate. This option as a last-mile (first-mile for the end-user) is considered by some European DNOs [2] to gather data from LV devices where the cost of deploying cables is comparatively expensive or it is not feasible to install cables in some geographical locations. This technology has now been widely discussed in the area of communication infrastructure for Smart Grid and further developments to this technology may be beneficial for the DNO applications.

A number of studies were carried out to compare WiMax technology with the existing cellular technologies and broadband over power line in [10] [14] [15] [16]. Different applications and key requirements of WiMax are summarised in Table 2.2 [16].

Table 2.2: WiMax support for different Smart Grid applications [16]

Applications	Key requirements
Remote surveillance of generation, transmission, and distribution assets Remote control capabilities	• High uplink throughput for remote cameras • Real-time connectivity with high availability and low latency • QoS • Secure connections
Remote real-time monitoring and control of generation, transmission, and distribution assets—e.g., with supervisory control and data acquisition (SCADA) systems and distributed control systems (DCS)	• Real-time connectivity with high availability • QoS • Secure connections
Smart metering for residential and business locations	• Support for a very large number of terminal devices • QoS • Secure connections
Connectivity to office and mobile workforce, including in-vehicle connectivity and fleet management, mobile access for field workers, and broadband connectivity from office locations	• Support for mobility • High throughput • VPN support • QoS • Secure connections • Low latency if using VoIP or video applications
Emergency connectivity through mobile base stations during emergencies	• Support for mobility • High throughput • High availability • QoS • Low latency if using VoIP or video applications • Secure connections

It is expected by analysts that the existing electricity grid will adopt the WiMax technology in the near future [15] as it is a cost-effective and feasible solution for the

Smart Grid applications. A comparative study for broadband over power line (BPL) and WiMax shows that WiMax outperforms the BPL under three different criterion, cost, coverage and network, as shown in Table 2.3 [15].

Table 2.3: BPL vs. WiMax [15]

	BPL	4G/WiMax
Cost	Installation: US $1000 per home (estimated)	Installation: $440 per home (estimated)
Coverage	Pervasive (accessible to any home with power lines)	Rolling out; becoming widespread in 2011
Network	Requires new broadband infrastructure, set up by power utilities (inexperienced broadband network operators)	Uses existing broadband infrastructure, set up by wireless carriers (experienced broadband network operators)

2.1.2 Wired Technology

Wired technology has been a popular communication medium for a long time among various users and it provides higher data rates compared to conventional wireless solutions. The installation cost and the limitation on scalability for future demand have raised questions about this option, mainly among DNOs, in the current financial downturn. The search for low-cost, secure and scalable solutions is inevitable therefore many projects [3] [4] [5] have been initiated to provide efficient solutions by improving the existing wired communication medium.

2.1.2.1 Power Line Communication (PLC)

The emerging Smart Grid visions have mandated the distribution network operators to consider existing communication technologies in the current market to enable smart functionalities. PLC is a low-cost solution however it experiences unpredictable channel conditions due to the unexpected behaviour at the MV/LV network. Electric devices are connected and disconnected at random times and the intermittent noise introduced by these devices is unpredictable. Future Smart Grid will introduce more renewable energy sources into the electricity grid and the two-way electricity flow introduces more issues to the PLC medium. The availability of the PLC during the power outages or grid maintenance activities is considered another drawback for the PLC therefore alternative (back-up) communication solutions are required. It is also critical for the network operators to control the grid using the PLC during outage or network maintenance. These issues are debatable and a common ground should be reached to trade-off the QoS against cost effectiveness.

PLC was initially intended for the transmission of electric power over power cables at 50/60 Hz. After the realization of potential data transmission over the same cables under different frequency bands, such as narrow band and broadband, ranging from kilo hertz (kHz) to Giga hertz (GHz), this option has been widely considered as a low-cost and suitable solution for LV/MV communication. Some EU Projects [3][4][5] are dedicated to developing technologies to support and enhance the use of PLC on a wide scale. However, there are number of limitations in PLC, such as signal attenuation, interference with radio frequency, various noise components, coupling issues, etc.

Smart meters and PLC based ICT infrastructure for the Smart Grid was developed using the OPNET simulator in [17] and a general communication infrastructure was discussed without detailed information about the modelling and simulation of the PLC link. Impact of ALOHA and polling media access control (MAC) protocols applied to the signalling channel of the PLC network and performance evaluation based on different packet sizes (1500 bytes and 300 bytes) were carried out in [18] using the YATS discrete time and discrete events simulator. A simple single-hop topology based in network simulator–2 (NS-2) was used to study the simulation-based PLC-MAC performance in [19] where different physical data rates (14 Mbps to 1 Mbps) and packet lengths were used. Simulation of PLC using the OMNeT++ was carried out in [20] using a compound module to model the PLC characteristics.

Initial tests were carried out in [13] as part of the HiPerDNO project on a simple office network environment and the results prove that PLC is an outstanding option, both in terms of throughput and latency, compared to the cellular network technologies.

PLC or distribution line communication (DLC) has been a low-cost communication medium for DNOs and many improvements have been achieved in recent years through extensive research and development to enhance its physical characteristics to support the stringent QoS required by different applications (data, control, voice and video over PLC). In the EU FP7 DLC+VIT4IP project [3], a high speed narrow band DLC was proposed as a solution for data rates up to 100 kbps for 9-500 kHz and EG, a HiPerDNO project partner, has considered this option as part of their distribution network communication. The development of standards specific to PLC for large scale infrastructures is being undertaken by EC-funded projects OPERA [4] and OPEN Meter [5]. The main research question is the trade-off between QoS (high throughput and low latency over short distance) and cost effectiveness (cheaper compared to existing technologies) for different types of PLC applications.

It is also important to notice that, with future surge of massive volume of bidirectional data transmission between LV devices and local concentrators/control centre this option hardly scales well hence an alternate solution should be suggested at this stage. DNOs tend to consider low-cost communication solutions for short term however it is advisable to consider longer term solutions to cope up with radical changes required in the conventional power grid communication infrastructure.

2.1.2.2 Optical Fibre

Optical fibre is an attractive and highly reliable communication technology that has been widely used in high reliable applications, from telecommunications to power industry. This communication medium offers high throughput and low latency however it remains sufficiently expensive and inflexible to be considered for anything other than 'last kilometre' applications. DNOs require reliable data transmission between critical electrical components and control centres to carry out their control and protection activities in the network. As optical fibres provide higher data rates (100s of Gbps) over longer distances (100s of km) compared to other existing wired and wireless communication links it is highly preferred as a potential candidate for the distribution networks communication. DNOs around the world prefer optical fibre for their time and mission critical DNO applications and they pay higher price for the service in return. DNOs in HiPerDNO project also use optical fibre and experience high performance data transfer for their critical applications [2]. It was proposed by UK energy research council

(UKERC) as one of the backhaul communication media for the distribution networks [21].

2.2 Communication Standards

There are number of communication technologies and standards available for the distribution network operation. Many of these advanced technologies are widely deployed around the world and well known organisations are involved in developing interoperable standards. These standards will enable the integration of ICT into the Smart Grid more conveniently in terms of network management and cost effectiveness. When using the proprietary standards the flexibility of integrating with different proprietary systems will be a challenge and the information and technology (IT) personnel need to convert between different protocols to make the whole system operable. This has been realised as a costly and time consuming task therefore different well established organisations are interested in developing interoperable open or common standards. The industry was keen in proprietary standards in the past however they are now driven by the interoperable standards to help reduce the cost and the burden on IT personnel from solving problems related to different proprietary systems.

There are number of well known standard organisations, such as international organisation for standardization (ISO), international electrotechnical commission (IEC), international telecommunication unit (ITU), institute of electrical and electronics engineer (IEEE), etc., who are responsible for developing new standards and enhancing the existing standards to make interoperable standards. European standards organisations include European telecommunications standards institute (ETSI), European committee for standardization (CEN), European committee for electrotechnical standardization (CENELEC), etc.

2.2.1 Substation Communication Standards

There are number of standards and protocols, such as IEC 61850, Process field bus Profibus, MODBUS, distribution network protocol (DNP3), etc., available for the substation communication. IEC 61850 has been a very popular standard for the last decade and it has been developing to include more functionalities. A detailed discussion about IEC 61850 is provided in Section 2.2.2 while brief descriptions of the other standards are provided in the following sections.

Profibus

In automation technology, Profibus is a standard for field-bus communication developed by German companies in 1987 and some of its key features are listed below [22]:

- Vendor-independent and open field bus standard for automation technology
- support for high-speed time critical and complex communication applications

MODBUS

MODBUS is a serial de facto communication standard published by Modicon in 1979 and it is mainly used for the communication between RTUs and control centre devices. It enables millions of automation devices to communicate based on request/reply (client/server) protocol (layer 7 protocol) [23]. There are number of variants of Modbus protocols, such as Modbus remote terminal unit (RTU), Modbus ASCII, Modbus TCP/IP, Modbus over UDP, Modbus plus, Modbus PEMEX, etc. and this standard is growing [23].

DNP3

DNP3 is a set of protocols (layer 2 protocol) used between different types of data acquisition control equipments. Its primary uses are in control centres, RTUs and IEDs and include the following features:

- Robust, efficient, compatible and secure protocol
- Time synchronization with RTU
- Event oriented data reporting

DNP3 is a more advanced protocol than the older MODBUS and comparison between these two are in Table 2.4 [24].

Table 2.4: Comparison between Modbus and DNP3 [24]

Feature	Modbus	DNP3
Open Domain	✓	✓
Active Users Group	✓	✓
Active Technical Committee	✓	✓
Comprehensive certification procedures	✓	✓
Multiple Data Types (see Table 1)	✓	✓
Standardized data formats		✓
Time-stamped data		✓
Data quality indicators		✓
Report by Exception (RBE)		✓
Unsolicited RBE		✓
2-pass control operations		✓

Functionality based comparison between MODBUS, IEC 60870-5-103, Profibus against IEC 61850 is shown in Table 2.5 [25] and IEC 61850 outperforms the others in most of the categories.

Table 2.5: Comparison between legacy protocols and IEC 61850 [25]

Functionality	MODBUS (Standard)	IEC 60870 - 5 - 103 (Standard)	Profibus	IEC 61850
Speed of Communication	9.6 kBPS, 19.2 kBPS maximum	9.6 kBPS, 19.2 kBPS maximum	9.6 kBPS to 12 MBPS	100 MBPS
Circuit Breaker Control	×	×	×	√
Disturbance Record Uploading	×	×	×	√
Remote Relay Parameterization	×	×	×	√
Time Synchronization Accuracy	×	± 1 msec	×	± 1 msec
Peer-to-Peer Communication	×	×	×	√
Interoperability	×	×	×	√
Multi Master Capability	Master Slave	Master Slave	Master Slave	Master Master
Level of Standardization	De Facto	Most implement ations using proprietary extensions	De Facto	Full application coverage defined in standard, including engineering

Several devices are interconnected within a substation to carry out different tasks which are assigned by the network operators remotely or by IEDs locally. These devices require different levels of support from the underlying protocols to carry out their activities efficiently to control and protect the distribution networks. In the past it was common practice to use proprietary protocols to fulfil the requirements from the DNOs. With the emerging concept of the Smart Grid, this conventional behaviour is about to change and interoperable standards and protocols are required. IEC 61850 is one of the advanced substation communication standard and provides high level of functionalities required by DNOs and enables interoperability between different vendors. It is clear from Table 2.5 that IEC 61850 satisfies most of the criterion compared to other legacy protocols and a detailed discussion about IEC 61850 is provided in Section 2.2.2.

Time synchronisation between sensors or smart meters is important. It can be observed from Table 2.5 that the time synchronization accuracy should be + or – 1ms and this accuracy is not realised in the current distribution network operations. With the emerging new DMS functionalities and standards fine granular accuracy in time synchronization is important to realise their full potential benefits to the DNOs especially with state estimation algorithms. Other DMS functionalities will also require high accuracy of time synchronization between sensors and raw data time stamps. High speed communication with fast response time between devices can provide this required level of accuracy and it is also dependent on the type of protocols and network configurations used within the communication.

2.2.2 IEC 61850

The IEC 61850 is a fast developing and well known standard for substation automation systems for electrical networks for more than a decade. IEC 61850 has become a very popular standard for substation automation systems and thousands of them have already been deployed around the world. As an emerging substation communication standard its communication requirements are specified to support different substation based activities, such as substation automation, fast transfer of events, data modelling and data storage. Many more functionalities can be added in future to realise its full potential for intra or inter substation level communication. This standard may also be applied to other applications as well and some of them are listed below [26]:

- Substation to substation (inter-substation) information exchange
- Substation to control centre information exchange
- Power plant to control centre information exchange
- Information exchange for distributed automation
- Information exchange for metering

The above applications significantly expand the scope and capabilities of IEC 61850 into a much larger area covering many aspects of the generation, transmission and distribution networks. Therefore, IEC 61850 standard can easily outperform any other existing standards in many aspects. IEC 61850 is divided into 10 main parts as shown in Table 2.6 [26] under the general tile *Communication networks and systems in substations [26]*.

Table 2.6: IEC 61850 with 10 parts [26]

System Aspects	
Part 1	Introduction and overview
Part 2	Glossary
Part 3	General Requirements
Part 4	System and Project Management
Part 5	Communication Requirements for Functions and Data Models
Configuration	
Part 6	Configuration Language for electrical Substation IEDs
Abstract Communication Services	
Part 7-1	Principles and Models
Part 7-2	Abstract Communication Services
Data Models	
Part 7-4	Common Data Classes
Part 7-5	Compatible Logical Node Classes
Mapping to Communication Networks	
Part 8-1	Mapping to MMS and ISO/IEC 8802-3
Part 9-1	Sampled Values over Serial Unidirectional Multi-drop Point-to-Point link
Part 9-2	Sampled Values over ISO 8802-3
Testing	
Part 10	Conformance Testing

IEC 61850 defines 13 different logical groupings and 86 different logical node classes as shown in Table 2.7 [26] .

Table 2.7: Different Logical groups and number of Logical Nodes in IEC 61850 [26]

Logical Node Groups	Group Designer	Number of Logical Nodes
System Logical Nodes	L	2
Protection functions	P	27
Protection related functions	R	10
Supervisory control	C	4
Generic References	G	3
Interfacing and Archiving	I	4
Automatic Control	A	4
Metering and Measurement	M	7
Switchgear	X	2
Instrument Transformer	T	2
Power Transformer	Y	4
Further power system equipment	Z	14
Sensors	S	3

The logical node examples include the following [27]:

- PDIF: Differential protection
- RBRF: Breaker failure
- XCBR: Circuit breaker
- CSWI: Switch controller
- YPTR: Power transformer

There are 355 different classes of data which are defined by IEC 61850 as shown in Table 2.8 [27].

Table 2.8: Different classes of data in IEC 61850 [27]

Data Classes	Number
System information	13
Physical device information	11
Measurands	66
Metered values	14
Controllable Data	36
Status information	85
Settings	130

Some common data classes include the following [27]:

- SPS: Single point status
- ACT: Protection activation information
- MV: Measured value
- WYE: 3 Phase measured value
- DPC: Double point control
- SPG: Single point setting
- DPL: Device nameplate

Its support for both client-server and publisher/subscriber models is an added advantage when modelling the communication aspects and this may also support expected high speed communication at different levels. Substation level automation using IEC 61850 communication model is important to support the novel DMS network service restoration functionality that will require input from distributed state estimation (DSE), CM and data mining (DM) [2]. Therefore, in the foreseeable future utilisation of IEC 61850 standard definitions will shape up the provision of communication technologies for distribution network. There are seven message types supported by IEC 61850 and they use simple and full OSI stack models. Generic Object Oriented Substation Event (GOOSE) message (commands, alarms and indications) requires stringent response time in the range of 1 to 10 milliseconds as shown in Table 2.9 [28].

Table 2.9: Message Type and Performance Requirement in SAS Network [28]

Message Type	Example Messages In PICOM	Transfer Time Range (ms)
1. Fast Message	Trigger	10-100
	Complex Block or Release	10-100
	Fast Broadcast Message	1
	Process State Changed	10-100
	Trip	1
2. Medium Speed Message	Process Value in r.m.s	50-1000
	Request for synchrocheck, interlocking	1-100
	Process State	1-100
	External State	1-100
3. Low Speed Message	Measure Value or Meter Value such as Energy	100-1000
	Non-electrical Process Value e.g. temperature	1000-5000
	Fault Value e.g. fault distance	0.1-5000
	Event/Alarm	100-1000
	Mode of Operation	10-100
	Set Point	100-1000
	Acknowledgment by Operator or auto.	10-1000
	Date and Time	100-1000
4. Raw Data Message	Process Value (sample voltage & current)	0.1-10
5. File Transfer	Report such as Calculated Energy List	1000-5000
	Mixed Fault Information	1000-5000
	Mixed Fault Data such as Disturbance Recording	5000
	Event/Alarm List	100-1000
	ID Data, Setting	1000-5000
	Diagnostic Data	5000
6. Time Synchronization Message	Synchronization Pulse	0.1-10
7. Command Message with Access Control	Command	1-1000

Time critical messages, fast messages and raw data messages, can be exchanged between devices using only application, link and physical layers (simple OSI stack). File transfer and messages requiring low or medium transfer speed can be used with full OSI stack (7-layers) and these messages can be based on client-server or publisher/subscriber communication models. IEC 61850 has become an acceptable intra-substation communication standard and in addition, the current standardisation process plans to extend this standard for inter-substation communication. This will enable automation and control for larger network area than before. This inter-substation level communication will further enhance DMS functionalities and may result in more intricate communication solutions for simple problems. Therefore, DMS functionalities should be defined with the following specifications:

- Intra-substation or inter-substation level performance
- QoS required for these two levels of operations
- Level of automation required with or without control from control centre

2.2.3 Generic Object Oriented Substation Event (GOOSE)

IEC 61850 supports a peer-to-peer communication between IEDs using the GOOSE messages that are generated when an event occurs within the substation. GOOSE messages require real-time performance guarantees to control and protect electrical devices using the IEDs within substation level (intra-substation). Other message types (Type 2, 3, 5, 6 and 7) that are not high priority compared to the GOOSE and sampled value (voltage, current and status) message types, require medium and low speed data transfer to meet their required performance guarantees. The time triggered sampled value messages require high reliability due to the transfer taking place only once compared to GOOSE messages where several GOOSE messages will be sent within a short period of time. Therefore, the priority tagging of these different messages is relevant [29] to make sure the guaranteed QoS levels are met during the substation automation (SA) activities.

GOOSE messages will be transmitted multiple times to the relevant IEDs to guarantee the delivery of the messages. The GOOSE messages are sent using the multicast mode to all the IEDs that are subscribed to receive the particular event notification. They require a strict end-to-end delay that has to be less than 4ms under any network conditions; therefore the underlying communication should provide the required performance level for real-time environment. Because the network configuration and the number of devices within that network may vary according to different substations this delay may also fluctuate. Therefore, it is important to carry out studies for worst case scenarios for a specified network to identify the effect on the GOOSE end-to-end delay and to propose suitable solutions to meet the guarantees required by the delay constraint.

Feasibility of using a process bus instead of hard wired (copper cables) connections for the communication between different IEDs has been proposed under IEC 61850-9 as follows:

- IEC 61850-9-1: Serial unidirectional multi-drop point-to-point link
- IEC 61850-9-2: IEEE 802.3 based process bus, i.e. Ethernet

Siemens and ABB demonstrated the IEC 61850 interoperability in Vancouver, Canada, May 2001 using the substation and process bus architecture as shown in Figure 2.2 [26]. This successful demonstration proves that the use of process bus for communication is definitely viable and development is ongoing to fully realise the required functionalities from it. It has already been included in several research activities to propose different techniques to evaluate the performance of the process bus under varying network conditions. The mapping of different message types specified by IEC 61850 with respect to different open system interconnection (OSI) layers is shown in Figure 2.3 [30]. It can be seen that the GOOSE and raw data samples require fast message transfer hence they are mapped with the 3-layer (application, link and physical) OSI model while the other types are mapped with full OSI model (all 7 layers). The time synchronization message requires fast response time hence the transport layer protocol UDP is used to avoid any unexpected congestion experienced by using the TCP. The overhead introduced when using the 7-layer OSI model has to be justified against reliability and fast response time.

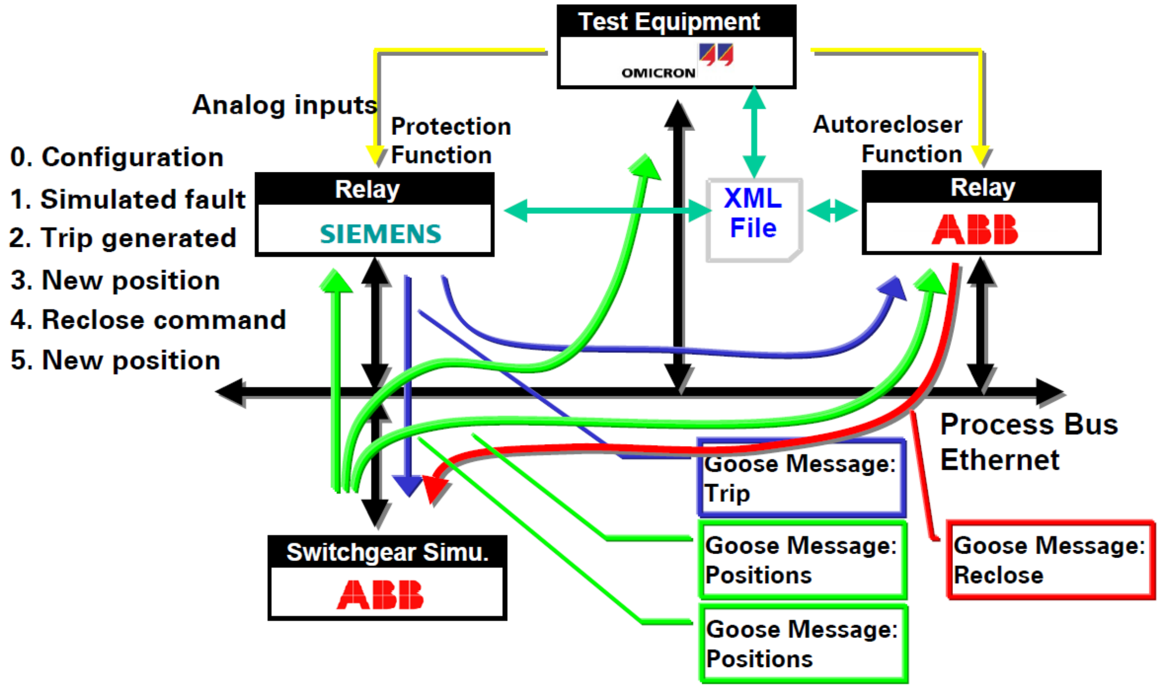

Figure 2.2: IEC61850 interoperability demonstration by Siemens and ABB [26]

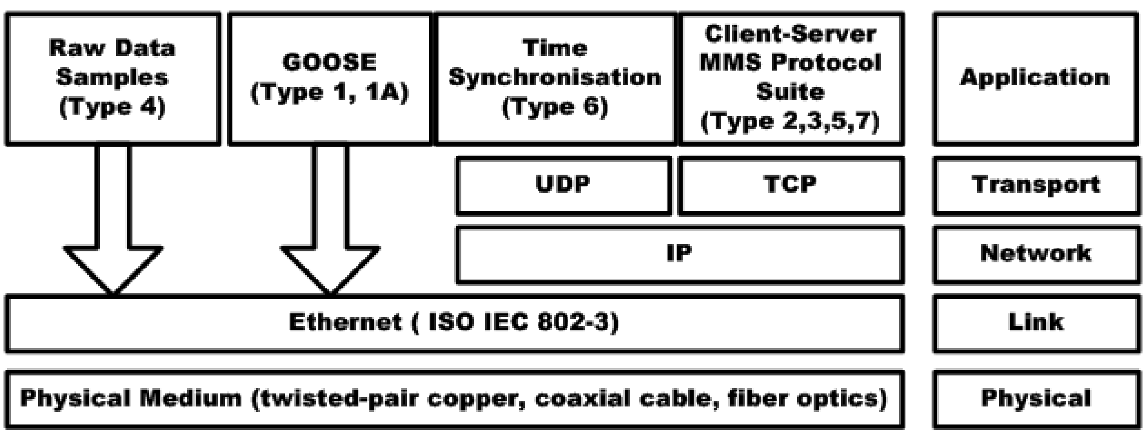

Figure 2.3: IEC 61850 message types and required OSI models [30]

Typical substation elements include switching, protection and control equipment, and instrument transformers. Substation operates in three levels:

1. Station level
2. Bay level
3. Process level

Station level devices include supervisor computer or station unit with human machine interface (HMI), station server for local data storage and gateway to connect to the network control center (NCC) or other remote systems (inter-substation communication). Bay level devices include control units, protection units, control and protection (C&P) units and switchgears. Process level devices include conventional instrument transformers (CITs), such as voltage transformer (VT) and current transformer (CT), sensors for measuring gas density or pressure and sensing switchgear or transformer tap changer positions. A high level interconnection of different primary and secondary devices within a substation is shown in Figure 2.4 and a switch-based Ethernet is shown with all three levels (station, bay and process levels).

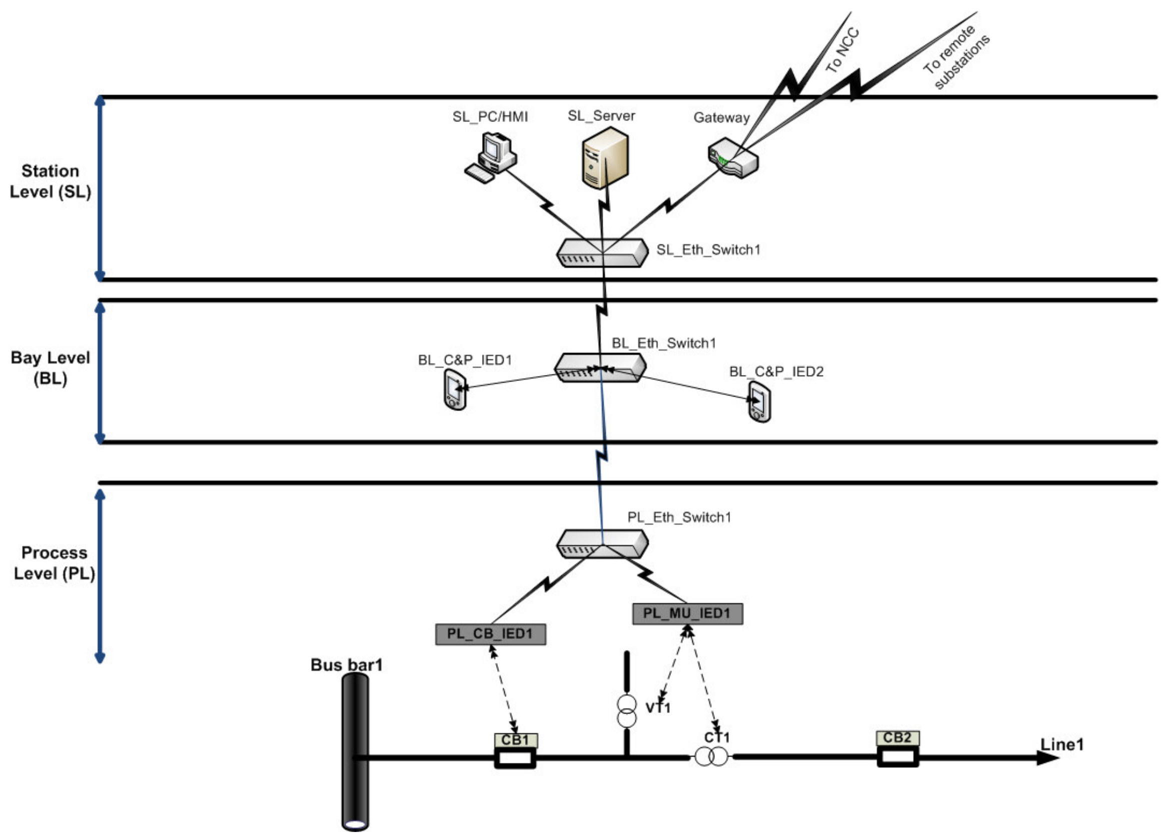

Figure 2.4: Ethernet switch-based star topology

Ethernet can support at all three levels and an attractive communication technology for the SA activities [31]**.** Optical fibre has been preferred over Ethernet for its high capacity, efficiency, coverage and security. But the cost involved with this technology is significantly higher and substation level automation can currently be supported by Gigabit Ethernet technology at low-cost. In the modern substation architectures optical fibre has been used in the process level physical devices to collect data from the primary devices because of its reliability against high voltage and electromagnetic interference, and compliance with IEC 61850 9-2 digital process bus requirements. Future vision of Smart Grid may require the optical fibre to be installed on primary substations for high QoS requirements and better interconnection between inter-substations for the future Smart Grid functionalities where interconnecting LANs and WANs will be common and will require fast responses between them.

As the communication medium should be bi-directional to exchange raw data and GOOSE messages between process and station level devices, the performance of the underlying medium should be evaluated for both uplink and downlink. Packet scheduling mechanisms (strict priority, round robin and weighted round robin) for substation IEDs to minimize the effect of GOOSE message delays during high congestion has been analyzed using OPNET simulation tool [31]**.** These mechanisms can be tested further at different levels of the substation to evaluate the optimum position of implementing the efficient packet scheduling. The effect of background traffic on the GOOSE or the sampled value messaging can be minimized by priority tagging the time critical messages against other messages as shown in [31]. NS-2 simulation tool has been used in [32] to evaluate the performance of Gigabit Ethernet using the IEC 61850 where three communication characteristics (packet end-to-end delay, packet drop rate and bandwidth consumption) for the GOOSE messaging have been mainly studied.

2.2.4 Utility Communications Architecture (UCA)

UCA was an EPRI project (1987-1999) and is commonly called as UCA 2.0 in IEEE Technical Report 1550 (IEEE TR 1550) [33]. UCA 2.0 was then considered as an important input to the IEC 61850 specifications and it was then decided to name the IEC 61850 standard series as the international standard while not to publish the IEEE TR 1550 as an IEEE standard. Table 2.10 [33] provides the basic difference between the IEC

61850 and IEEE TR 1550 (UCA 2.0) and this clarifies common confusions between them.

Table 2.10: Differences between IEC 61850 and UCA 2.0 [33]

IEC 61850	IEEE TR 1550 (UCA 2.0)
International standard (IEC)	Technical report (IEEE; GOMSFE version 0.82)
Comprehensive, modular information models – open for easy extensions applying a name space concept	information models (provide for extensions, however name space concept is not included); GOMSFE Bricks are compatible in concept with Logical Nodes in IEC 61850-7-4
Configuration language (XML based) for a simplified substation configuration	no configuration language provided
Using **prioritized** Ethernet (Ethertype/VLAN) providing high-speed and preferred transmission of GOOSE messages	no priorities supported with UCA2.0-GOOSE
Flexible IEC-GOOSE to exchange any information from any data object (digital, analogue, …)	UCA2.0-GOOSE to exchange fixed number of digital Information
Sampled value transmission for CTs/VTs	no sampled value transmission supported
Information models and communication services are **independent** from protocols; multiple mappings, e.g., MMS (ISO version 2003) and web services allow for future proven technologies	mapping to MMS (ISO/IEC version 1991); development was refocused on IEC 61850 as a single international standard
control model with **enhanced security**	restricted control model

Main advantages or benefits of UCA are highlighted below [34]:

- Interoperability, expandability, extensibility and ease of maintainability
- Self-defining devices
- Time Synchronisation
- Peer-to-peer communications
- Open Data Access and automated Reports
- Network Management
- Remote Control Substation Events Handling
- Security/Integrity

2.3 Middleware Architectures

Middleware is a piece of software layer placed between the application and the operating system [36] [37] and its requirements are listed below:

- QoS
- Scalability, reliability (fault-tolerance) and predictability
- Load balancing
- Transparency
- Group Requests
- Security

There are mainly four different types of middleware as listed below [37] [38]:

- Transactional middleware - supports transactions
- Message oriented middleware (MOM) – supports message exchange (IBM's MQSeries and Sun's Java Message Queue)
- Procedural middleware – supports remote procedure calls (RPCs)
- Object/component middleware – object oriented version of procedural middleware

2.3.1 Client/Server Architecture

Client/server architecture is very common in many applications from IP networks to distribution networks. Mainly in the internet, the number of users accessing a particular file from a server is very common where the access could be for small or large files over the IP network. There are many commercial applications using this architecture to carry out day-to-day activities by accessing the applications from a common server that could be anywhere in the world. The server should be able to accommodate several clients at a given time hence it should possess high capabilities to meet these requirements. Therefore a number of key issues can be highlighted in client-server architecture as listed below:

- the scalability
- high capacity and high speed computing resources
- single point of failure
- application access delay

Some of these key issues can be overcome by using the peer-to-peer architecture such as publisher/subscriber as discussed in Section 2.3.2.

In power systems, the client/server (request/response) architecture is used in many applications such as file transfer between different levels in substation communication using IEC 61850, polling smart meter data, downloading software updates from central servers, etc. Type 2, 3, 5 and 7 messages in the IEC 61850 require client/server architecture [30]. The communication services using centralised solutions at the control centre level use the client/server architecture [39]. If a specific electrical device should be controlled by the control centre then the required communication architecture is client/server. The publisher/subscriber architecture may not be able to control specific devices due to its loosely coupled behaviour in the network.

2.3.2 Publisher/Subscriber Architecture

The publisher/subscriber architecture is gaining popularity compared to the conventional client/server architecture due to some key advantages such as scalability and loosely coupled modules [38]. Because many subscribers can be subscribed to a specific topic or the content at a time the response time will be significantly reduced. The intermediate modules or databases should be able to handle the published messages from several publishers and to route the messages to relevant subscribers. Publisher/Subscriber system can be categorised under the message oriented middleware type [36].

There will be huge demand for managing the communication network efficiently once the smart metering infrastructure is fully deployed. The conventional client/server based architecture may not be able to support the requirements from the DNOs and the alternative architecture, publisher/subscriber, should be used to handle large volume of data communication. As part of the HiPerDNO project, a middleware called InfoBridge has been developed by IBM Haifa that supports both publish/subscribe and point-to-point services.

The publisher/subscriber architecture is used in IEC 61850 standard to send trip (Type 1 and 1A) and sampled value messages (Type 4) [30]. This architecture can be used in time critical control applications in power systems to increase the performance of the distribution network operation for the DNOs. A real-time publisher/subscriber communication model for distributed substation systems was proposed in [40] satisfying the specifications in IEC 61850. Decentralised solutions such as applications at the substation level or below can use the publisher/subscriber architecture [39].

Development of an initial publisher/subscriber model using the OPNET simulator was carried out by the MSc students in Brunel to study the performance of client/server against pub/sub architecture. Wireless and wired communication media were used as the underlying physical medium and the test was mainly carried out to study the scalability of the two architectures. Further work can improve this simple test-bed include advanced functionalities supported by a middleware architecture such QoS guarantees, content aware volume reduction, etc. Because the publisher/subscriber architecture gains more popularity it would be beneficial to implement this architecture in a simulation or emulation environment to compare with the commercial software developed by companies such as IBM.

2.3.3 InfoBridge

The InfoBridge is IBM's proprietary middleware developed for the HiPerDNO project and its Alpha version has been released for testing purposes with the aim of its full version to be available before the end of the project. This middleware architecture will provide data volume management through flow control and data volume reduction mechanisms. It is emphasized that the real-time and reliability QoS monitoring is important for guaranteed data communication services required by DNOs.

IBM previously developed a high speed messaging technology called 'WebSphere MQ Low Latency Messaging' [41] which delivers the following:

- Very high messaging throughput with low latency

- One-to-many multicast messaging
- Point-to-point unicast messaging
- Support for Support for UDP and TCP
- Positive or negative message acknowledgement
- Stream failover for high availability
- Flexible, fine-grained message filtering
- Traffic rate and congestion control
- Robust monitoring of application and network statistics, including internal and external latency
- Support for Linux, Windows and Solaris platforms

With massive data volume to be handled with the deployment of millions of smart meters in the UK, this type of middleware architectures are required by key stakeholders in the distribution network operation.

2.4 HiPerDNO Project

Smart Grid has been widely discussed in current energy markets to replace the existing conventional power grid infrastructure. This revolutionary transformation demands significant change in operational behaviours from a range of people involved in the process of energy generation, transmission, distribution and consumption. Currently, the communication between these different parties, particularly between distribution and end users, are mostly one-way where the electricity is distributed to the households and the flat bill payment is made at the end of month. This conventional behaviour is about to change in the near future with the emergence of adaptive energy pricing techniques which are realistic only when two-way communications are fully accomplished in the Smart Grid environment.

HiPerDNO [2] is a European Community's Seventh Framework Programme (FP7 2010-2013) under the ICT-Energy call. The main goal of this research project is developing a new generation of distribution network management systems, exploiting novel near to real-time HPC solutions with inherent security and intelligent communications for smart distribution network operation and management.

Integration of ICT into the Smart Grid is a key driver in order to realize the Smart Grid vision in a future energy market. Providing a two-way communication is essential due to the transmission of timely and critical information from end user to control centre or vice versa. Current power grid communication systems scarcely support the need for two way communication in MV and LV large scale network environments based on near to real-time operation. Control centres in many countries have deployed convenient communication technologies without a full specification of future requirements of these systems for supporting a large number of MV/LV devices generating huge amount of data (4 million customers with roughly 4 Terabytes (TB) of data volume per day [2]). This poses huge challenges with respect to the transmission and storage of such vast amount of data, and becomes unfeasible using the existing communication infrastructure and storage devices. Hence, novel, secure and low-cost ICT solutions are inevitably required.

2.5 Challenges

Through the above literature about the communication solutions for the distribution networks it can be highlighted that the existing distribution network operation should revolutionise their conventional activities to meet the challenges posed by the Smart Grid visions. It is challenging to change physical infrastructures within short period to study the effect of different components within the infrastructure. Therefore, the emulation and simulation has become a cost effective and easy to use solution to carry out many of the tests and help design a suitable infrastructure. This realisation reduces the cost and effort involved with the actual physical infrastructure changes to carry out small tests. It was evident through many experimental tests that the time and effort for carrying out several experiments by varying the different set of parameters was not an easy task and needed considerable effort. With the help from emulators and simulators this difficulty has been overcome and many industrial and academic researchers use several emulators and simulators before deciding the physical implementation of any solution.

This has been the case for several energy and ICT related projects [2][3][4][5] where several open source (NS-2, NS-3, OMNeT++, etc.) and commercial (OPNET) simulators have been used to carry out preliminary performance evaluation of communication infrastructure related studies. These simulation studies were then used as input to the design and development of the actual solutions. This reduces the cost and effort by many folds as the bottleneck of the required solution can mostly be realised at the simulation study stage. Several standards have also been tested using the design and simulation tools prior to their full deployment into the actual network.

2.6 Concluding Remarks

In this chapter the communication solutions for the emerging Smart Grid and the challenges faced by the stakeholders were discussed in detail. Although several communication standards and technologies are available to enable various distribution network functionalities, choosing the relevant communication solution is important for the DNOs. With the emerging massive data volume generation and transmission the underlying middleware architectures should reduce data volume in order to use the available communication bandwidth efficiently. The data storage systems should be capable of archiving large amount data locally or centrally for longer time. These challenges can be overcome by using commercial or open source ICT solutions that are developed and provided by several academic and industry partners worldwide. From local substation to control centre a combination of different communication standards can be used and the interoperability between them is a huge challenge. Therefore, several international standard organisations, IEC, IEEE, etc., have engaged in proposing common standards to solve the interoperability issues. This is beneficial for the DNOs as they would require efficient and low-cost solutions to carry out their network operation activities. This also helps several other stakeholders to work on common standards to reduce complications due to several proprietary standards or systems. IEC 61850 substation communication standard is now widely deployed worldwide and gaining momentum due to many benefits it provides for intra- or inter-substation communication. Several DNOs have already seen its potential role in the future Smart Grid and started to adopt it within their networks [2].

Chapter 3 ICT Requirements in Distribution Network Operation

Integration of ICT into the existing distribution networks is a key enabler for the distribution network operators with the emergence of the Smart Grid visions. Many projects are ongoing around the world to provide efficient communication solutions to make the Smart Grid visions a reality in the near future. Investigation about the available communication solutions and the required improvements to them to support for future demand is important. Advanced and novel communication technologies have been developed in the recent years to compensate or to improve the performance experienced with the existing solutions. The amount of data exchanged between devices within substation level or over wider area networks is growing rapidly with the connections of many IEDs into the network for improving visibility and management of the network. Sensors are used to monitor the status of the critical electrical devices and the data are collected for further processing to plan the relevant management activities [2]. More frequent data collection is useful and important for the network operator to carry out network operations effectively. But the cost involved with the vast amount of data generated, processed and transferred should be justifiable for the DNOs.

Near to real-time network management require high availability from the underlying communication medium. Distribution network operators will have to justify their cost for the ICT solutions hence they tend to achieve low-cost solutions. This is a trade-off between the required high performance and low-cost solutions. Therefore, they have to sacrifice one or the other during the decision making process. This introduces an interesting research challenge to produce communication solutions with differentiated QoS with the cost benefit analysis carried out for each of the solutions. The ENA, UK produced a number of studies regarding the smart metering in the UK. These studies can be used to derive approximate values for data traffic and communication cost, and to forecast the future surge of data by varying different parameters.

In this research project the reference [6] was mainly used to derive use case scenarios and to use the estimate communication parameters to assist in the OPNET simulation studies. A UK perspective on smart meters for Smart Grid is discussed in [21] where a high level communication system architecture consisting different communication media for the distribution network (MV/LV network) is realised as shown in Figure 3.1 [21].

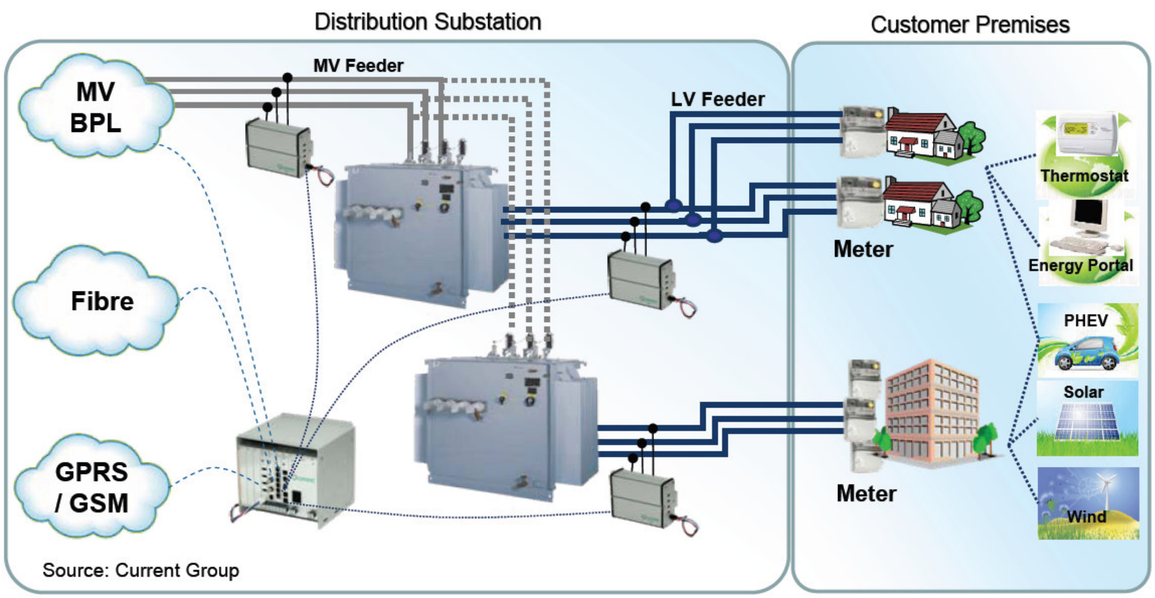

Figure 3.1: UKERC Smart Meters for Smart Grids, UK Perspective [21]

It can be seen from Figure 3.1 that the backhaul communication medium can be from MV BPL, Fibre or GPRS/GSM according to the perspective. The communication solutions for the last-mile are not fully defined within this perspective and it can consist of several combined communication solutions depending on number of factors. Some of these key factors are listed below:

- The location of the LV devices
- The distance from the local concentrator
- Access for the available communication medium
- Priority and criticality of the end user
- Availability of distributed energy resources (DERs)
- Frequency of the unidirectional or bidirectional data transmission

When planning or defining the required communication solutions for the MV/LV network these factors can be taken into consideration to provide a scalable, low-cost and secure communication medium.

Integration of communication infrastructure is important to enable functionalities required to maintain its normal network operation running smooth and to troubleshoot any unprecedented faults arising from the MV/LV substation or LV devices. There are number of DMS functionalities that require guaranteed and differentiated QoS from the communication network. Section 3.1 discusses about these requirements from the communication perspective and how they will support the novel DMS functionalities.

The Smart Grid is defined and explained differently throughout the world and it is not finalised yet. But the functionalities to support this vision have started emerging and an ongoing research projects investigate about developing novel functionalities to enhance the existing ones and to develop novel functionalities by integrating the communication architecture efficiently into the power grid. Millions of smart meters, sensors and other devices will be connected to the existing power grid to enable the initial vision of the Smart Grid. These new devices will be generating vast amount of raw data which have to be locally or centrally processed and stored for input to DMS functionalities to support different distribution network operation.

3.1 Requirements Specification for Data Processing and Storage

Two case studies were carried out to estimate the smart meter data traffic using UK and Belgium perspectives.

Estimate smart meter data traffic analysis for the UK and Belgium

ENA carried out detailed analysis regarding the data flow volumes associated with smart meter data traffic for a range of UK use case scenarios [6]. This analysis provides important information to evaluate critical performance metrics relating to communication media, protocols and technologies to accommodate future surge of data from millions of smart meters. A detailed evaluation regarding communication media for smart meters in Flanders (Belgium) was carried out in [11] focusing on various transaction types against time criticality.

The data generated per meter depends on number of key parameters such as, number of electricity/gas transaction types, sampling period, etc. According to ENA, assuming an average of 4 Bytes for each electricity parameter (real power, reactive power, voltage, power factor, etc.) is reasonable and this value can be used in order to calculate the raw data traffic per meter. Then, there is an additional communication overhead introduced by different protocols which add considerably high amount of data (for example 500 Bytes for each TCP/IP data transmission overhead).

A comparative study regarding the amount of smart meter data generated per annum for the UK and Belgium cases are shown in Table 3.1 [6][11]. The UK case considers 1.5 megabytes (MB) for single smart meter per annum (p.a) and 30-40 TB per annum for 27 million smart meters and a detailed calculation of these values (estimated values only) can be found in [6].

Table 3.1: Time and data size requirements per transaction type per smart meter [6][11]

Country	Meter Type	Single Meter p.a.	Total Meter Population p.a.
UK	**Electricity** (27 million meters)	Less than 1.5 MB	30-40 TB
Belgium	**Electricity** (3 million meters)	0.5 MB	1.28 TB

For the Belgium case, the estimated data volumes for single smart meter and for all 3 million smart meters per annum are 0.5 MB and 1.28 TB respectively. It can be noted from Table 3.1 that the amount of data for single smart meter per annum for Belgium (0.5 MB) is smaller than the estimate for the UK perspective. This difference is understandable as the smart meter functionalities may vary according to countries and other user specific requirements, such as number of electricity parameters recorded at the smart meters.

These indicative values are useful to the DNOs in order to plan and prepare their communication and computing infrastructure support to accommodate this amount of data generation and transmission. The above comparison also suggests that the required communication media may vary for different DNOs around the world and the optimum solution can be derived if the accurate smart meter data traffic can be calculated for the particular DNO.

There are two main scenarios that need to be considered when analysing smart meter data traffic:

1. Primary storage of raw data at the meter level
2. Transmission of the raw data using different communication media and protocols

Depending on the number of electricity/gas parameters, the local and central storage capacity may vary considerably and some estimated values can be determined as described in Table 3.1 for both the UK and Belgium cases. Communication requirements for the transmission of the raw data to the control centres may differ extensively for different European DNOs depending on their required level of performance when collecting data at different levels of the distribution networks. The following three cases provide the total TB of data for 27 million electricity smart meters per year for 5 seconds granularity:

ENA: 14400 TB/year [6]

Belgium: 1519.96 TB/year [11]

HiPerDNO Annex DoW Part B: 9855 TB/year [2]

These numbers are estimates and the considerable variation is due to inconsistent electricity parameters per smart meter. Further investigation has to be carried out in order to understand and verify the amount of data traffic generated by smart meters from different European countries based on varying electricity/gas parameters. This will then contribute towards defining the required data rate against the response time for different transaction types between control centres and smart meters.

3.2 Requirements for High Performance Computing

Future distribution network operation requires scalable, secure and low-cost communication and computing solutions to accommodate the challenging requirements in both transmitting and storing vast amount of data from millions of smart devices. This mandates the expected high performance computing (HPC) platform to support the processing of large volume of data to comply with real-time data analysis and control requirements specified by the DNO for making the near to real-time operation a reality. There is trade-off between the high performance of the computing resources to provide real-time environment and the amount of power consumed by these computing hardware resources involved in processing huge amount of data. One of the constraints for the HPC systems is the power consumption [42]. This should be addressed and analyzed effectively to produce low-cost, high performance and low-power HPC solution. As the HPC platform is expected to function at multi Tera FLOP (TFLOP) capability the power consumption poses huge challenge and should be reduced to meet the low-cost investment for the entire system. Power consumption estimation for different scale of HPC systems are listed below [42]:

- 3 teraflop machine - less than 400 KW
- 100 teraflop machine - about 1500 KW
- petaflop machine – 2-7 MW
- exaflop machine – 60-130 MW

The following functionalities and requirements are relevant to justify the added value against the computational requirements when using HPC [1] [2]:

- Reliability of hardware and software to provide overall required levels of QoS
- Multiple services to be supported through low-cost and flexible architecture
- Data visible at different levels of granularity (temporal and spatial)
- Real-time resource scaling depending on future demand
- Flexible support for different protocol standards
- Details about energy consumption and price/performance ratio

- Reliability of hardware in order to provide required levels of quality of service
- Efficient cost-effective computing power (capacity computing)
- Cross-platform interoperability

Data system should initially support the following requirements [1] [2]:

- Localized processing of its area of DNO information
- Support of web service access through interfaces to the local database with security and resilience guarantees
- Multiple TB of data to be stored for large metropolitan network consisting of multi million customers (for 4 million customers will generate about 4TB/day depends of sampling rate [2])
- Multiple small systems each with multiple TFLOP capability to maintain resilience of the system
- System latency must be significantly reduced to support real-time monitoring and control through the network
- Data back-up

3.3 Requirements for High Speed Communication

The existing distribution network operation uses a number of communication technologies [43] to carry out their day-to-day activities within the network. With the increasing number of devices connected to the network the amount of data generated increases exponentially. This huge amount of data can be stored locally (within a local concentrator) and polled on regular basis to the control centre for billing, network management, capacity planning and many more activities by the network operators. These conventional activities are about to change with the emerging Smart Grid visions which require some of these activities to be automated for smarter control and monitoring of the distribution networks. Therefore, the need for scalable, secure and low-cost communication solutions is inevitable to make these visions a reality. Some of these advanced DMS functionalities require the data transfer in real-time (near to real-time). High speed communication technology is a key enabler to the Smart Grid and several research projects [2] [3] [4] [5] have already investigated about these solutions. The following sections discuss two different scenarios for finding the requirements for the high speed communication.

3.3.1 Scenario 1: Outage alarm

This scenario considers the required communication capabilities for the outage alarm use case and compares the theoretical requirements from Table 3.2 [6] against the experimental results provided in Table 3.3 [13]. Three different communication technologies, GPRS, UMTS and PLC were used to study the suitable solution under this scenario. This comparison is useful for the DNOs to plan their communication infrastructure design effectively to avoid any bottleneck in the system when the number of electrical devices increases in future. The following list highlights the main criteria for each communication medium under varying alarm conditions. Because some outage alarms require the actions to be taken in seconds than minutes or hours, these alarms require a higher performance in order to meet the required level QoS by the DNO.

Therefore, the underlying communication media should support these requirements and be able to scale well with future demands for data communication as well.

Table 3.2: Outage alarm from different number of meters [6]

No. of Meters	Speed per packet depending on response time required						
	Response time required: 5 sec	Response time required: 30 sec	Response time required: 3min	Response time required: 5min	Response time required: 15min	Response time required: 1 hour	Response time required: 12 hours
	kbps	kbps	kbps	kbps	kbps	kbps	kbps
200	191	32	5	3	1	0	0
400	382	64	11	6	2	1	0
600	573	96	16	10	3	1	0
800	764	127	21	13	4	1	0
1000	955	159	27	16	5	1	0
5000	4,776	796	133	80	27	7	1
10000	9,552	1,592	265	159	53	13	1

Table 3.2 is a 3-way table that shows the relationship between three parameters, speed per packet, number of smart meters and response time. For example, if 5 seconds response time is required for 1000 smart meters then the required speed per packet should be 955 kbps. These values are considered as the worst case [6] and are useful for DNOs to plan the required and relevant communication support for the distribution networks with different DNO applications.

Table 3.3 provides the results for the experimental tests to test the performance of GPRS, UMTS and PLC communication media by stress testing the network [13]. These throughput and latency results can be compared against the speed per packet and response time values in Table 3.2 to analyse the suitable communication solution for varying number of smart meters. For example, the GPRS with UDP or TCP (21-22 kbps) can be used to support 800 smart meters with the minimum response time of 3 minutes. If the number of smart meters has to be increased or the required response time should be decreased then this communication medium will no longer be a solution for the DNO.

Table 3.3: GPRS/UMTS and PLC tests results for maximal case [13]

Technology	UDP		TCP	
	Throughput	Latency	Throughput	Latency
GPRS	22 kbps	6 sec	21 kbps	10 sec
UMTS	363 kbps	102 ms	239 kbps	311 ms
PLC	50.3 Mbps	3.1 ms	13.4 Mbps	95 ms

The suitability of different communication media for varying number of smart meters and response times is discussed under the following points:

- If the alarm to be escalated to the SCADA within 3 minutes for 10000 meters UMTS/UDP and PLC can be used
- If the response time is 30 seconds then PLC is the only solution
- All three communication media can support 10000 meters if the response time greater than 1 hour

3.3.2 Scenario 2: Direct control

Under this scenario, support for the control of electricity devices from the control centre using the underlying communication medium is discussed using the GPRS, UMTS and PLC technologies. The control signals can be issued centrally from the NCC or locally from the automated functions embedded within IEDs at the substation level. Even though the control is issued locally, the event notification should be sent to the NCC for network management and planning purposes. Control of several electrical devices (hundreds if not thousands) within short period of time (near to real-time) is a challenge for the network operator and it depends on number of factors as listed below:

- size of the network
- number of electrical devices connected at a time
- priority of the devices or the end users
- level of criticality and accessibility to the communication network

These parameters will contribute towards the design and management of the relevant communication infrastructure for differentiated network control applications. The following section considers the direct control over a number of household appliances for varying response time requirements (Table 3.4 [6]) and checks the support provided by the underlying communication media (GPRS, UMTS and PLC) using the experimental and simulation results in Table 3.3.

- If the demand side management (DSM) to control household appliances requires less than 3 minutes response time for 10000 meters then PLC can be the only solution
- UMTS/UDP can support 10000 meters with 5 minutes response time while GPRS can support only with 12 hours response time

Table 3.4: Exert direct control over a number of household appliances [6]

No. of Meters	Speed per packet depending on response time required						
	Response time required: 5 sec	Response time required: 30 sec	Response time required: 3min	Response time required: 5min	Response time required: 15min	Response time required: 1 hour	Response time required: 12 hours
	kbps	kbps	kbps	kbps	kbps	kbps	kbps
200	382	64	11	6	2	1	0
400	764	127	21	13	4	1	0
600	1,146	191	32	19	6	2	0
800	1,528	255	42	25	8	2	0
1000	1,910	318	53	32	11	3	0
5000	9,552	1,592	265	159	53	13	1
10000	19,104	3,184	531	318	106	27	2

UMTS with UDP (363 kbps) from Table 3.3 can support the direct control for 1000 smart meters with the response time of 30 seconds (318 kbps) as shown in Table 3.4. But if a different TCP is used with UMTS (239 kbps) then only 800 smart meters can be supported as seen in Table 3.4.

3.4 Concluding Remarks

This chapter discussed about the requirements for high speed communication and computing using case studies. The required communication architecture for distribution network depends on the size, type of DMS functionalities and different QoS requirements from the DNO. These remarks match well with the proposals by several ICT and energy related projects where not a specific communication or computing solution is proposed for a specific DMS functionality. The theoretical estimates and actual experimental results were used to identify the suitable communication medium for a specified application. These indicative figures will help DNOs and researchers to base their requirements for communication solutions and to evaluate the performance of DMS functionalities during experimental and simulation studies. However, before deciding the suitable communication media for the relevant DNO application, extensive experimental tests should be carried out to validate the estimate data rate and response time values. There are several factors contributing to these estimates therefore careful consideration should be taken when defining the testing criterion.

Chapter 4 QoS Monitoring Test-bed

4.1 Introduction

With the emergence of millions of smart meters in the near future the distribution networks will have to deal with massive about of data which have to be transmitted from the local concentrators to the control centres. This can be considered as a bandwidth intensive application because large volume of data will have to be streamed to the control centre. Therefore, the development of the proposed QoS monitoring test-bed can be modified to include the performance evaluation of wide area network communication infrastructure and this can eventually be applied to the distribution networks as well.

This chapter describes the QoS monitoring test-bed developed using the Java program to evaluate the delay, jitter and packet loss for video streaming application. An existing Client-Server based Java program was significantly modified to include a gateway to act as a monitoring node in the network. This monitoring concept can also be applied in the distribution networks to monitor the QoS of the communication medium in real-time and is beneficial to the DNO. It can be integrated with the control centre (SCADA system) and can be used in parallel with the electricity network monitoring systems to provide better observability and performance improvement of distribution network components.

Figure 4.1 [2] depicts a schematic for the integration of HPC, messaging layer and other LV network devices with the high speed communication links realised as a combination of satellite, GPRS/UMTS, PLC, etc.

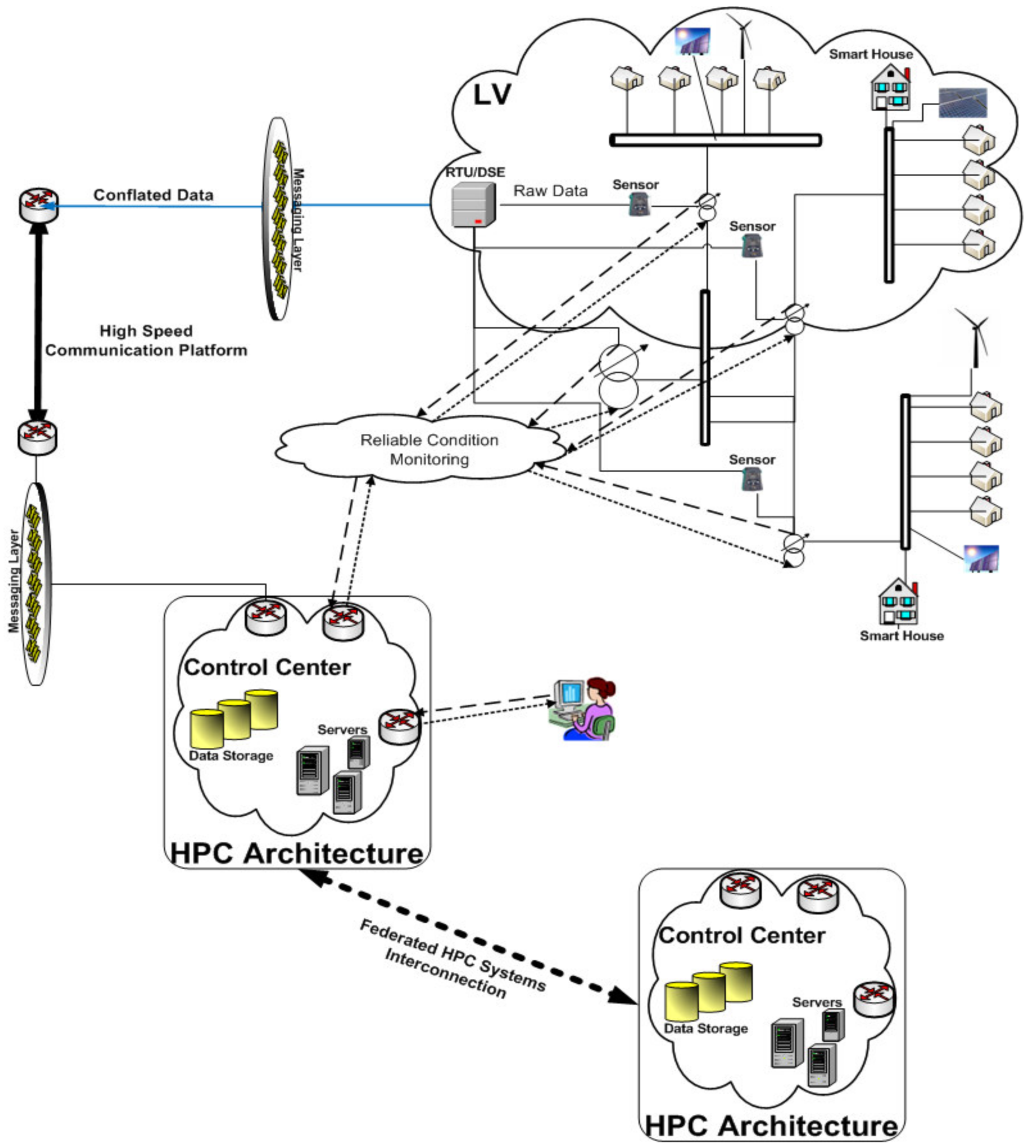

Figure 4.1: Detailed schematic of the integration of ICT into the Power Grid [2]

The federated HPC system may be composed of different computing platforms as follows:

- Cluster: LAN
- Cloud: private or enterprise computing; utility computing
- Grid: virtual organisations managed over WAN [35]

The performance of computing and communication systems have to be monitored in real-time to provide the DNO with the capability to assess and control the relevant network by means of some bespoke monitoring tools integrated into the SCADA system or a dedicated monitoring tool which will monitor and manage the network as a whole. The monitoring API should provide the following statistics to predict the service levels:

- Intermediate node statistics
- Transmitter statistics
- Receiver statistics
- QoS statistics for all nodes

The monitoring system can monitor a large scale network and provide those required statistics to relevant parties for management and control of the network. The requirements for monitoring distribution network and the embedded devices within the network for future power systems are relatively important to monitor and control the output level and on/off schedule for smaller generators and other sensor devices where the grid-computing can be utilised to provide inexpensive technological solution [35].

4.2 Real-time Bandwidth Intensive Applications

With the emergence of smart phones in the recent years the real-time bandwidth intensive applications undergo revolutionary changes to adopt many of the modern functionalities. Several new applications are developed in a more frequent manner compared to the past and the number is growing rapidly. Some of these advanced real-time bandwidth intensive applications can be categorized as follows:

1. Smart metering data transmission
2. Data transmission from other smart devices in the distribution networks
3. Video/ audio conferencing/video/audio calling
4. Interactive web conferencing/file sharing, e-learning, online gaming, etc.
5. Interactive social networking (Facebook, Twitter, Flickr, Skype, etc.)
6. Video surveillance for security (closed circuit television-CCTV)

With the emergence of smart technologies in the recent years, this list is growing as more interactive real-time applications are introduced into the market on a fast pace. These applications are mainly used for work and leisure related activities on a daily basis by millions of people around the world. Several well established companies such as Microsoft, Google, Yahoo, Apple, Nokia and Samsung, encourage the use of these modern multimedia applications using their services. These several activities pose huge challenges to the IT personnel to provide a suitable and convenient multimedia management and control technologies and solutions to the network providers so that the network can be managed and optimized during the disruptive network conditions. The following sections discuss about the requirements and challenges from these different real-time applications.

4.2.1 Real-time Requirements

Video communication over IP and proprietary networks has been considered a viable and low-cost solution for many multi-national companies to conduct their day-to-day activities conveniently. Travel time required between their different branches worldwide is considerably high and the travel cost involved is also questionable. Moreover, the current climate change and global warming issues introduce extra burden on companies where they have to meet certain CO_2 emission criteria set by governments. Bandwidth intensive applications requiring real-time QoS guarantees are highly volatile and require stringent resource allocations in terms of communication medium used. With the emergence smart devices in the recent years, the QoS guarantees for the end users have to be met under varying network conditions. Millions of smart phones used around the world and thousands of smart applications enable the end users to carry out their day-to-day activities conveniently.

One of the well known multimedia applications, is the video conferencing/video calling that requires high communication bandwidth. When many end users use the video conferencing the maximum bandwidth of the underlying communication medium can easily be reached and if more users would like to connect to that the network they will have to experience unacceptable delay and jitter. This will invalidate the guaranteed QoS requirements for these users. If the QoS monitoring tools are capable of providing the real-time information about the performance of the underlying communication medium to the new end users it will help them to decide whether they want to proceed with their activity or to return at a later time when the network congestion is at acceptable level.

The acceptable delay for video and voice (mouth-to-ear) is 150ms and the jitter value to be less than 30ms (and this may vary depending of the SLA with different customers). If the delay is above 400ms then the quality of the audio or video is unacceptable according to the specifications in ITU-T Recommendation G.114 one-way transmission time requirements [44]. This recommendation also found out from a test result that some interactive speech, video conferencing and interactive data applications may even be affected by delays below 100ms. Therefore, these upper or lower limits on delay and jitter may vary in future with regards to the demands posed by future high performance interactive applications. This has been the case for some commercial customers where they require the delay and jitter to be tens of milliseconds or even in microseconds due to their critical business environments.

There is also number of real-time applications in distribution networks which requires stringent QoS guarantees. The control and monitoring of electrical devices within a substation using the GOOSE messaging is a typical example which requires the end-to-end delay of GOOSE message to be less than 4ms. State estimation requires the devices status to be exchanged to the control centre to effectively manage the network in near to real-time. Condition of transformers, cables and other electrical devices should be monitored in real-time for some critical networks in order to react in time if a fault occurs or about to occur. The network has to be restored in near to real-time to avoid penalties due to customer minute lost (CML). These different applications in distribution networks will require the network operators to handle the situations using convenient control and monitoring tools.

4.2.2 Challenges with Bandwidth Intensive Applications

The ever-growing internet traffic imposes huge challenges to the bandwidth intensive applications over the IP network. Private or dedicated networks are required for users with high QoS requirements. The end users tend to pay less for better quality hence an optimised level of QoS should be agreed between the end users and the network operators. This paradigm introduces the provision of differentiated services (DiffServ) which will provide guarantees according to different applications. Video and audio applications require strict end-to-end delay and can tolerate an acceptable packet loss hence this can be considered under one service class. Some other applications such as file transfers and E-mail which does not require guaranteed end-to-end delay but strictly no packet loss so they can be classed into another service type. This categorisation introduces added challenges to the network operators as they may have to differentiate the users based on their agreed service level agreement (SLA). If this SLA is violated, penalties will apply.

4.3 Survey on QoS Monitoring for Real-time Applications

4.3.1 Commercial Software Tools

The analysis on the following section provides key findings to help develop the required bandwidth intensive applications monitoring tool compared to the existing tools. The table of comparison at the end of this section summarises the different characteristics between those tools and provides easy to understand details at a glance.

A high level comparison between several commercially available tools such as SolarWinds [45], SwissQual [46], AGT-Fathom [47] and FlukeNetworks [48] are summarised in Table 4.1 [45] [46] [47] [48].

Table 4.1: Comparison between commercially available tools [45] [46] [47] [48]

Features	*SolarWinds*	*SwissQual*	*AGT-Fathom*	*Fluke Networks*
Available tools	ipMonitor, Orion, VoIP Monitor,	QualiPoc, Diversity, QualiPoc Handheld	Commander, Commander console, Analyzer 1000, Video Analyst	OptiView, NetFlow Tracker,
Web-based platform	All-in-one Web-interface	NQWeb provides web access via Internet,	Commander Console	Graphical displays (Windows based)
Alerting mechanism	E-mail,	Automatic reporting and alarming	Not specified	E-mail, pager, log files etc.
Wireless network	WAP,	Supports wireless, mobile networks	Not specified	Wi-Fi
Wired network	WAN, LAN	Not specified	Not specified	WAN, LAN, Ethernet environments
QoS monitoring	Using the custom reports created.	Using radio network parameters & messages, real-time speech, data & video measurements,	Provided using prevention of potential problems method	Extensive VoIP QoS analysis
Information collection	Packet loss, latency, jitter, availability & response time, ping time, bandwidth, CPU & disk utilization, etc.	Radio performance & QoS KPIs of wireless networks,	Packet loss, end-to-end network delay, , jitter, call quality & call set-up delay	Utilization, error rate, top senders/receivers, VLAN traffic analysis, application response time, etc.
Network protocols	SNMP,	TCP/IP, RSTP, UDP, H.245, H.324M, WAP, HTTP, FTP, L1, L2, L3	H.323	SNMP, RMON, VoIP, etc.
User interface features	Dashboard, full screen NOC view for all devices,	Tables, graphs, charts, MapEtreme interface, etc.	Graphs, tables, etc.	Application bounce charts
Services	Device discovery, quick search facility, VoIP performance monitoring, etc.	Voice, data, browsing, messaging, video & mobile TV, etc.	H.323 audio& video traffic measurements, real-time view of video endpoints status, fault isolation, etc.	WLAN, VLAN & switch/router configurations, network health, routine audits, etc.
Database	SQL, XML, SNMP MIB,	Microsoft's SQL	Not specified	CSV files, Supports standard-based MIBs
Scalability	Application scalability	Highly modular & scalable	Not specified	Scalable protocol analysis
Applications	HTTP, HTML, exchange servers, Windows, UNIX & Linus server, etc.	Active service tests of voice & video calls, mobile TV, video streaming, HTTP, web browsing,	IP video networks & IP endpoints	Packet capture & analysis, network degradation & traffic monitoring, SNMP traps, etc.

4.3.2 Open Source Software Tools

Open source software tools allow users to access source codes and to modify the software according to the users' requirements. These characteristics have encouraged many professionals to choose open source tools in academic and commercial areas. Free of charge and easy accessibility are considered the main reasons for choosing these tools while not guaranteeing SLAs and meeting some licensing conditions are some drawbacks. The following discussions about the commonly used open source tools help to evaluate competitive tools when developing commercially viable software. Therefore, in depth understanding about a required and suitable tool is crucial for the required development platform and its satisfactory requirements for various applications. Many of these tools can also be used in the electricity distribution networks for data acquisition and storage, and monitoring purposes as discussed in the following sections.

A. RRD (Round Robin Database) tool

This open source tool is an industry standard high performance data logging and graphing system for time series data [49] and can be used to suit individual development environment for monitoring or creating specified applications. RRD tool provides some key features that are beneficial to DNOs regarding the data acquisition, processing, storage and display as listed below:

- Data acquisition: Making the data available at a constant interval for accessing the system state, updating the log-file at any required time and it allows storing exactly the type of interested information.
- Consolidation: The consolidation function (CF) (average, minimum, maximum, total, etc.) in RRD can be used to define the intervals (storing data in 1 minute, 2 hour intervals), at which the consolidation should occur and to store data for long time.
- Round Robin Archives (RRAs): This archiving method allows RRD to store data values of the same consolidation setup over a certain amount of time using the known and limited storage space.

- Unknown data: This method is used to store UNKNOWN data values into the database when no new data is available to be written to RRD.
- Graphing: Numerical and graphical reports can be generated using the stored data in one or several RRDs and the graphing configurations, size, color and contents of the graph, can be defined freely using the graph function in RRD tool.

B. Wireshark

Wireshark (formerly Ethereal) [7] is an open source protocol analyzer that is widely used by academic and industrial researchers for capturing network packets and displaying the relevant packets' information in a user friendly manner. Some key features from this tool are listed below:

- Multi-platform: Runs on Windows, Linux, Solaris, FreeBSD, OS X, NetBSD, etc.
- Live capture and off-line analysis
- Captured network data can be browsed via a GUI, or via the TTY-mode TShark utility and the most powerful display filters in the industry
- Read/write many different capture file formats: tcpdump (libpcap), Catapult DCT2000, Cisco Secure IDS iplog, Microsoft Network Monitor, Network General Sniffer® (compressed and uncompressed), Sniffer® Pro, etc.
- Live data can be read from Ethernet, IEEE 802.11, PPP/HDLC, ATM, Bluetooth, USB, Token Ring, Frame Relay, FDDI, and others (depending on your platfrom)
- Decryption support for many protocols, including IPsec, ISAKMP, Kerberos, SNMPv3, SSL/TLS, WEP, and WPA/WPA2
- Output can be exported to XML, PostScript®, CSV, or plain text

C. Nagios®

Nagios® [50] is an open source system and network monitoring tool, which monitors user specified hosts and services utilising the alerting mechanism when good or bad network conditions are encountered. This tool provides the legal authorization to copy and modify under certain conditions defined and published by Free Software Foundation. Main features supported by the Nagios can be summarised as below:

- Monitoring of network services (SMTP, POP3, HTTP, NNTP, PING, etc)

- Monitoring of host resources (processor load, disk usage, etc.)
- Simple plug-in design that allows users to easily develop their own service checks
- Ability to define network host hierarchy using 'Parent' hosts, allowing detection of and distinction between hosts that are down and those that are unreachable
- Contact notifications when service or host problems occur and get resolved (via E-mail, pager, SMS, IMs or user-defined method)
- Ability to define event handlers to be run during service or host events for proactive problem resolution
- Optional web interface for viewing current network status, notification and problem history, log file, etc.

This tool is an open source where it does not guarantee any kind of SLAs such as design, merchantability or fitness for specific purpose. This characteristic makes this tool unreliable under critical situations when encountered by the user.

D. Zenoss [51]

This software is an open source (free, GPLv2, source code included) monitoring tool which effectively manages configurations, health, network performances, servers and applications. Zenoss includes the following features:

- Single Integrated Product - to monitor entire IT infrastructure
- First Commercial Open Source CMDB - a single repository for IT assets
- Easy To Use Browser-Based GUI - no Linux skills needed, access from anywhere
- Enterprise-Ready Architecture - tiered architecture that scales to thousands of nodes
- New in 2.1 - Google Maps Mashup, Network Visualization, Java Apps Management

E. Ground Work [52]

This open source product provides the following features:

- Monitoring servers, devices, applications, performance
- Agent-based or Agent-less monitoring
- Basic auto discovery and configuration

- Multiple data sources (traps, Logs, WMI, etc.)
- Reporting and exception analysis
- SLA reports
- Unlimited number of monitored devices

4.3.3 Types of Monitoring Techniques

The initial research on bandwidth intensive applications monitoring tools helped to classify the monitoring techniques according to the following:

- Active network monitoring
- Passive network monitoring
- Wired network monitoring
- Wireless network monitoring
- Real-time applications monitoring
- QoS monitoring
- Distributed/ centralised monitoring

Although there are many classifications, for the purpose of this project the above main classifications are considered.

A. Active network monitoring

Active probing technique [53] can be used to perform fault localization when developing monitoring tools. Probe stations' set selections for problem discovery and determination are discussed in [53] by considering a variety of design issues. Number of probes and fault diagnosis time can be reduced significantly compared to the conventional methods when this technique is used effectively. The future works on developing probe station selection and real-time diagnosis algorithms were suggested by the authors for the considerations.

B. Distributed/ Scalable Monitoring

Monitoring routers using WATCHERS protocol is discussed in [54] where, the protocol detects and responds to routers that drop or misroute packets by using 'flow in a network' conservation principle, that is defined as ' all data bytes sent into a node, and not destined for that node, are expected to exit the node'.

A distributed network monitoring structure for high speed broadband network is considered in [55] to solve the problems, such as tapping point, packet loss on NIC, packet loss on bus, processing performance and recording performance.

Aggregation and refinement based monitoring (ARM) mechanism [56] is used to reduce the amount of information exchange between network nodes. Collection of data from network nodes using a dynamic QoS data aggregation/refinement technique is enabled by this mechanism while processing information differently according to its measurement objectives. The scalability of this monitoring framework, in monitoring network QoS, can be configured to run with diverse objectives and it has achieved considerable reduction in overhead and scaled fine over a broad range of traffic loads. A distributed network traffic monitoring system based on embedded NetFlow hardware and software engines was designed and implemented in [57] where the successful system implementation was used for high speed campus network monitoring. Network movement identification, diagnosis and determination of flow control for variety of network environments have been effectively tested and resulted in overcoming the limitations from commercial NetFlow collectors. Figure 4.2 shows the basic architecture of the monitoring system. The in-depth analysis of embedded traffic monitoring solutions, performance of switch/router, routing table information, use of SNMP and flow analysis, have endeavoured future researchers to think about the developments on different areas of network monitoring, such as detailed characterization of packet flows, itemised audit, intrusion detection on many levels, etc.

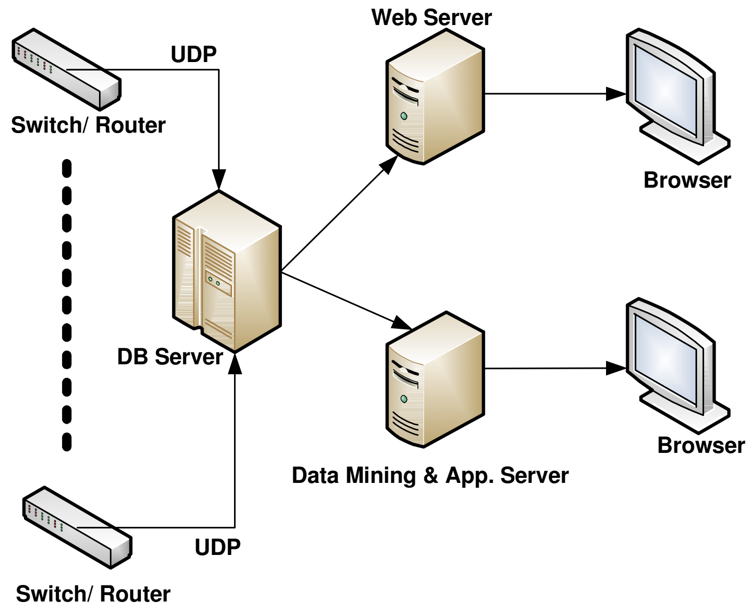

Figure 4.2: Components of the flow monitoring system [57]

The SNMP protocol was implemented in OPNET Modeler and the integration of real network components into OPNET Modeler Co-simulation process was realised in [58]. The architecture of the evaluation test-bed is shown Figure 4.3. This architecture enables the real environment to interconnect with the simulation environment using the SNMP messages through the external system (ESYS) interface.

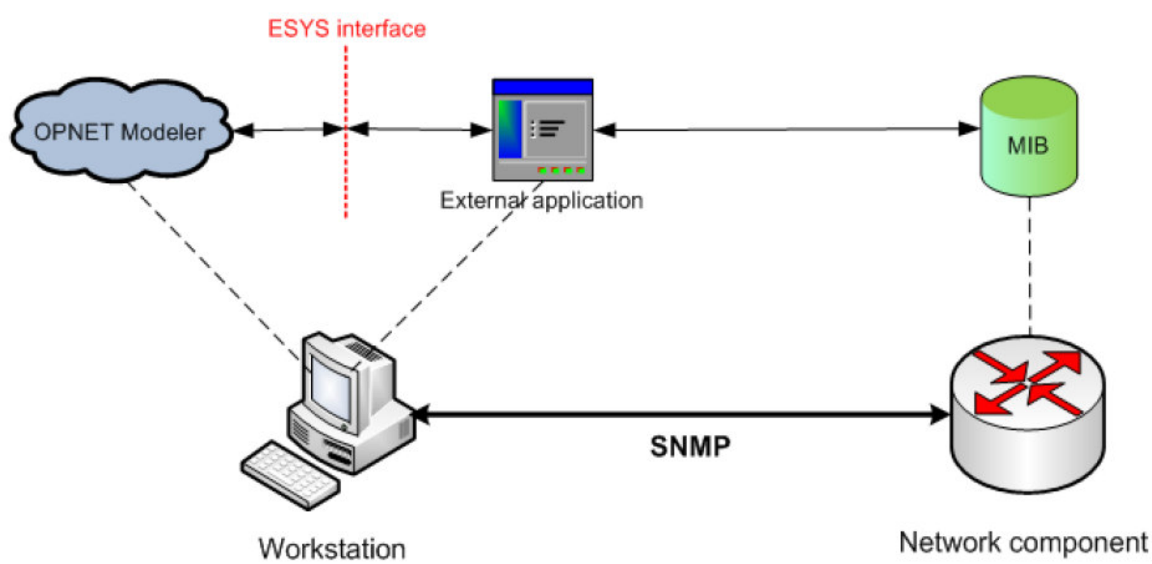

Figure 4.3: Architecture of the evaluation test-bed [58]

Providing network monitoring support in the application layer for QoS policies is discussed [59] by using scalable network monitoring service for real-time applications. The identification of traffic created by bandwidth intensive applications is based on monitoring utilization on network devices.

C. Passive network monitoring

A comparison of passive network monitoring of grid application traffic with active probes is discussed in [60] where a prototype for 'Wren' bandwidth monitoring tool for measuring timely available bandwidth was developed. The technique uses passive measurement when the application is running and active measurements when no applications running. The evaluation of the efficiency for Wren tool is implemented for bulk data transfer traffic and distributed burst grid applications environments. Different types of traffic, including audio and video streams, measurements and analysis are performed using the passive network traffic measurement tool, AKQUI [61]. This tool collects the traffic information over a long period of time, analyses the traffic off-line and provides access to the entire payload of the traffic that enables the study of diverse protocol layers.

D. Wired network monitoring

Solutions for problems, such as packet loss on NIC and bus, processing and recording performance, in broadband network environments were discussed in [55] and a description of a structure for monitoring the network was also given. The following structure describes the solution for high speed network monitoring situations:

- Optical splitter, tapping signals from the optical fibre in broadband network
- Flow distribute, distributing the network flow to a set of low throughout channels. Efficient filter technology is used in this point
- A group of network flow processors. Each processor deals with a channel of network flow
- A data collector, collecting the data to be logged
- A set of off-line retrieval and analysis tools to provide advanced analysis

As the modern era is rapidly growing towards high speed broadband network this distributed monitoring structure motivates the research towards high speed broadband monitoring.

E. Wireless network monitoring

Wireless network technologies are growing rapidly these days and this make the development of monitoring tools for wireless networks critical.

Monitoring software for sensor network applications, NanoMon [62], in an adaptive method allows users to customize their own sensor types and custom GUI components. The widely used MySQL database is used for managing data and node information of variety of sensor network applications, and the Java language is used for making NanoMon platform independent. WANMon (Wireless Ad-hoc Network Monitoring) tool [63] is used to monitor resource usage, such as network, power, memory, CPU usages, on a wireless node where it is installed.

4.3.4 QoS Management and Monitoring

Enthrone [64] for monitoring services inside wired & wireless networks and also in user's side ensures the service performance verification related to the QoS guarantees agreed according to the SLA between the provider and the user. Measurement system, for QoS parameters for session initiation protocol (SIP) based Internet Telephony service is discussed in [65] and this system alerts telephony users in real-time when network conditions are not suitable to initiate a call. A real-time monitoring scheme, Decision Algorithm [66], combines information constantly from real-time transport control protocol (RTCP) control packets and with MAC layer's help to trigger recovery mechanism when changes in network is observed which in turn adjusts the session configurations to updated parameters to maintain the acceptable QoS.

This technique consists three phases monitoring, adaptation and recover phases. Generation of more RTCP packets during abnormal situation can introduce extra traffic on the network which may result in QoS degradation.

4.3.5 Real-time Applications

The *Clearing House* policy architecture for regulating and controlling resource allocations to diverse groups of traffic for providing QoS management is discussed in [67]. Future works on studying experimental result have to be carried out to validate this model to show that it can improve the flexibility and assurance while high level of network utilisation is maintained. A portable bandwidth intensive QoS monitor tool, p3m [68], is designed and implemented to analyse the stream packets in the kernel space and to support greatly reducing resource requirements by optionally storing the multimedia packets of interest. The p3m tool has been implemented to monitor campus network and use of the tool in monitoring QoS in public internet continues. Implementation of QoS management in internet protocol (IP) networks using software based agents for QoS management in response to variations of user, customer application requirements, and of the network state is realized in [69]. An simple network management protocol (SNMP)-based Visualisation Monitor, SVM, for QoS monitoring by accessing QoS MIBs in DiffServ routers is implemented in [70] where the design of SNMP-based monitoring system is described to support omnipresent access and real-time visualisation of traffic flow, using low-cost tools. Monitoring arbitrary object IDs (OIDs) and classifying OIDs into graphs and logs are suggested as future works. An Adaptive Class Switching Algorithm (ACSA) [71], for real-time bandwidth intensive applications under the DiffServ environment provides good QoS and price based on QoS feedback and user utility.

In congested network state the perceived QoS in the DiffServ environment is not guaranteed, even for priority class with higher rank. In some cases the higher price class may not be able to provide better QoS than the lower price class and this situation may violate the SLA agreed with the user.

4.3.6 Network Protocols

Network protocols play a major part in developing applications monitoring tools from basic to high level implementations. Better understanding of these key protocols provides huge benefit in defining the initial prototype, which provides the foundation for the required tool. Following section on network protocol overviews the most prevalent protocols and summarises the key features of them.

A. SNMP

Communicating management information between managing entities, agents, managed devices and managed objects in a structured method is carried out efficiently by the SNMP.

Trap message: Generated when exceptional changes happen and notified to the managing entity about the kind of change [72]. SNMP uses Management information base (MIB) for storing computing information

B. RTP/RTCP

In real-time interactive applications the importance of real-time transport protocol (RTP)/RTCP combination is highly appreciated as the implementation of these protocols are prevalent in industries and academic areas. The IETF and ITU standards bodies have been working for long time to make these protocols interoperable between new and forceful products with independent companies.

RTP: This is an IP-based protocol and widely used for providing the support for the transport of real-time multimedia applications (video, audio, etc.) [73]. RTP services include:

- Time reconstruction (time stamping)
- Loss detection (sequence numbering)
- Security and content identification

RTP does not [74]:

- guarantee QoS for Real-time services
- guarantee packet delivery
- make sure timely delivery of packets
- prevent out-of-order delivery
- include any flow control mechanism

Integration of RTP and UDP bring forward an intelligent feedback control scheme [75] to analyze RTP data packets and to compute packet loss rate using the RRs from the client to guarantee the video quality and real-time service. The server then adjusts rate control parameters according to the current network status to produce a reasonable video resolution which is acceptable by the end user. Considering transmission delay to get an ideal performance is suggested for future work.

RTCP: Quality of data delivery and membership information are sent to the RTP session participants periodically to communicate the service feedback. Control information is carried using the following 5 RTCP packet types [73]:

1. **RR**-Receiver report (Quality feedback about data delivery, highest packet number received, amount of lost packets, inter-arrival jitter and timestamps)
2. **SR**-Sender report (reception quality feedback, sender information section, inter-media synchronisation information, cumulative packet counters and amount of bytes sent)
3. **SDES**- Source description items
4. **BYE**- End of participation
5. **APP**- Application specific functions

RTCP services include:

- QoS monitoring and congestion control
- Source identification (user's name, telephone number, E-mail, etc.)
- Control information scaling (adjusting the RTCP generating the rate according to the number of participants and limiting the control traffic to 5% of the overall session traffic)

S-RTCP [76] is an enhanced hierarchical structure for improving the shortcomings from the traditional RTCP in a multicast environment. Grouping of members in a multicast to form local regions, summarizing RRs from the local members using the Aggregator (AG) and sending this summary to the upper manager for decision making are some main functions of this scheme and they enable the manager to monitor the transmission quality and to recognize high congestion regions.

C. Resource Reservation Protocol (RSVP)

End-to-end QoS request can be made by the receiver using the RSVP during the data flow between the end devices. RSVP provides best-effort and Real-time services where it reserves the essential resources, for Real-time services, at router for providing availability of bandwidth during the transmission along data stream paths [73]. Providing requested service by maintaining router and host states and negotiation of connection parameters between routers are some of the RSVP's responsibilities.

D. Real-Time Multimedia Transport Control Protocol (RTMTCP)

A new technique for real-time data transmission over transport network layer is implemented in [77] and this method uses feedback and priority weightings for determining the packet transport over the network. The improvement over the current RTP and RTCP proves that RTMTCP achieves same QoS, bandwidth requirements and maximum number of calls at the worst case scenario. The following concepts were investigated to improve the QoS using RTMTCP:

1. speech packet loss probability
2. priority weighting
3. new network states
4. new flow/congestion control mechanism

Comprehensible understanding on the above protocols provides firm groundwork on developing an efficient prototype and then implementing this on software. Clearly, the RTP/RTCP combination has great potential on identifying and providing QoS related information and controls over the RTRM applications monitoring with required QoS.

4.4 Design and Implementation of the Test-bed

A number of QoS monitoring tools were investigated during the initial phase of the design and are briefly described in the following section.

A test toolkit to evaluate the streaming server's performance is discussed in [79] however the network application level performance monitoring is not considered. Adaptive forward error correction based streaming using real time streaming protocol (RTSP) and RTP is discussed in [80]. Monitoring of these streaming applications was not considered in that research and this creates an opportunity to concentrate on RTRM applications monitoring based on QoS parameters. Using only packet loss rate information to send receiver reports to Server and adjusting coding rate and video resolution according to this information is analyzed in [81]. A QoS monitoring system for IP telephony to evaluate network quality and to create reports for SLA analysis has been analyzed to alert the users in real-time about varying network conditions [82]. The technique proposed in [82] can be used for multimedia applications. Four main principles, packet classification, degree of isolation among traffic flows, use of resources (link bandwidth, buffers)as efficiently as possible and call admission process depending on available resources, are discussed [72] in detail for providing QoS guarantees to multimedia applications. End users are more conscious about their experienced service levels during any conferencing. If the agreed QoS is not met then the SLA is violated. But the violation could be from end user, such as, not conforming to the negotiated traffic profile, congestion due to various computational processing delays hence RTP [83] packets may receive low level priority over the other normal packets. As DiffServ based routers are very common these days, packets based on their priority markings might receive differentiated services. When the high burst occurs in the router, oncoming RTP packets might be marked differently hence packet delay and packet loss are more likely to occur. Some newly emerging technologies such as Multi-protocol Label Switching (MPLS), QOSPF, etc. make the routing selection more intelligent. The network congestion can be ignored when calculating the packet delays [84] as there is enough bandwidth to avoid this congestion. The additional processing delay in the Client due to packet discarding with various other processing delays causes significant contribution towards the packet delay in the receiver (Client) side.

The proposed technique in this project is to identify a mechanism to monitor the QoS for real-time video/audio conferencing in a flexible and innovative way by reducing the computational processing delay in end systems. Therefore this tool will identify RTP packets from other packets and process them separately to eliminate unnecessary delays for network application. The QoS parameters will also be stored for real time and future analysis to resolve any network application issues.

4.4.1 Design of the Test-bed

The initial literature review and analysis about different monitoring tools for multimedia applications led to the proposed software based test-bed development. Initial test-bed was designed based on a simple Client-Gateway-Server architecture using Java programs [85]. The Gateway was designed from scratch to simulate the network conditions and to capture specifically all RTP packets during the streaming. The emulation of the Gateway is an important part in this test-bed to define and control the performance of the application by introducing delay and packet-loss to the packets being transferred between Client and Server. This emulation considers the transmission of video using the RTSP protocol and uses an example 'movie.Mjpeg' file for transferring the frames upon the request from the Client.

This Client, Server and Gateway programme can be run in three different hosts to emulate the real network environments and the required modifications to the Gateway can be done during the transfer of the video file to change the network conditions such as introducing delay, packet-loss and jitter.

It has been deduced from the initial literature review process that the available QoS monitoring tools embed different functionalities within them to monitor several applications at a given. This introduces extra processing overhead for each of the services which result in additional performance degradation for some or all of the services being monitored. Dedicated QoS monitoring tool is the apparent solution to this issue. This has been the driving factor, as highlighted within the literature review, behind the development of our QoS monitoring tool. This tool includes the following features:

- Real-time delay, packet loss and jitter displays
- Off-line analysis can be carried out using the data stored in separate files
- Reduced processing overhead in the intermediate nodes
- Less memory required for the programme
- Easy to install with the Java environment
- Capable to create many Gateway modules for routing packets to several nodes

The following section provides more information about the design and implementation of our monitoring tool.

The design of the proposed QoS monitoring tool is described under this section.

RTSP [86] is used to control the Client, Gateway and Server Application Programming Interface (API) where TCP is used as the transport protocol. UDP is used to transmit the RTP packets during this streaming to meet the timeliness of the packet delivery to the end user (Client).

The Client can issue commands such as, Setup, Play, Pause and Stop, to stream the video from a Server according to the user's requirements. The user has to specify the location, port number and the media name to stream the video application in real time. The three programs, Client, Gateway and Server, can be installed in one computer or in different computers depending on the application requirement. For this implementation these programs are used in two different computers within Brunel University's LAN. As there were security restrictions on accessing the computers from outside the Brunel LAN, the initial testing was carried out within Brunel LAN.

4.4.2 Test-bed Implementation

Figure 4.4 illustrate the basic network configuration for the real time video streaming application during the test-bed implementation.

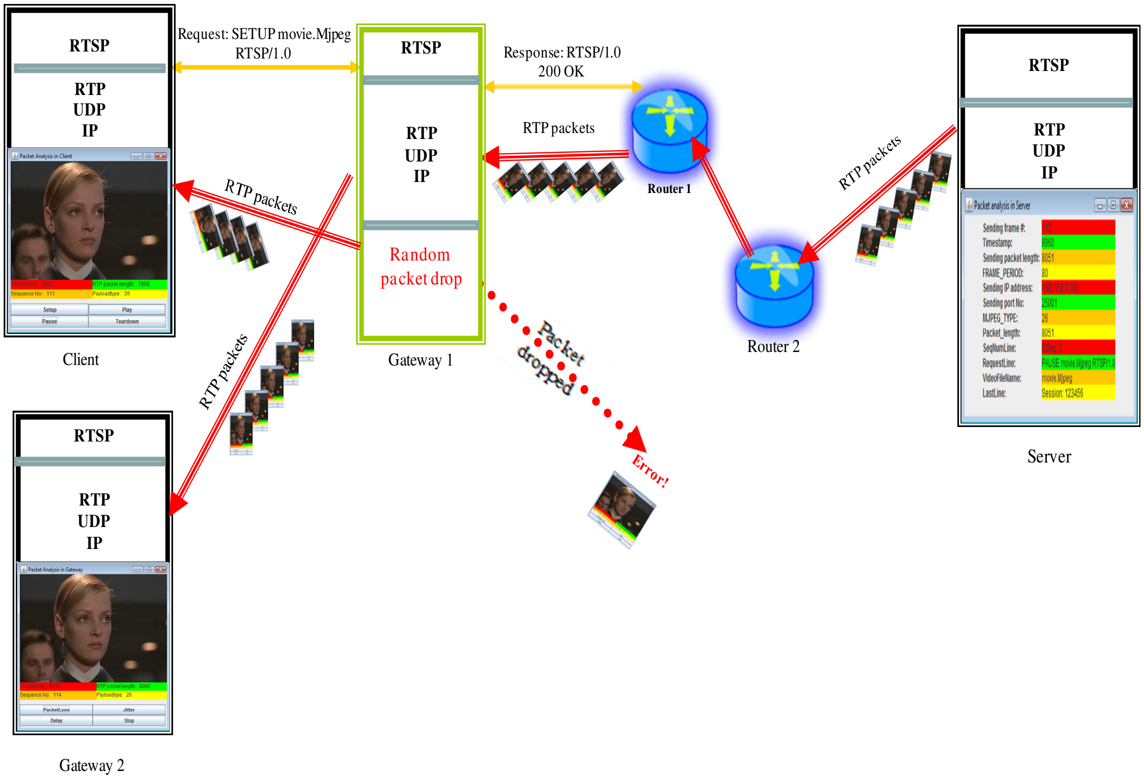

Figure 4.4: Network Configuration for the Test-bed implementation

A more simplified diagram is also shown in Figure 4.5 and it describes the LAN configuration of this test-bed implementation. Different components of this LAN configuration are described in the following sections.

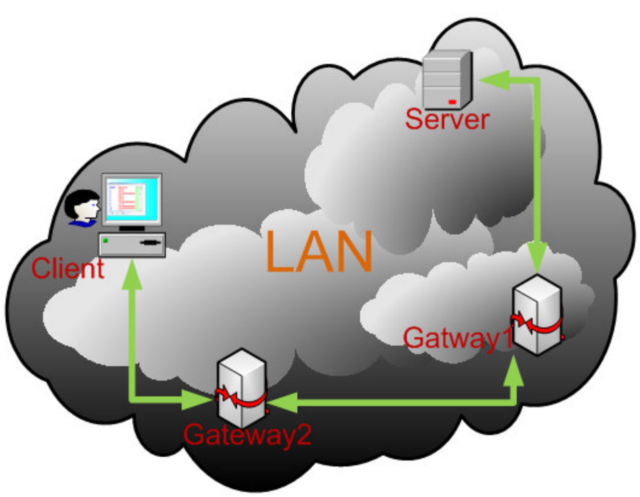

Figure 4.5: Basic Test-bed LAN Configuration

A. Client

The end user is the Client in this configuration and streams the video file from a Server using the RTP protocol. If the particular video file exists on the Server side, the user will receive an RTSP 'Ready' response message. This is done using the Setup button on the Client and an RTSP/TCP connection will be established between Client and Server. But the actual video data are transmitted using RTP/UDP/IP combination as a real time application.

The following code is used within a batch file for convenient configuration of the Client side of the video streaming application.

----

javac Client.java

java Client %IP% 6666 movie.Mjpeg

The first line of the code compiles the Client.java file. Once the compilation is successful the second line will call the IP address (%IP%) of the PC where the Server program is running and assign a port number (6666) with the relevant video file name (Ex. Movie.Mjpeg) to be streamed from the Server. Because the Client and Server are running on the same PC the IP address of that PC accessed using the %IP% method. It will wait for the response from the Server to set-up the complete streaming application. If a positive response is received to stream the required video file it can select the 'Play' button to stream the video and can use 'Pause' button to pause the video at any time. This interactive mechanism highly depends on the established communication between the Client and the Server, and the allocated communication resources will have an effect on the perceived QoS of the streaming application. Therefore, monitoring the QoS parameters in real-time while streaming the video is an added advantage which will help the user to compare the objective QoS performance with the subjective measurement values such as packet delay, jitter and loss as seen in Figure 4.6.

This will help the end user to decide whether the user wants to continue viewing the video or to tear it down using the 'Teardown' button to join at later time. The number of parameters watched in the real-time on the Client window can be adjusted according to the user requirements. For example, there are 8 different parameters are watched in real-time as shown in Figure 4.6 and this number can be adjusted.

The user can control the actions from the GUI, Figure 4.6, by selecting appropriate buttons from the Client GUI. The Client will extract the RTP packet from the received UDP packet and the media information is then extracted from the RTP payload for playing or storage purposes. Figure 4.6 illustrates the GUI for the Client side that enables the Client to control the streaming of the video using the Setup, Play, Pause and Teardown buttons. The information displayed on this GUI is stored in files for off-line analysis and this may help to detect patterns for QoS related issues using historic data over a period of time under various congestion conditions. The off-line data is stored using the text files and can easily be viewed using the Excel spreadsheet for further QoS performance related studies in future.

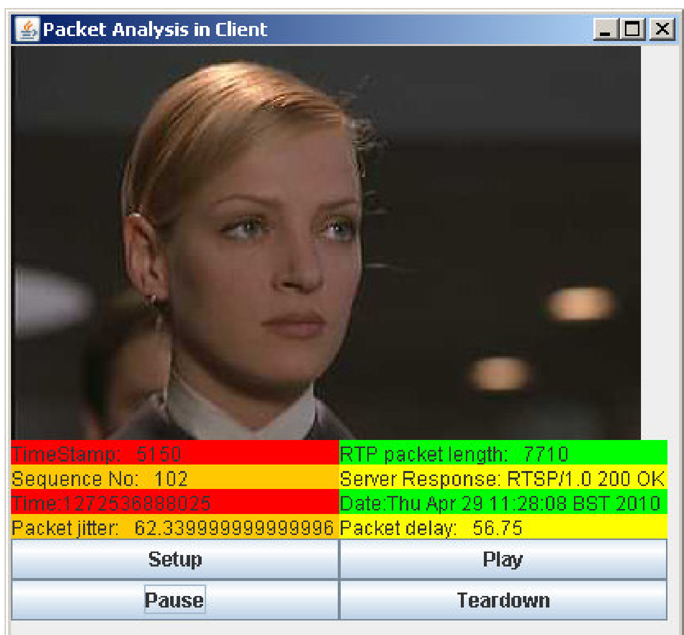

Figure 4.6: RTP packet analysis in Client

B. Gateway

The Gateway program is configured in a way so that it can use both active and passive monitoring of the streaming application. Because the Client and Server are configured to exchange the control and data packets through this Gateway the packets can be interrupted to active monitor the status of the application. If the application should not be interrupted then the passive monitoring can be used. For the passive monitoring, the packets passing through the Gateway is duplicated and the QoS parameters are evaluated separately to minimize the effects on the original packets.

The Gateway is configured using the following code which is inside a batch file. The first line of the code compiles the RTSPGateway.java file and if the compilation if successful the second line is implemented. The second line requires 3 inputs which are two IP addresses and packet loss rate. In this example, the two IP addresses are the same as the Client and the Server are in the one PC during the video streaming and the packet loss rate is set to 0.5 (50% of the packets will be dropped). The first IP address is used to listen to the connection from the Server side and the second one is used to send the packet to the Client or any other nodes. A random number is generated and compared against loss rate to decide whether to introduce any packet loss or not. If the random number is less that the loss rate then the packet drop will be introduced and this will result in QoS performance degradation at the Client side. This loss rate can be allocated depending on the network condition. For a highly congested network condition a larger loss rate and for a less congested network a smaller value can be allocated.

```
javac RTSPGateway.java
java RTSPGateway %IP% %IP% 0.5
```

In order to simulate the real network conditions, packet drop and additional network delays are introduced to the original RTP packets within this Gateway1 and the modified RTP packets are then sent to the Client. Duplicate RTP packets can also be sent to the Client for testing the objective quality of the streaming application and significant performance degradation can be perceived by the end user.

Video streaming between Client and Server is monitored using the Gateway1 program which is designed to read the RTP packets and extract the relevant information, such as time stamp, sequence number, payload type, etc., from the RTP packets for monitoring purposes. This information is then used to calculate the QoS parameters to evaluate the performance of the streaming application. These parameters are then displayed in the Gateway1 GUI window in real-time as shown in Figure 4.7.

Gateway1 also sends the RTP packets to Gateway2 without any modifications to compare the effect of modifications in Gateway1 with and without additional packet loss and delay. Figure 4.7 illustrates the GUI for Gateway1 where the QoS parameters can be viewed in real time while the video is streamed by the Client. This information is also stored at this Gateway1 for off-line analysis. Gateway1 also acts as a multicast node which sends the packets to many nodes in the network configuration for QoS comparison purposes. Gateway1 can also route the packet to any other nodes within the network if the IP address and the port number are provided hence it acts as router under this scenario.

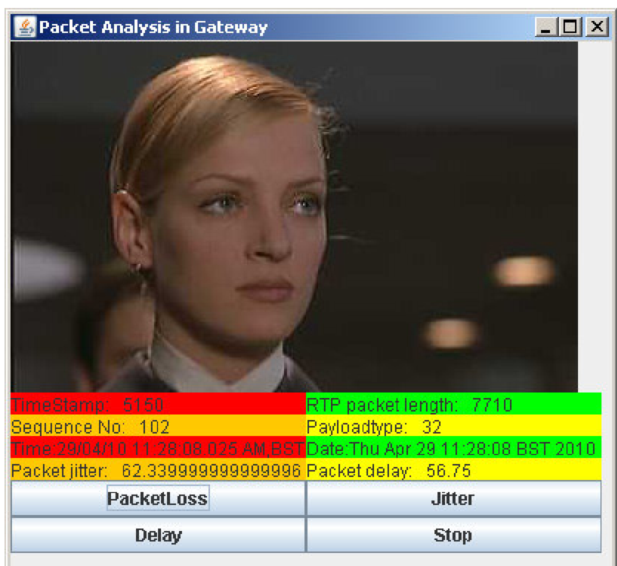

Figure 4.7: RTP packet analyses in Gateway

The different buttons in the Gateway1 GUI is used to display different QoS parameters (Packet delay, loss and jitter) in real-time and the ‘Stop’ button can be used to terminate the video streaming application at any time. This functionality is useful for the network administrators as they can choose to allow or deny the particular application on the network by just using the ‘Stop’ button. If the network administrator is using this Gateway1 GUI, see Figure 4.7, they can view the statistics for the full session of the streaming by just clicking the ‘PacketLoss’, ‘Jitter’ or ‘Delay’ buttons where a separate window will open with all the past QoS parameters in order of the record as can be seen in Figure 4.8. This functionality is very useful for the network administrator to evaluate the performance the particular application in real-time and to decide whether the network performance is at acceptable level. If several applications are running in parallel then the administrator can prioritise the applications to allow or deny the continuation of the application depending on the time varying network conditions. If the network condition is deteriorating significantly then the corrective action can be taken by stopping the low-priority applications first and then the high priority ones.

Figure 4.8: QoS Parameters Display at Gateway

If the network condition is improved when the low-priority applications are stopped then the QoS for the high performance applications can be maintained to satisfy the high priority customers. While monitoring the network condition further it can also help the administrator to notify the low-priority customers about when they can initiate their application again. This fast response from the administrator is useful for the end users as they know what goes wrong in the network when their applications experience unacceptable performance degradation. This spontaneous human (administrator) interaction can be automated to reduce the delay introduced by human actions in the real network environment so that the end user will not be able to notice any delays during the correction actions.

C. Gateway2

Gateway 2 is used to introduce another node in the network to realise more realistic network configuration. Because the packet delay, loss and jitter parameters can significantly be affected during the real streaming scenario and the packet will have to travel using many hops (through several routers/gateways), the Gatewa2 acts as a node in this network to introduce delay, to drop packets and to store QoS related information at that node for further off-line analysis in future. Gateway2 also displays the video stream without any modifications from Gateway1. Gateway2 program is required only for the simulation purposes to compare the quality of the video streaming between the modified and non-modified video streams. In the real time application environments the packets will be dropped randomly during the transmission and the loss can occur anywhere between the Client and the Server. But when using this simulation environment, packet loss is introduced in a particular area where the Gateway2 program is installed. Although these gateway programs are installed on one computer for testing purposes, they can be deployed in different nodes on the network configuration for real application purposes.

D. Router

Router is a multipurpose element in network and the packet forwarding mechanism helps to solve many issues regarding packet delay, packet loss, priority marking, etc. Packets have to be distinguished in order to transmit them according to their specified priorities. The routers should be able to route the RTP packets to the specified ports of the end points so that the required monitoring can be done as configured. The identification of the RTP packets can be done using the payload type in the UDP packets.

When the router detects any incoming RTP packets it will route those original RTP packets or the copy of them, to the monitoring area for further analysis hence the burden of packet processing in the router is reduced hugely and the delay experienced by the normal traffic is considerably minimized. For this network configuration we consider the router as intelligent and flexible network component for identifying RTP packets and forwarding them to appropriate node in the network for further processes. The proposed test-bed considers the Gateway as a router which forwards and processes the RTP packets for extracting the required QoS parameters.

E. Server

The Server is hosting the video streaming application and the Client can stream the video by specifying relevant IP address and the port number. The RTP packets are generated on the Server side using the following rule. The specified media is encapsulated within an RTP packet, this RTP packet then put inside UDP and finally that UDP packet is wrapped within IP for transmission over the Internet. There are two other programs, processing video content and generating RTP packets, for the specified video file processing and these programs abide by the RTP format defined in RFC 3550. In real environment RTP packets could be created using different mechanisms depending on the type of codec being used on the end user (Server). Figure 4.9 shows the Server GUI used for real-time monitoring of the video streaming application.

The Server also stores the QoS parameters of the streaming application in a text file for off-line analysis. This information can then be used for comparison between different servers to identify any common pattern of QoS related issues to the Server side for the required real time rich media (RTRM) application. A range of server platforms can process the video/audio applications differently hence the packet processing time may vary. These effects can easily be analyzed using the files which stored the required QoS information. There are number of parameters being monitored at the Server side as shown in Figure 4.9. These parameters can be used to identify the status of the streaming application by looking at sending frame, timestamp, sending IP address and port number, sequence number and many other parameters.

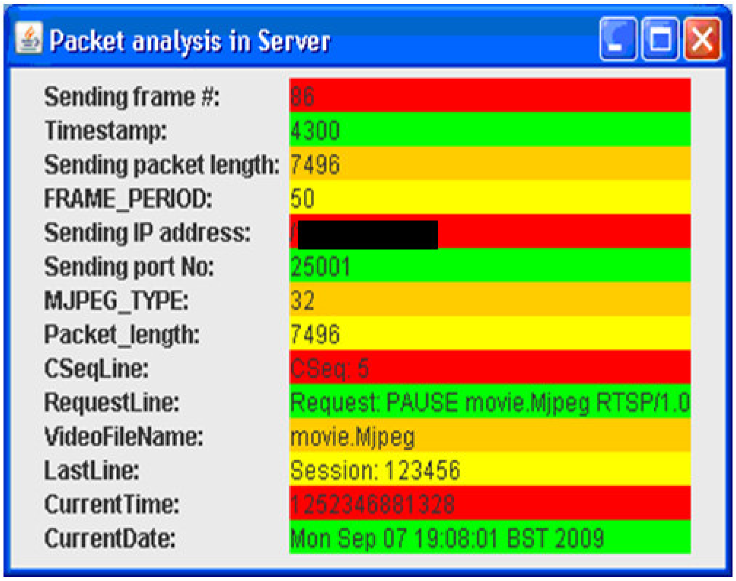

Figure 4.9: RTP Packet Information in Server

The following code is embedded within a batch file for convenient Server side configuration.

----

javac Server.java

java Server 6666

The first line compiles the Server.java file and if the compilation is successful the second line will be executed to listen to any connection from the Client on the specified port number (6666). If the connection is established successfully then the Server will communicate with the Client using RTSP for control commands and will send the raw video data using the UDP. Whenever a control command (Play, Pause, Stop or Terminate) issued from the Client, the Server will act accordingly. When the 'Terminate' command is issued by the Client, the Server will terminate the streaming application by closing the port.

4.5 Evaluation of QoS Parameters

The evaluation of different QoS parameters (packet delay, packet jitter, packet loss and packet sequence) is carried out in detail in the following sections for the example video streaming application used within this test-bed.

4.5.1 Packet Delay

Multimedia applications are sensitive to packet delay hence importance should be given to optimise the end-to-end packet delay especially for the video applications because the visual quality degradation is easily noticeable in video applications rather than voice applications. The acceptable delay for audio and video should be less than 150ms [44] and should not be higher than 400 ms as per the ITU-T Recommendation. The commercial level targets for maximum or allowable packet delay may vary depending on the SLA agreement with the end user and the criticality of the business environment of the customer. Certain critical business environments may require the packet end-to-end delay to be in micro seconds and the network operators should be able provide this level of QoS by using dedicated communication medium such as fibre optics for fast data transmission. Then the trade-off between the cost and QoS should be studied carefully to find an optimum SLA agreement so that both parties (service provider and the customer) can abide by this.

Therefore, evaluating the end-to-end delay for the video streaming application and displaying this delay in real-time will provide valuable support for the network administrators when designing or monitoring the network conditions in real-time.

For this test-bed, the packet delay between two RTP packets, D(i, j), is calculated using Eq. (1).

$$\mathbf{D(i, j) = (R(j) - R(i)) - (S(j) - S(i)) = (R(j) - S(j)) - (R(i) - S(i))} \qquad \text{Eq. (1)}$$

Where Ri & Rj are the time of arrival in RTP timestamp units for packets i & j respectively. Si and Sj are the RTP timestamps from packets i and j respectively [83].

Using UDP instead of TCP to transport RTP packets is more suitable for time sensitive applications such as audio/video applications. The trade-off between the reliability and timeliness has to be considered carefully when deciding the transport layer protocols (TCP/UDP). The channel environment is not 100% guaranteed for reliable transmission, especially over the internet. Therefore, packet loss is more likely to cause QoS degradation under various channel conditions. TCP enables the reliable delivery of packets to the destination using the retransmission mechanism. This will cause considerable delay in the packet delivery hence time sensitive applications may not fully satisfy the SLA. Recovery of the lost packets is down to the efficiency of the type of codec been used at the end user. Certain codecs are very efficient in compensation based techniques which could replace the lost packets with duplicate packets.

4.5.2 Packet Jitter

The variability of packet delays within the same RTP packet stream is known as packet jitter and the packet jitter cancellation (using de-jitter buffer – the buffer rearranges the timely order of the packets [44]) can be used at the end user to minimize or neutralize this effect at the end systems. A detailed study has been carried out in [87] where the cause of jitter, how to measure jitter and how to compensate jitter in packet voice networks are discussed. It has been widely discussed and proposed that the jitter value of less than 30 ms is acceptable for audio or video but a persistent value of 30 ms for longer period may cause severe performance degradation which can be noticeable by the end user. Therefore the corrective measures to reduce the effect of jitter in audio or video should be taken to keep the jitter below the target level (this is mostly between 0-30 ms).

Even though the packets are generated periodically with equal time difference between them from the sender side (Server), the variability of the path they take during transmission, causes the packets to arrive with variable time difference at the receiver end (Client). The congestion in the link between the end points of a conferencing is also a significant cause of unacceptable packet jitter.

The packet jitter, J, is calculated as per the RFC 1889 recommendation [83] as shown in Eq. (2).

$$\mathbf{J = J(i\text{-}1) + (|D(i\text{-}1, i)| - J(i\text{-}1)) / 16} \qquad \text{Eq. (2)}$$

where, J - Jitter and D (i-1,i) is the difference in delay for the current packet and the previous packet in order of arrival (not necessarily in sequence). D(i-1, i) is calculation using the Eq. (3) as per RFC 1889 recommendation [83]:

$$\mathbf{D(i\text{-}1,i) = (R(i) - S(i)) - (R(i\text{-}1) - S(i\text{-}1))} \qquad \text{Eq. (3)}$$

The maximum packet jitter value can be used to analyse the performance of the network and required corrective actions can be taken to resolve the cause of any unacceptable packet jitter. If the time of this occurrence is stored and compared with any abnormal performance of the network then the cause can be deduced easily to reactively or proactively act if this problem arises in future.

QoS parameters are calculated at different nodes in the network (Client, Gateway or Server) and stored as text files for future analysis; therefore the pattern of the problem can be identified using these historical data to predict any future problem situations and to act proactively instead of reactively.

4.5.3 Packet Loss

Multimedia applications can tolerate certain level of packet loss but the timeliness of the packet delivery is important to maintain the real-time requirements. There is close relationship between the packet loss and the jitter. It was observed during the experiment that when there is higher packet loss introduced there is high jitter for certain period. Therefore, minimising the packet loss will result in jitter minimization.

Packet loss is calculated by comparing the expected number of packets and the actual number of packets received as shown in Eq. (4).

Packet Loss = Expected packets – Received packets Eq. (4)

Where,

Expected packets = Highest SeqNum – First SeqNum

Received packets = Count of total packets arrived

SeqNum: Sequence Number

Detecting packet loss is not easy when using UDP because of its connectionless transmission therefore, RTP helps to detect packet loss using its sequence number characteristic. Therefore, by monitoring the sequence number of the RTP packets any loss of packet can easily be detected. This can also be checked in real-time using the Gateway GUI and selecting the relevant QoS parameter command. The 'QoS Parameters' window will display the SeqNo column (1^{st} column) and any missing sequence number can be located.

Main causes for packet-loss are due to buffer overflow in routers, bit errors in transmission medium, etc. Instead of waiting for the retransmission of the lost packet, packet recovery mechanisms can be used to recover the sent information on the receiver side. There are number of compensation techniques to overcome this problem in video/audio coding methods. But huge rate of packet loss may cause unacceptable degradation on the quality of the perceived application due to the loss of some prediction information. In video coding the motion compensation is done by predicting the upcoming packets using the previous packets. But if the upcoming packets are also lost then the prediction of the future packets could be inefficient. This method might work for video applications but when it comes to audio this loss may cause considerable degradation on the receiver side hence may violate the agreed SLA.

The packet loss is introduced in the Gateway using a random process and the loss rate can be defined by the user. The Wireshark monitoring tool captured the video streaming RTP packets as shown in Figure 4.10 [7] and the lost packets can be observed. The sequence number is used to detect the lost packet as seen in this Wireshark RTP Stream Analysis window. If the packet sequence is in order then the status message is ‘ok’ and if not then the message is ‘Wrong sequence nr’ as seen in the final column of the Figure 4.10.

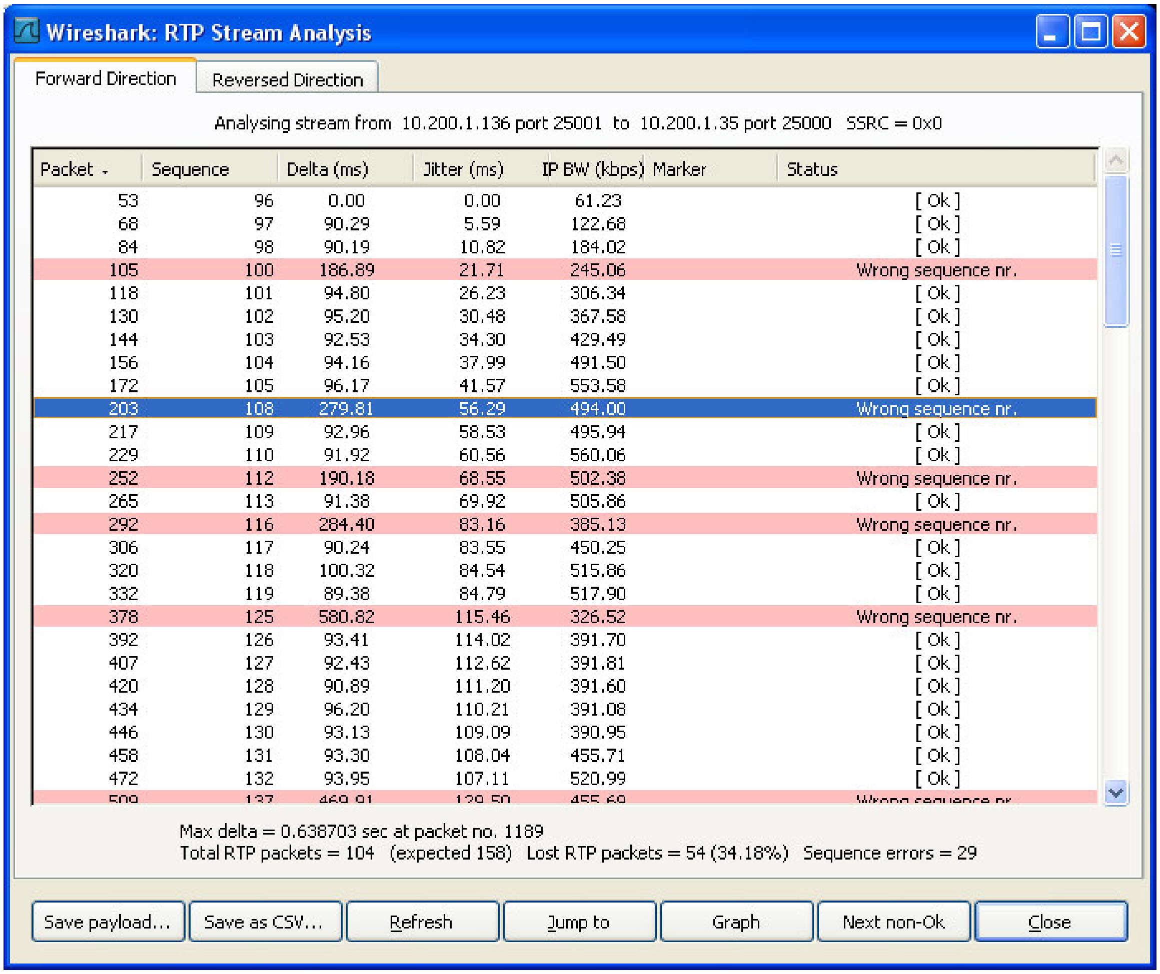

Figure 4.10: RTP Stream Analyses in Wireshark [7]

The packet drop process carried out by the Gateway can be summarised using the sample snapshot of the command window as shown in Figure 4.11 where several information regarding the video streaming application is captured. Some of these information is displayed using the Gateway GUI in real-time.

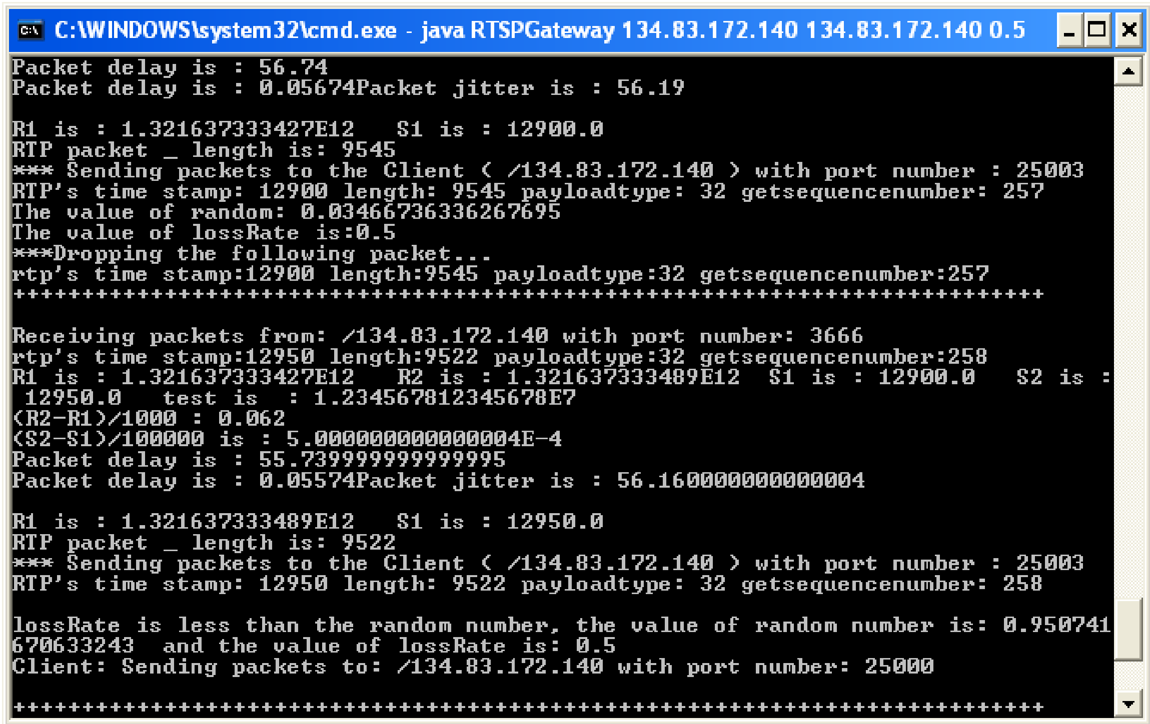

Figure 4.11: Output at the test-bed Gateway

4.5.4 Packet Sequence

Monitoring the sequence number is important in the streaming because the delivery of the packets in correct sequence is not guaranteed when using UDP. Some real-time applications, especially video, requires the packets to be in correct order so that the decoding can be carried out effectively to produce a high quality video output to the end user. If the packets start to arrive in wrong orders then the perceived quality of the video will be noticeably affected.

By checking the sequence number of the RTP packet, the packet loss can be calculated easily. The difference between the highest and first SeqNum gives the expected number of RTP packets during the transmission. The importance of the sequence number is reflected in reliability check [80] for streaming applications using RTP and also used in Eq. (4) for packet-loss calculation. Packet sequence number has been widely used in our test-bed implementation and helped to analyse the test results efficiently. If random packet loss is introduced between Client and Server then detecting the number of lost RTP packets can be made simple by using the packet sequence number. The GUIs for different nodes display the packet sequence number as part of the QoS parameters which are monitored in real-time.

4.6 Test Results and Analysis

In this section the test results for the initial simulation test-bed are presented and compared against the Wireshark monitoring tool under several scenarios. The test-bed is packaged as a batch file and can readily be run on different computers without any major modifications to the source code for evaluating the QoS performance of the RTRM application. The proposed monitoring tool captures the RTP packets between the Client and the Server, and the packets are then processed by the Gateway for analysing the QoS parameters. These QoS parameters are viewed in real-time and stored in text files for offline analysis depending on the type of monitoring required by the end user. Client may experience varying packet delay and jitter depending on the type of network the Server is located in and the number applications running on the computer during the test. Initially we have used the Brunel University LAN environment hence the delay and jitter parameters are considerably small and this may vary according to the change of network environments at different times of the day. Packet delay and jitter analysis are compared against the 'Wireshark' open source monitoring tool.

Several tests were carried out to evaluate the performance of the proposed test-bed against the Wireshark. The monitoring of the video streaming application was carried out using both the proposed test-bed and the Wireshark using one PC and two PCs. The packet delay and jitter calculations are carried out using the equations, Eq. (1) and Eq. (2) respectively for both tools. This ensured that the conditions for both monitoring tools were kept same therefore their performance can be evaluated correctly. The following section evaluates the performance of the proposed test-bed against Wireshark.

Only two test results are shown here for different times of the day to study the effects of the varying network conditions on the packet delay and jitter parameters. The proposed test-bed performance shows better improvement compared to the Wireshark under the packet delay and jitter analysis. Packet delay analysis is compared in Figures 4.12 and 4.13 respectively.

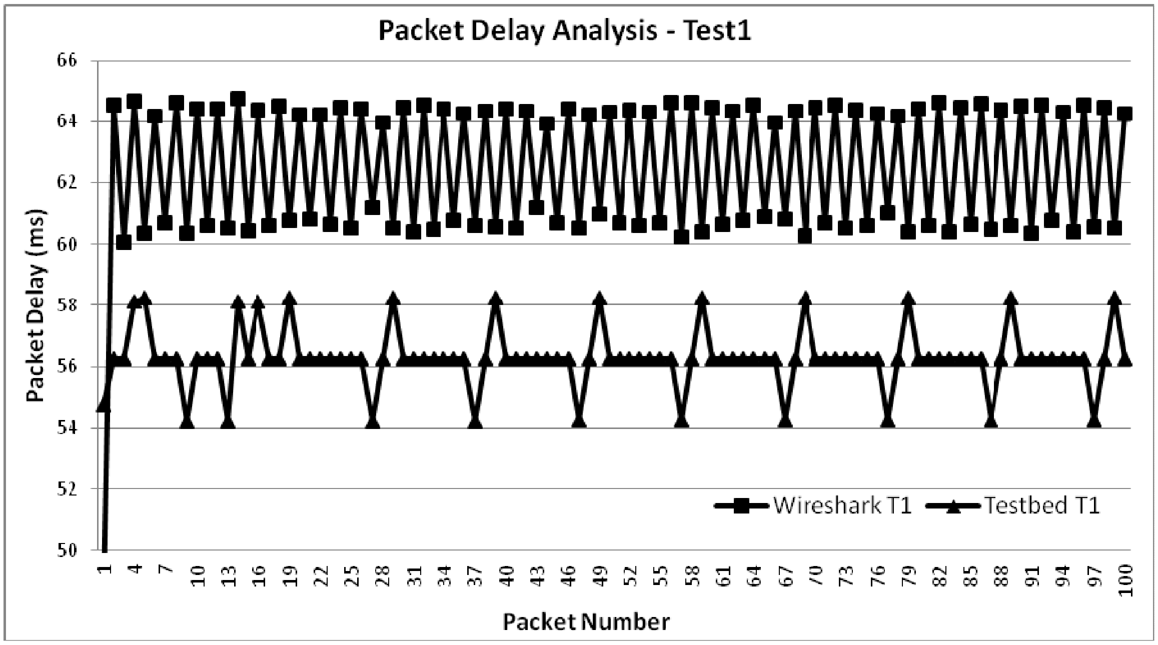

Figure 4.12: Comparison of Packet Delay Test1

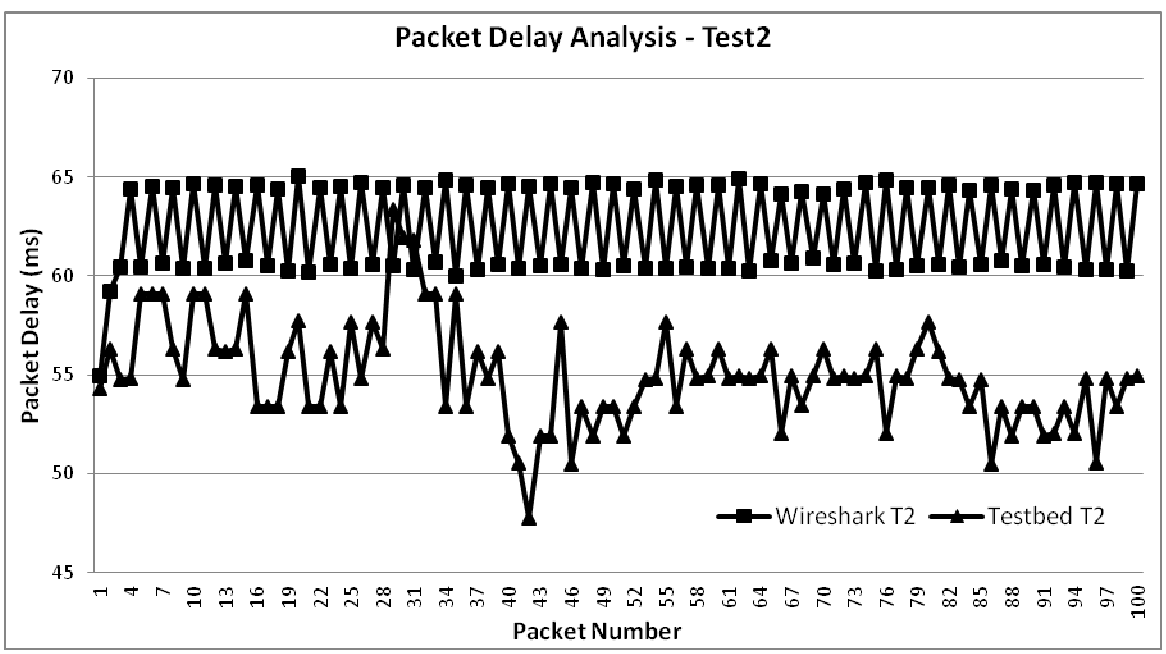

Figure 4.13: Comparison of Packet Delay Test2

Packet jitter analysis is demonstrated using Figures 4.14 and 4.15 respectively. Three different test cases are carried out under varying load conditions on the Client and Server configuration on two different PCs.

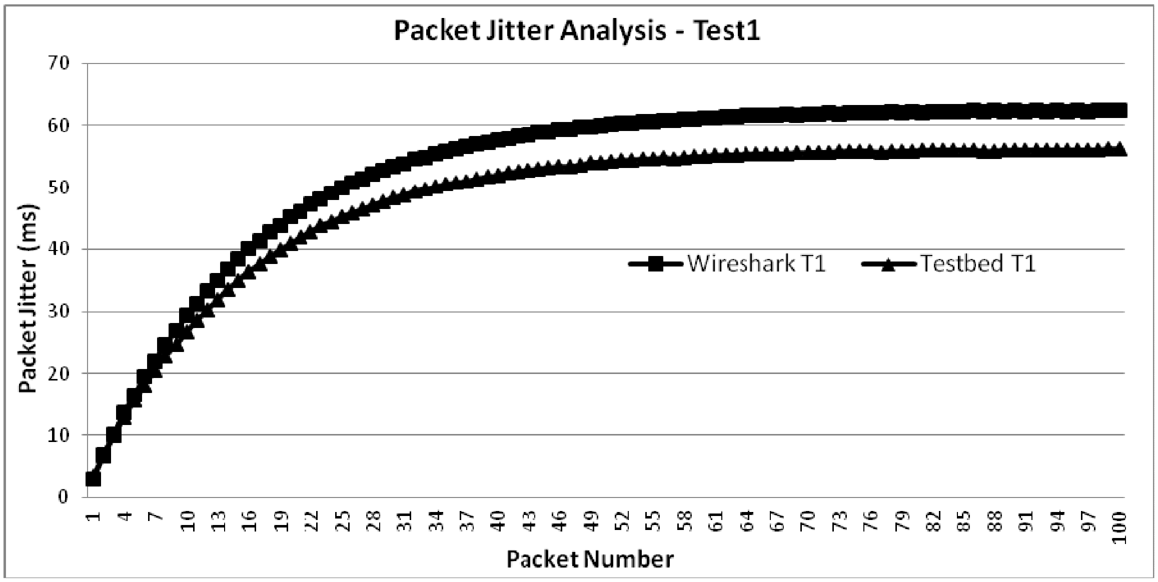

Figure 4.14: Comparison of Packet Jitter Test1

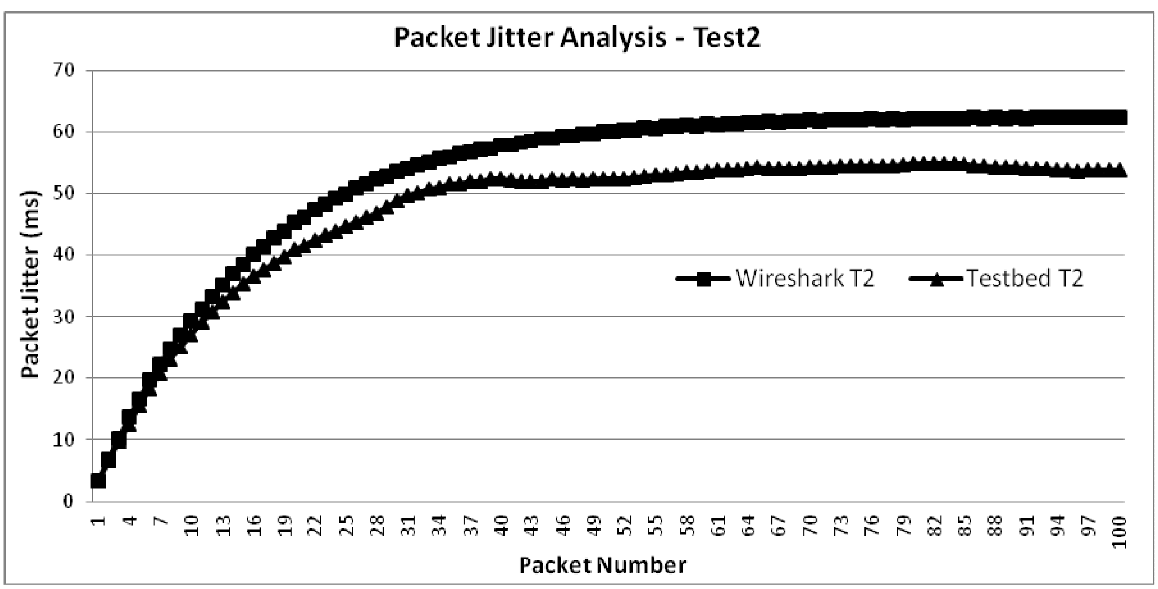

Figure 4.15: Comparison of Packet Jitter Test2

Further analysis was carried out to test the capability of the proposed test-bed using one PC and two PCs scenarios. When using the one PC the Client, Gateway and Server programs were run on the same PC and the relevant QoS parameters were measured to evaluate the performance. Then the Client was placed on one PC and the Gateway and the Server were placed on another PC for testing the similar performance criteria.
Figure 4.16 shows the packet delay effects when using one PC and two PCs scenarios where the two PCs scenario experienced noticeable packet end-to-end delay compared to the one PC scenario. The end-to-end delay is still within the acceptable delay threshold (150-400 ms) therefore the objective or subjective quality of the video streaming application was not affected distinctly. There were totally 500 packet numbers but figure shows only up to 50 of them because to demonstrate the results clearly on a graph.

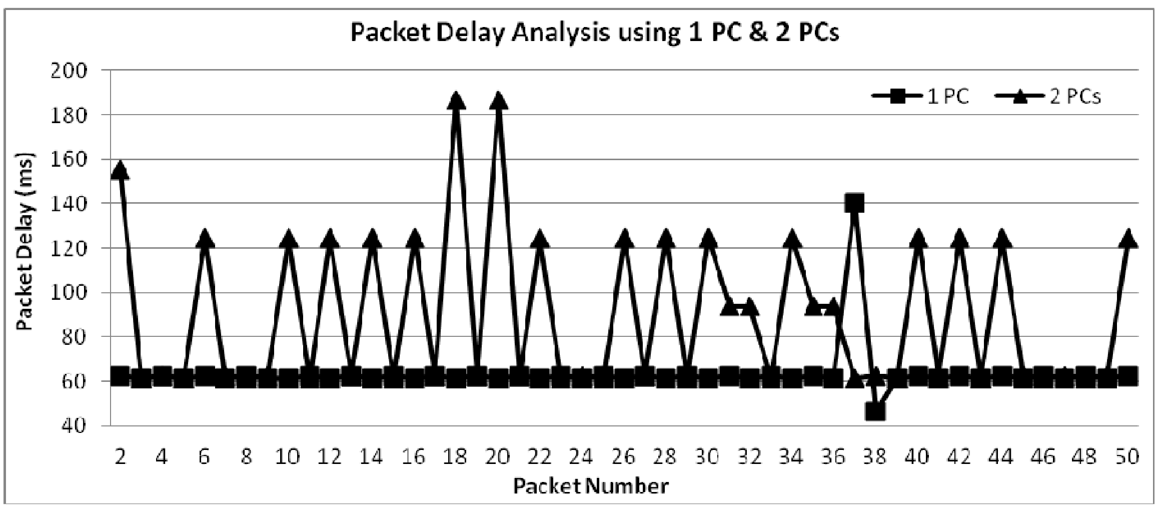

Figure 4.16: Comparison of Packet Delay for 1 PC and 2 PCs scenarios

Figure 4.17 demonstrates the packet jitter performance for one PC and two PCs scenarios where the packet jitter for the two PCs scenario was clearly higher than the one PC as expected.

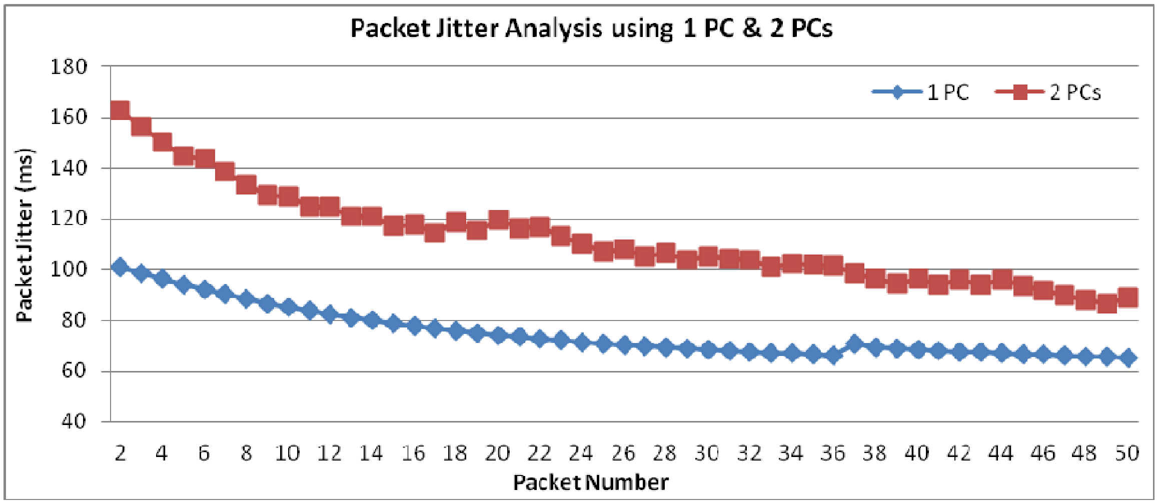

Figure 4.17: Comparison of Packet Jitter for 1 PC and 2 PCs scenarios

The test-bed was then used to evaluate the performance based on the packet delay and packet jitter when different packet error rates (PERs) were used. This scenario considered using the two PCs and the PERs were 0%, 25% and 50%. These PERs were introduced at the Gateway node and the relevant QoS were stored for the analysis. The packet delay and packet jitter results for this scenario is summarised using the Figure 4.18 and Figure 4.19 respectively. It can be seen for the packet delay in Figure 4.18 that the maximum delay reached 500 ms and the objective quality degradation was noticeable in the video streaming application.

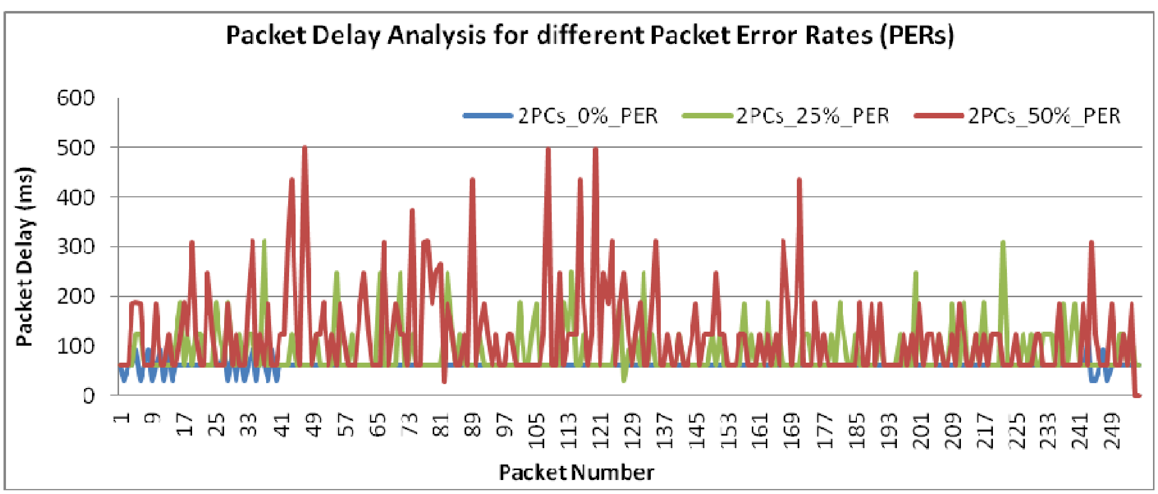

Figure 4.18: Comparison of Packet Delay for varying PERs

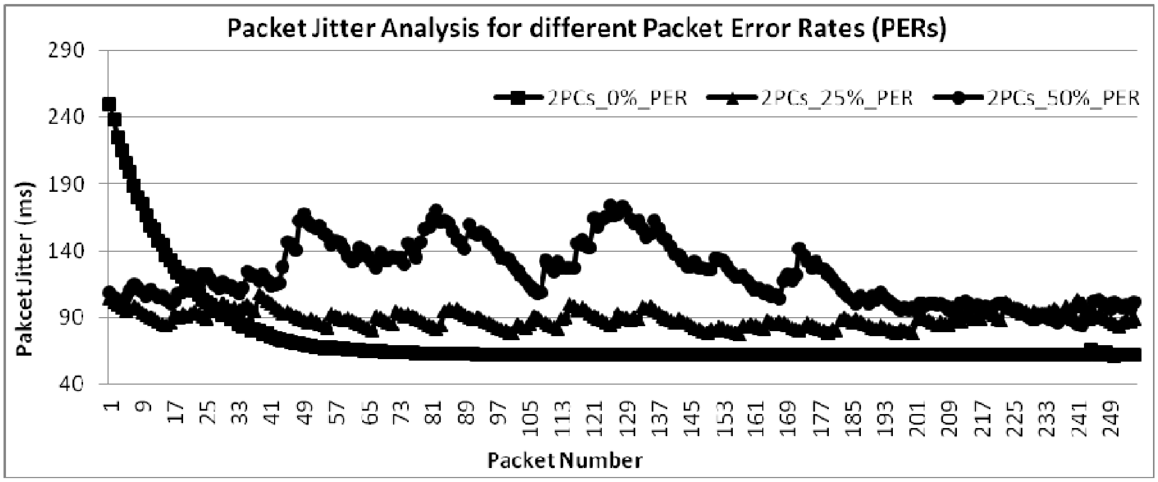

Figure 4.19: Comparison of Packet Jitter for varying PERs

4.7 Real-time Graph

Real-time display of the QoS parameters using graphs is demonstrated in the following section. The QoS parameters stored using files at different stages of the test-bed is used as an input file to the draw the graphs in real-time using the LiveGraph tool [88] which is also written in Java. This tool contains four different GUIs as discussed below:

1. **Data file setting window:** If the QoS parameters data file name is provided with the correct path the LiveGraph will display the data graphically in real-time. The original text file from the test-bed was modified to match the requirements for the LiveGraph data file format. The 'Update frequency' option in this window helps to define how frequently the graph should be updated and if the manual update option in selected then the 'Update now' button should be pressed to update the graph manually.

2. **Graph settings window:** This window helps to define the display of the graph with minimum and maximum x-axis and y-axis limitations. The x-axis series can be selected depending on the user requirements. For example, the RTP SeqNum is selected as the x-axis.

3. **Data Series window:** The labels can be selected as the y-axis series during the graphing and more than one of these labels can be selected to be displayed on the plot area. For example, the Packet delay and Packet jitter labels are selected in this testing and their colour schemes are shown under the Colour column.

4. **Plot window:** Once the first three windows are set properly according to the user requirements, the video streaming application can be started to view the QoS parameters graphically in real-time.

4.8 Concluding Remarks

Although several monitoring tools for the bandwidth intensive applications are available in the market, development of specific user oriented monitoring tool is beneficial for the users to improve their objective and subjective QoS experience. This research project endeavoured us to propose a simple, easy to use and flexible test-bed for bandwidth intensive applications and to monitor the performance of these applications to identify the issues with end systems. Proposed technique is network application specific hence reduces the packet processing time and complexity. It provides a platform for evaluating the real time video streaming application performance using packet-loss, packet delay, packet sequence and packet jitter QoS parameters. A number of studies were carried out to evaluate the performance of the tool by varying different parameters (number of PCs, packet error rates, etc.). This tool was then integrated with the LiveGraph tool to display the QoS parameters graphically and to store such data in databases for future analysis.

Test results prove that our tool can outperform the conventional Wireshark tool by reducing the packet delay and packet jitter. Further modifications to the proposed tool can be carried out to include applications from the smart distribution networks, such as smart meter data transfer for large scale smart metering infrastructure as discussed under Chapter 6. This small emulation set-up can also be used to emulate a wide area networks and to evaluate the performance of the bandwidth intensive applications to integrate with the smart metering infrastructure and messaging middleware for performance analysis.

The real-time QoS monitoring test-bed proposed in Chapter 4 can be integrated with the distribution network to monitor the performance of the electrical devices, such as IEDs, transformers, etc., to report the status of these devices to the network operator for efficient and effective management of the network. Chapter 5 provides detailed performance analysis of the underlying communication media to support the distribution network operation. With the emerging Smart Grid functionalities many challenges will arise regarding the monitoring and control of different critical devices within the distribution networks. This will generate vast amount of data that have to be transmitted in real-time to the control centre using different communication media. Therefore, the bandwidth intensive application testing is required and the test-bed in Chapter 4 may help to achieve these objectives. This test-bed will further help to evaluate the performance of the underlying communication medium by monitoring the different QoS parameters and to alert the network operator when the communication network experiences any problems during operation. Chapter 5 discusses about the performance evaluation of different communication media that can easily be integrated with Chapter 4 for monitoring purposes as well. The smart metering application can be used to test the network performance for worst case scenarios compared to the video streaming application in Chapter 4 and this scenario was then further considered under Chapter 5.

Chapter 5 Performance Evaluation of Communication Media

5.1 Introduction

Distributed behaviour of the new embedded power generation consisting of photovoltaic, solar, and wind, poses challenges to DNOs in monitoring and controlling network devices within the same grid. Scalable and universally adaptable approaches are proposed in [89], which considers distributed monitoring and control means for future power systems. QoS and real-time requirements of data delivery and processing compel the use of appropriate communication and application layers. Internet transport and application layer protocols such as TCP/UDP and HTTP are used in the Java based middleware, Narada Brokering to evaluate the performance requirements of power grid functionalities [89].

UK use case scenarios and cost-benefit analyses (CBA) for different communications technologies were produced by the ENA [6]. The analysis includes the volumes for smart meter data traffic from two different viewpoints:

- Local storage of raw data
- Transmission of the raw data to the control centre

Analysis of the amount of data to be transmitted, real-time communication requirements and means of communication technologies for Belgium case was given in [11] using several use-cases. Comparison between different communication media with varying data rates is presented along a cost-benefit analysis.

The IBM messaging layer was used for stock market centres and synchronized server cluster applications and it provides advanced message aggregation techniques, high communication speed and enhanced processing time functionalities [90]. The effects of its usage were analytically evaluated and an order of magnitude increase in throughput was achieved. This achievement strengthens the concept of message aggregation at different levels of distribution network to attain high throughput with low latency. Data transmission rate and message delivery latency were investigated in [84] and an analytical model using simulation for real-time data dissemination was presented.

In Section 5.2 the brief introduction to the OPNET simulator, the comparison between different simulation tools and the selection criteria for the OPNET are discussed. The throughput and latency performance evaluation of different communication media (GPRS/UMTS and PLC) using the experimental and the simulation tests results are discussed in detail under Section 5.2. Some concluding remarks related to the experimental and simulation tests and the benefits for the DNO applications are briefly summarised under Section 5.3.

5.2 OPNET Simulator

The following sections provide an overview of the OPNET simulator, comparison study with other available simulation tools and the selection criteria for this simulation tool compared to others.

5.2.1 Overview of OPNET Simulator

OPNET simulator is a powerful and commercially available discrete event simulation tool used in many academic and industrial research and developments activities throughout the world. It has been frequently updated with different versions and the latest one is OPNET Modeler 16.0.1.6 [91]. It consists of many advanced communication technologies and models to support the simulation studies required for modelling and simulating state-of-the-art technologies in the current market. Full configuration of different communication networks can be designed and simulated easily with simple drag and drop facility and the results can be achieved in different formats such as graphics, in Excel file or in text file.

The work flow for OPNET Modeler can realised as shown in Figure 5.1[91].

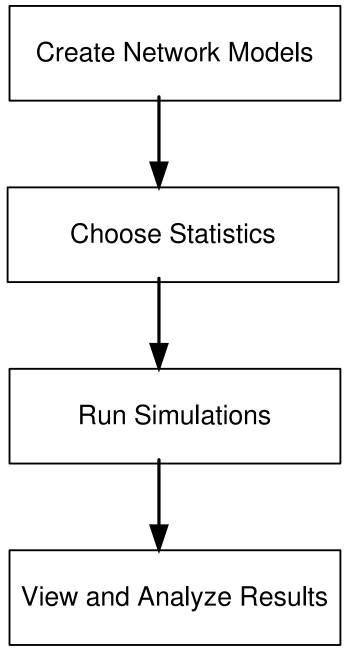

Figure 5.1: OPNET Modeler work flow diagram [91]

There are number of different editors available for creating a network scenario and some of them are explained below:

1. **Project editor**: This is the main areas where the high level network scenario is created for the network simulation using the standard libraries. Other models such as node, process and packet format can be accessed from this editor.
2. **Node model editor**: This editor is used to define different node modules (Ethernet, IP, UMTS, WLAN, WiMax, Zigbee, etc.) for each network object and each module can be connected using packet streams and statistic wires.
3. **Process model editor**: The core functionalities of the specified node model are defined using this editor and finite state machines (FSMs) are used to represent each process model.
4. **Link model editor**: Different link objects can be created using this editor and number of link attributes can be defined for different link types (bus link, eth_coax link, fibre optic link, etc.).
5. **Packet format editor**: Different packet formats can be defined using this editor and fields are used to structure the format of the packet.

The simulator allows the developer to modify the existing models or to create new models from scratch and the above editors are helpful during the designing stage of the network.

5.2.2 Comparison of Different Simulation Tools

There are number of popular open source and commercial network simulation tools available such as OPNET, OMNeT++, NS-2/NS-3, SimPy and JiST/SWANS. Selection of a particular simulation tool depends on number of characteristics such as user requirements, availability (open source or licensed), accuracy of models, easy to modify or create models, type of programming language used, presentation of simulated results (easy to plot on a graph, download to spreadsheet for off-line analysis or easy to change axis), running on different operating systems (Windows, Linux, etc.), memory usage and easy to use and run without sacrificing considerable time running the simulation. A detailed performance comparison study between OMNeT++, NS-3, SimPy and JiST/SWANS are carried out in [92] where NS-3 demonstrated best overall performance. Another study to compare the accuracy of OPNET Modeler and NS-2 network simulators has been performed in [93] where both simulators provided very similar results. Although the freely available NS-2 compared to the commercial OPNET Modeler has been preferred and attractive to the researchers, support for more features and well developed advanced models in OPNET is convenient and very attractive to network operators and researchers. A qualitative comparison of network simulation tools has been carried out in [94] where the OPNET Modeler and NS-2 simulators are compared. This comparative study used the mobile ad-hoc networks (MANETs) under different scenarios to test the performance of these two simulators. Simple Client-Server based network was setup to test the throughput performance under varying background traffic rates.

5.2.3 Selection Criteria for OPNET Simulation Tool

OPNET is a commercially available powerful discrete event network simulation and modelling tool which is widely used in many network and communication related research area. Its development environment is based in C/C++, also called as Proto-C, and can be interconnected with external modules for extending the simulation criteria. Main models can be readily used to develop required network models and new models can also be created from scratch to match or exceed any requirements from the user. Its graphical user interface helps to drag and drop network objects in a work space to create small to large network topologies and to assign required statistics parameters for results collection within minutes. Displaying the simulated results in graphical displays and to change the graphs in different representations, help the user to present the results in various formats which are easily done within short time. Advanced wireless and wired communication link models (UMTS, LTE, WiMax and Fibre) are already available in latest versions of OPNET and these models can readily used in simulation studies with respect to the state-of-the-art network simulation and modelling requirements. Research area is experiencing fast developments in communication and network technologies for newly emerging demands to tackle many challenges in the modern world where several ICT related issues have to be resolved in real-time. Therefore the network simulators should also be able to cope up with these demands so that the network operators can design and development network models in simulation environments well in advance. OPNET's user group is well established and the help on designing, modelling or troubleshooting simulation models can be achieved in many ways. Because the software is licensed and maintained by professional support team either from particular academic/industrial company or from the OPNET IT support directly.

OPNET has also its disadvantages and they are typical any commercial software tools. The main disadvantage is the cost involved with its license and maintenance compared to freely available open source simulators. Limitations on how much modification can be done to the existing models within a particular OPNET version and how the modules outside this version can be accessed are other disadvantages.

Many open source simulators can hardly provide the above features and some of them are still under huge development phases to capture and include users' requirements. This is expected as those open source simulators are developed and supported mainly by volunteers from research groups around the world hence managing and releasing updated versions of these tools will consume considerable time. Therefore the development and improvements between different versions hurdle the use of these tools in the state-of-the-art network simulation studies to cope up with the fast moving developments in the ICT infrastructure in internet and the Smart Grid.

OPNET has been a suitable and convenient simulation tool for this research hence most of the performance evaluation and comparison studies are carried out using OPNET modeller 16.0. This did not limit the use or consideration of other open source network simulation tools such as NS2 or OMNeT++. Initial investigation based on simple models and tutorials have been carried out in both NS2 and OMNeT++ to evaluate their performance in terms of user friendliness, support for the required communication media, dependability of operating systems, simplicity of network creation and easy use of graphical user interface and convenient to present and interpret the simulated results for online or off-line analysis. OPNET satisfies most of the above mentioned performance criteria compared to other simulators as discussed and highlighted in the previous section.

5.3 Experimental and Simulation Tests for GPRS, UMTS and PLC

This section describes the experimental and simulation test cases carried out as part of this research project. The experimental tests were aimed at evaluating throughput and latency performance of GPRS/UMTS and PLC communication media with UDP and TCP transport layer protocols. A simple office network shown in Figure 5.2 was used during the initial experimental tests [13]. This network configuration consisted of 7 nodes and different communication medium was used to send data between the nodes to evaluate the performance.

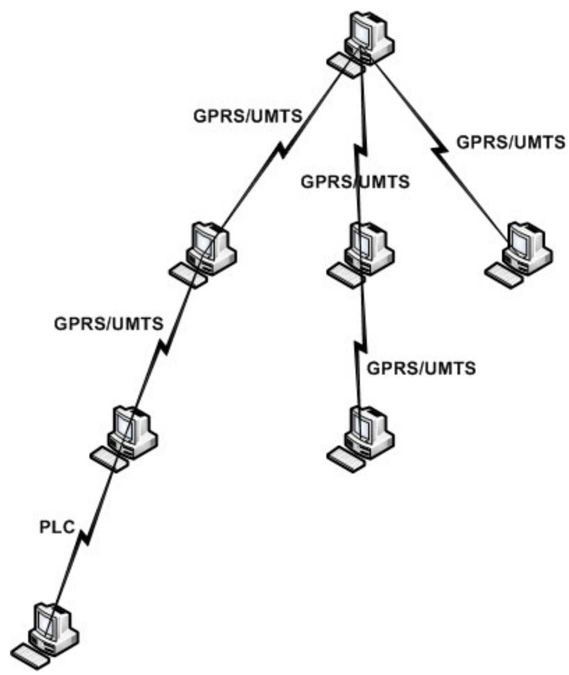

Figure 5.2: Simple Office Network [13]

Different network configurations, such as Point-to-point (p2p), Many-to-One and Many-to-Many, were used during the tests to evaluate the throughput and latency performance for each of these configurations. These configurations are described in the following sections and the method to evaluate the throughput and latency performance is also described.

Point-to-point (p2p) tests, as shown in Figure 5.3, between two nodes using GPRS/UMTS and PLC links were carried out to identify the maximum and minimum performance capabilities of the links. These tests revealed throughput and latency statistics related to each communication medium tested.

Figure 5.3: Simple p2p test between two nodes

Throughput Performance Evaluation

Maximum throughput results were obtained by performing stress tests, up to the maximal capacity range of the link. Note that for both GPRS and UMTS technologies the bandwidth constraints are defined by the up-link capacity. During the test, rate values were computed during intervals of fixed pre-defined length [13].

Latency Performance Evaluation

Minimum latency results were obtained by performing tests sending only a few messages per second, so as to obtain a minimal latency. During the test, latency values were computed for each message as follows. A message was transmitted from station A to B, and back from B to A. The round trip time (RTT) A → B → A was measured in station A, by time-stamping the transmission time and reception time of the packet. The latency equals RTT/2 [13].

Figure 5.4 shows a set up for a many-to-one configuration and many devices (B, C and D) will be communicating to a central station node (A) where the aggregation of the data for further transmission. In this configuration, the devices below the station node will have to compete for the resource because nodes B, C and D attempt to transfer data to the node A at the same time. Therefore, evaluating the actual throughput and latency for these three nodes separately is important to identify any bottleneck in the communication medium and to adjust the parameters in those nodes to efficiently utilise the communication medium under congestions.

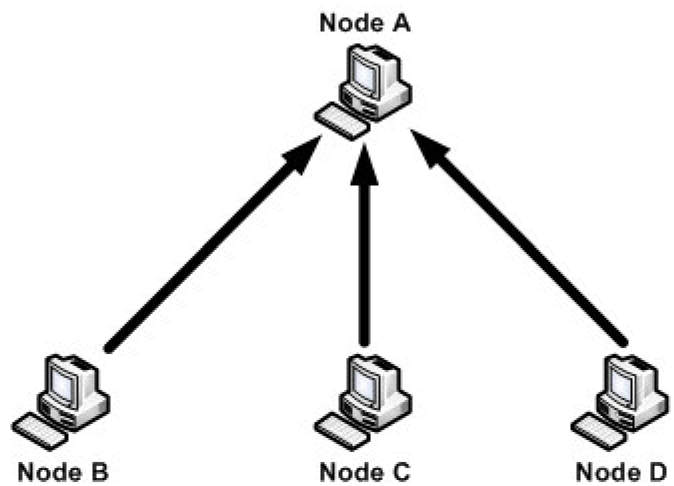

Figure 5.4: Many-to-One 1-level hierarchical test configuration

Two transport layer protocols (UDP and TCP) were used to test the throughput and latency under this scenario and their performance was evaluated for different data rates. The maximal throughput and the corresponding latency were recorded to identify which data rate will be suitable to achieve the optimum performance of the underlying communication medium. Another scenario was considered to test the performance of the communication medium using a multi-level hierarchy as shown in Figure 5.5.

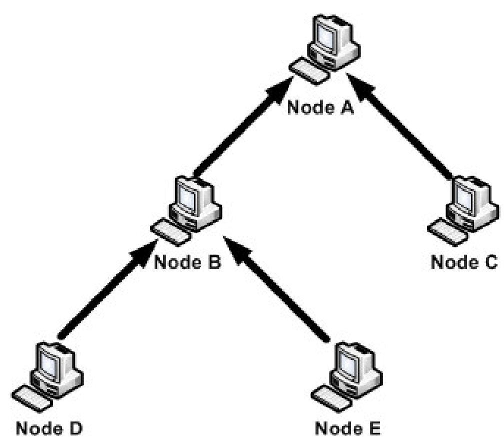

Figure 5.5: Many-to-One multi-level hierarchical test configuration

The configuration in Figure 5.5 consists of two local data concentrators (node A and B) and other nodes (C, D and E) will be communicating to the concentrator nodes. Again, the throughput and latency performance were evaluated for this configuration by changing the data rates at the nodes B, C, D and E where B will transmit the concentrated data to the upper level node A. UDP and TCP were used to evaluate the performance of the communication medium at different levels of this configuration to identify any bottleneck and to correct the data rate accordingly.

5.3.1 GPRS/UMTS Tests (Experimental and simulation)

The real world GPRS/UMTS cellular infrastructure was used during the experimental tests and its high level schematic is shown in Figure 5.6.

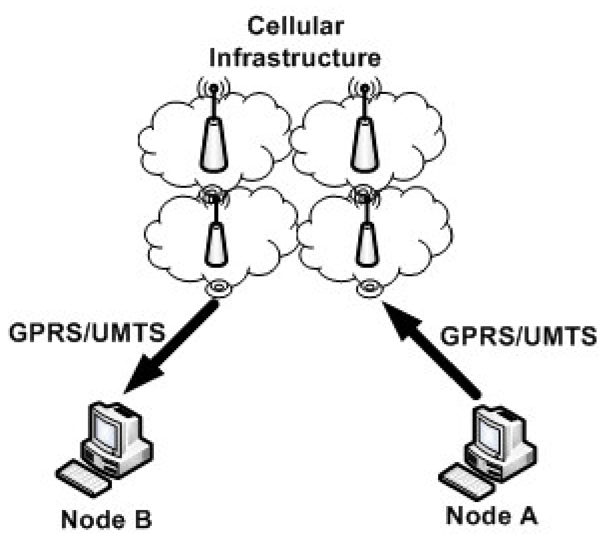

Figure 5.6: Simple cellular network infrastructure configuration [13]

This configuration demonstrates that one node (Node A) is transmitting the data (uplink) and the other node (Node B) receives this data (downlink). Therefore, testing the network under real conditions may reveal the actual throughput and latency performance of this communication medium. As both GPRS and UMTS are packet switched networks the major difference is the ability to support two different data rates where GPRS supports about 57 kbps and UMTS supports about 384 kbps. These data rates may vary for different techniques used within the cellular infrastructure to improve the performance of these technologies.

Wireless 2G and 3G cards were used to evaluate the performance of GPRS and UMTS respectively. UDP and TCP were used as the transport layer protocols to test the performance by varying the transmitter data rates to identify the maximum throughput and the corresponding latency. Several tests were carried out because the real cellular network experiences unpredictable network congestion due to its time varying characteristics. Therefore, the throughput and latency values may vary when performing different tests. This was evident through the experimental tests because different throughput and latency values were obtained when the tests were carried out at different times of the day or at different days. Therefore, the stress tests were carried out continuously to test this network to identify the maximal capacity of the communication link. The relevant throughput and latency values were recorded at every test for off-line analysis and for comparison with simulation test results.

Existing OPNET models for different communication technologies, GPRS, UMTS and bus-link, were modified and adapted for simulating communication technologies in OPNET simulator. Modification at the application layer was carried out as described below and other layers were left intact. Inbuilt voice and FTP applications were used for the simulation to test UDP and TCP transport layer protocols respectively. This required a delicate modelling and tune up following the instability of the cellular network environment during the experimental tests, mainly due to concurrent communication usage of other users/applications. Throughput for different scenarios was observed during simulation for varying data rates at the sending node. UMTS is an inbuilt model in OPNET 16.0 version and contains the following nodes: work station, Node_B, radio network controller (RNC), serving GPRS support node (SGSN) and gateway GPRS support node (GGSN). Work station supports the full TCP (UDP) / IP protocol stack and modification can be done in each layer. Inbuilt applications (voice, video, FTP and HTTP) supported by the work station were used to generate raw data. This raw data was then sent through the intermediate nodes to reach the destination node where the end-to-end delay (latency) is calculated. Throughput was calculated at the link (uplink) between Node-B and RNC. Real GPRS/UMTS network was congested due to other data traffic hence OPNET model was modified by adding the required delay at the SGSN node to match the experimental test results. The maximum data rate of the links between the nodes in the UMTS model was set to 384 Kbps and the application raw data rate was varied to get the expected test results. UMTS and GPRS models in OPNET are similar in terms of network configuration and data rate of the link models between the end nodes was modified to specify the GPRS data rate (56 Kbps).

Different data rate statistics were calculated for the both experimental and simulation tests, including: average, median, minimum and maximum values, as well as different order statistics (5%, 10%, 90% and 95%) values. Several tests were carried out to find the maximum throughput for GPRS, UMTS and PLC and the corresponding latency for these throughput values was measured. These values were then used as reference values during the simulation and several tests were performed in OPNET to match these results. The simulation environment did not experience instability and modelling the exact experimental conditions required a complex simulation setup.

5.3.2 PLC Tests (Experimental and Simulation)

A real PLC communication medium was used to test the performance of the PLC. Two TL-PA201 Ethernet power adaptors were used to construct a simple p2p network. This adaptor, see Figure 5.7, is HomePlug AV, IEEE 802.3 and IEEE 802.3u standards compliant, and supports TCP/IP protocol with data rate of up to 200Mbps and in house range of 300m.

Figure 5.7: Typical TL-PA201 Ethernet power adaptor

The simple PLC p2p network configuration can be visualised as shown in Figure 5.8 with two nodes where Node 1 will transmit the data (uplink) and Node 2 will receive this data (downlink).

Figure 5.8: Simple p2p PLC network configuration

Bus-link model was used in OPNET simulation and required modification was done to model the characteristics of PLC. There are six bus transceiver pipeline stages in OPNET: transmission delay, closure, propagation delay, error correction, error allocation and collision. These pipeline stages perform different functionalities of the bus-link and modification to these transceiver pipeline stages enables the realisation of PLC characteristics. More details about these pipeline stages can be found in [91].

5.3.3 Performance Comparison of the Test-beds

Experimental and simulation test results are presented and analyzed under this section. Average throughput and latency values are used for the comparison and are highlighted in the result tables.

Table 5.1 presents maximum throughput results for a GPRS/UMTS link over UDP/TCP protocols. A higher rate is achieved when UDP was used (significant in UMTS), as this protocol has no additional overhead of performing flow and congestion control algorithms.

Table 5.1: Maximum throughput results for GPRS/UMTS

		Maximum Throughput (Kbps)							
		GPRS							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	8	45	**25**	20	8	13	44	44
	TCP	21	23	**21**	21	21	21	22	22
Simulation	UDP	3	46	**22**	21	4	6	38	42
	TCP	18	26	**22**	22	22	22	23	23
		UMTS							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	359	365	**363**	364	360	361	364	365
	TCP	171	259	**239**	242	232	234	250	252
Simulation	UDP	361	368	**364**	364	362	362	367	367
	TCP	59	267	**245**	254	230	236	263	266

Table 5.2 presents the latency results when the data is transmitted at maximum capacity of the communication link. Most of the experimental and the simulation test results matched relatively well but some results are not matched well because of the unpredictable and time varying cellular network environment.

Table 5.2: Latency in case of maximum throughput

		Latency for Maximum Throughput (milliseconds)							
		GPRS							
		min	Max	avg	median	5%	10%	90%	95%
Experiment	UDP	5143	8050	**6704**	6779	5502	5761	7395	7601
	TCP	3138	5012	**3977**	3882	3307	3410	4635	4713
Simulation	UDP	5640	12664	**7067**	6744	6069	6146	8594	9046
	TCP	3977	4688	**4269**	4231	3981	3982	4564	4629
		UMTS							
		min	Max	avg	median	5%	10%	90%	95%
Experiment	UDP	698	850	**739**	738	715	718	761	771
	TCP	253	1149	**720**	721	362	460	986	1018
Simulation	UDP	681	1207	**738**	719	692	695	807	852
	TCP	100	1398	**749**	773	217	273	1193	1254

The GPRS experienced higher latency than UMTS as expected under both UDP and TCP transport layer protocols. The minimum latency performance was also evaluated to identify the minimum capacity of the communication link. The smaller data rates were used at the transmitter node and performance was evaluated. Table 5.3 presents the minimum latency achieved for a GPRS/UMTS link over UDP/TCP protocols, while Table 5.4 presents the throughput achieved for data transmitted with minimum latency. It can be observed from these tables that TCP achieved a higher latency, mainly due to buffering that is performed as part of its flow and congestion control algorithms.

In case of congestion (maximum throughput), the latency achieved is higher than the minimal latency (Table 5.2 vs. Table 5.3), mainly due to queue load and buffering time of the messages. Interestingly, in this case, the latency achieved using UDP is higher than TCP, as opposed to the case of minimal latency, where UDP outperforms TCP. The reason is that in cases of congestion, TCP is more effective due to its flow and congestion control algorithms.

Table 5.3: Minimum latency results for GPRS/UMTS

		Minimum Latency (milliseconds)							
		GPRS							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	1119	2102	**1593**	1580	1270	1332	1864	1966
	TCP	1662	6493	**2967**	2688	2030	2145	4871	5590
Simulation	UDP	1481	3514	**1640**	1609	1512	1522	1776	1839
	TCP	1566	5117	**2794**	2863	1566	1674	3920	4014
		UMTS							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	85	251	**109**	104	93	95	120	142
	TCP	222	552	**399**	397	245	281	513	532
Simulation	UDP	92	179	**100**	99	95	96	103	105
	TCP	207	511	**377**	377	316	317	439	447

Table 5.4: Throughput in case of minimum latency

		Throughput for minimum latency (Kbps)							
		GPRS							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	5	20	**9**	8	5	5	16	17
	TCP	7	10	**8**	8	7	7	9	9
Simulation	UDP	5	15	**10**	9	7	7	12	13
	TCP	6	10	**8**	8	7	7	9	9
		UMTS							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	67	92	**78**	78	71	74	83	87
	TCP	68	94	**79**	77	71	71	88	89
Simulation	UDP	71	87	**78**	78	72	74	81	83
	TCP	65	95	**77**	77	67	69	85	86

The maximum throughput and minimum latency achieved for both PLC and bus-link using experimental and simulation tests are presented in Tables 5.5 and 5.6. The average throughput and latency values indicate the highest performance for PLC and bus-link compared to GPRS and UMTS.

Table 5.5: Maximum throughput for PLC

		Maximum Throughput (Mbps)							
		PLC/bus-link							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	25.4	54.9	**50.3**	51.8	37.5	48	53.3	53.7
	TCP	9.3	15.1	**13.4**	13.9	10.7	11.7	14.5	14.7
Simulation	UDP	33.5	50.3	**50.2**	50.2	50.2	50.2	50.3	50.3
	TCP	11.8	14.9	**13.3**	13.2	12.5	12.7	14.1	14.2

Table 5.6: Minimum latency for PLC

		Minimum Latency (milliseconds)							
		PLC/bus-link							
		min	max	avg	median	5%	10%	90%	95%
Experiment	UDP	2.2	4.6	**3.1**	3	2.3	2.4	3.5	3.9
	TCP	5.3	209	**95**	95	31.7	44.7	148	167
Simulation	UDP	3.1	3.1	**3.1**	3.1	3.1	3.1	3.1	3.1
	TCP	95	95	**95**	95	95	95	95	95

Figure 5.9 and Figure 5.10 show the maximum throughput achieved for UDP with GPRS and UMTS respectively. The results are presented in ascending order of throughput value, demonstrating the general behaviour for both simulations and experiments. It can be seen that simulation results show a clear linear throughput performance, while the experiments show a more variable performance. There are a number of factors affecting the experimental behaviour; for example in an unpredictable real network environment, other applications may access the GPRS / UMTS network. As UDP does not require acknowledgements for received packets, the packets are sent continuously.

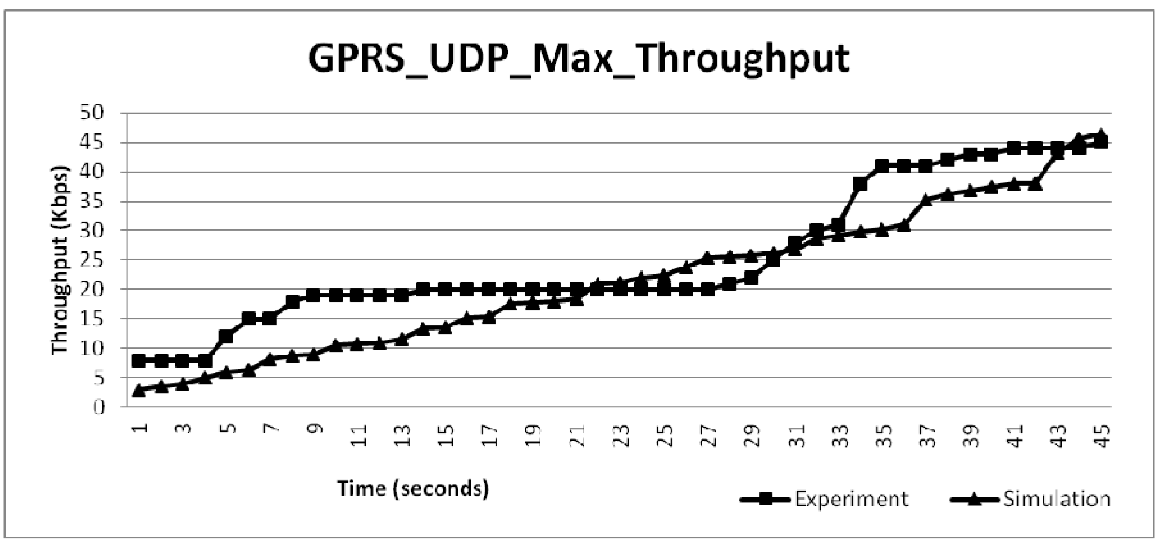

Figure 5.9: Maximum throughput for GPRS/UDP

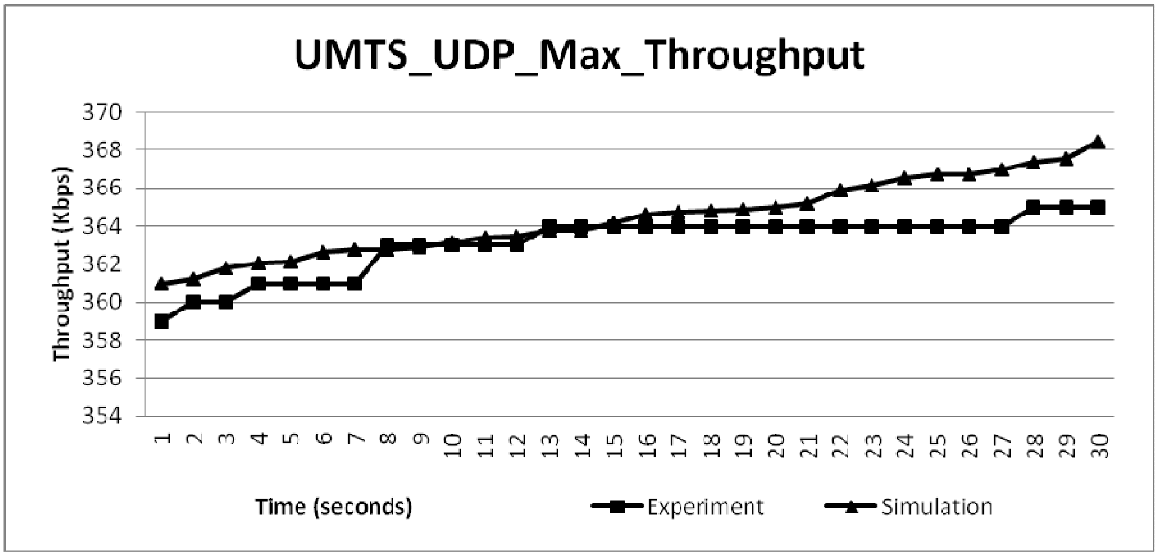

Figure 5.10: Maximum throughput for UMTS/UDP

In case the network is less congested, a fairly constant throughput performance is reached (similar to the one achieved by TCP), as can be observed by the experimental curves in Figures 5.11 and 5.12, that reach a saturation during a significant (aggregated) amount of time. The rate increase observed during the experiments is likely to be caused following a burst transmission of buffered packets. Note also that the UDP connection is characterized by a higher instability when using GPRS than when using UMTS. The reason for this is the bandwidth resources are much more restricted in GPRS, causing higher and more frequent congestion situations, which are not handled by the UDP protocol.

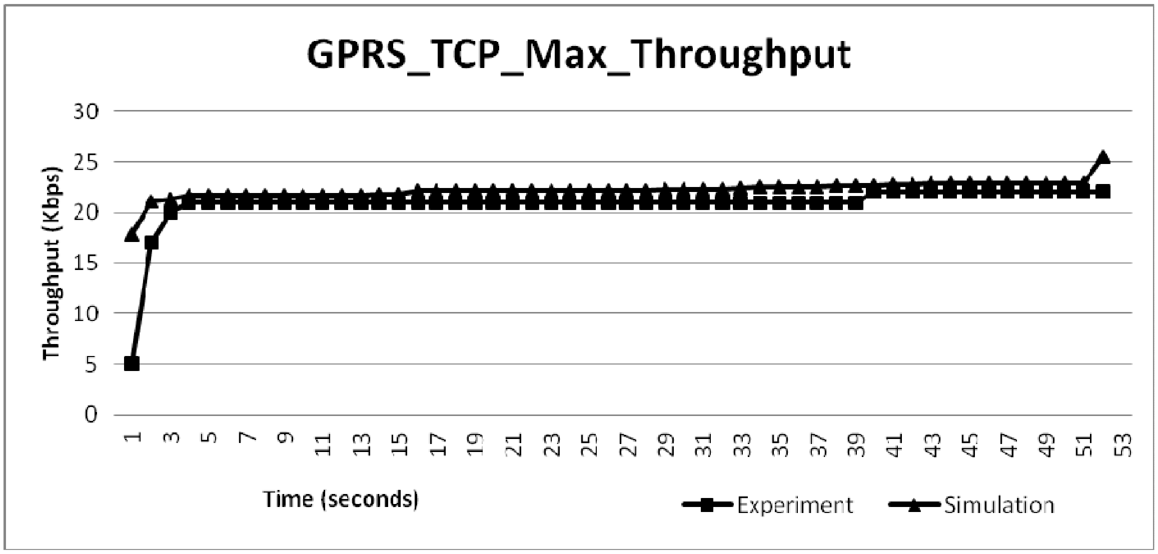

Figure 5.11: Maximum throughput for GPRS/TCP

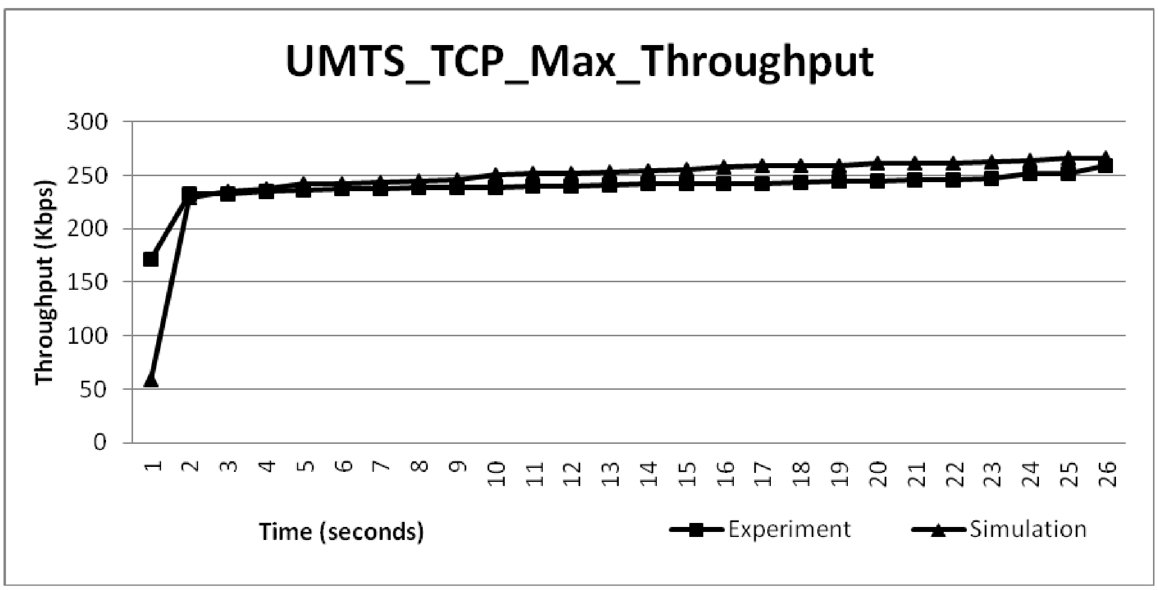

Figure 5.12: Maximum throughput for UMTS/TCP

Both experiment and simulation for the maximum throughput cases for TCP with GPRS and UMTS are well matched (Figures 5.11 and 5.12). The flow and congestion control algorithms in TCP enable this constant throughput performance due to its connection-oriented behaviour compared to the connectionless UDP transport protocol. This was shown throughout several test results comparison for UDP and TCP.

5.4 Concluding Remarks

OPNET simulation test results were compared with experimental test results, focusing on throughput and latency performance for GPRS, UMTS and PLC media. Latency and throughput performance were analyzed for TCP and UDP transport layer protocols over the respective communication media, demonstrating the trade-off between the reliable and unreliable protocols. Results achieved by this analysis for both simulations and experiments suggest that the simulation model can be used to evaluate communication performance for larger networks.

Average throughput of 360 Kbps and latency of 0.1 seconds were achieved for UMTS/UDP compared to an average of 20 Kbps and 6 seconds by and GPRS/UDP. Average throughput for PLC/UDP was 50 Mbps with latency of 3 milliseconds. Similar tests were performed for UMTS/TCP, GPRS/TCP and PLC/TCP. It was noted some DMS functionalities require latency of tens of milliseconds and this may not be supported by GPRS or UMTS as their minimum latency is in hundreds of milliseconds. Further work is required to understand better the performance of PLC under stronger physical constraints; these characteristics may affect the performance of PLC if deployed in larger scale networks.

Additionally, a trade-off between latency and throughput performance was demonstrated, as well as performance difference between TCP / UDP transport protocols for the respective analyzed cases. It was seen that UDP outperforms TCP in terms of throughput and latency, as a result of the reliability and congestion/flow control mechanisms supported by TCP (requiring the acknowledgement and retransmission of packets) which represents an overhead in terms of performance. On the other hand, when bandwidth resources are constrained and high data rates are used, UDP experiences a higher latency due to its poor congestion/flow management. Timely and critical applications requiring strict performance guarantees should consider these aspects when using UDP and TCP as transport layer protocols. The performance trade-offs provide an incentive to the need of a dedicated messaging layer for data communication within the Smart Grid.

The performance evaluation of the smart metering infrastructure was carried out in Chapter 6 using the PLC medium that was used in Chapter 5. Further studies were carried out in Chapter 6 to test the scalability and performance of the PLC using different scenarios and this may help the DNOs during the design and planning stages of their network infrastructure. The validation of the PLC medium in Chapter 5 is useful to use that in further studies in Chapter 6 and to extend the work to realise a larger smart metering infrastructure in simulation environment. The performance achieved by the PLC medium compared to other GPRS/UMTS media makes the former a low-cost and suitable communication solution LV network hence the selection of PLC as the communication medium was chosen for the smart metering infrastructure testing in Chapter 6.

Chapter 6 Performance Evaluation of Smart Metering Infrastructure

This chapter discusses about the simulation of smart metering infrastructure and the performance analysis using the OPNET simulation tool under various scenarios. A smart meter network was set-up using the OPNET. A number of smart meters (100, 200 and 400) and a number of data concentrators (1, 2, 4, 8 and 16) were used to study the performance and scalability of the test-bed. Data transmission time and successful transmission rate were recorded to compare the results between different scenarios as listed in Section 6.1.

6.1 Simulation Set-up and Test cases

PLC is a preferred communication medium for LV networks it can be used to transmit smart meter data to control centres. Several hundreds of smart meters can be connected to the concentrator near the transformer unit using the PLC medium. From the concentrator to the control centre different communication media (GPRS/UMTS, fibre optics or satellite) can be used depending on the amount of data transmission.
To simulate different scenarios of the smart meter network, the simulation was set-up in OPNET using workstation (as smart meters), server (as concentrator) and the bus-link (as PLC) as shown in Figure 6.1. A detailed discussion is in the document published by the ENA [6] where the theoretical analysis of the smart meter data traffic using several use case scenarios was explained. Different number of smart meters for varying response times was used to estimate the packet speed that is required for the DNO applications.

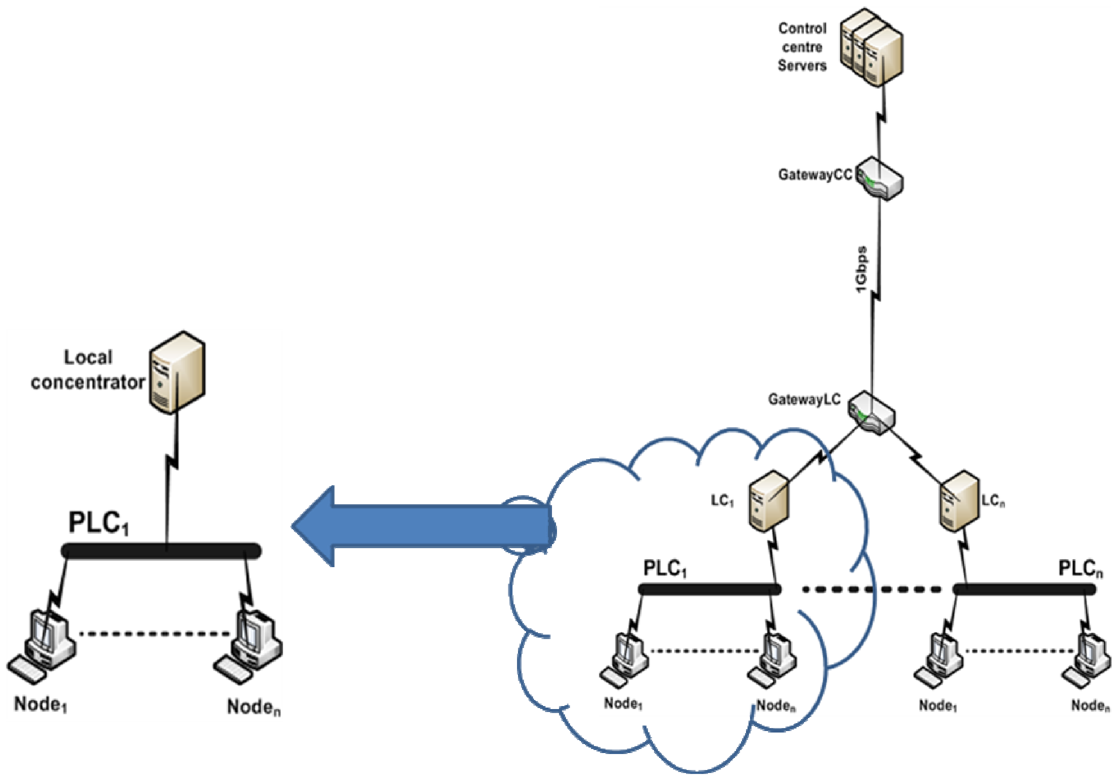

Figure 6.1: Smart meter network set-up using PLC

The purpose of this simulation was to evaluate the scalability of the PLC network by increasing the number of nodes (smart meters) and concentrators.

Initially, the OPNET-based PLC network was used to evaluate the transmission time between local concentrator and a smart meter for varying data sizes (100 to 145888 bytes). PLC is a shared medium hence more number of smart meters on the PLC network will result in higher consumption of the available network resources. This limitation was studied by varying the total number of smart meters and concentrators connected to a PLC medium. Also the success rate for each configuration was evaluated. The existing server node model in OPNET was able to support 100 connections at a time. Therefore, if 200 nodes are to be connected then two servers are required to make sure that all 200 nodes managed to send data.

Several scenarios were used to analyse the simulation study and some of them are listed below:

Scenario1: Transmission time vs. number of nodes (10, 20, 40, 60, 80, 100, 200 and 400) for 145888 bytes (maximum data size) and for 100 bytes (minimum data size)

Scenario2: 400 nodes with 1, 2, 4, 8 and 16 concentrators (with separate PLC link for each concentrator)

Scenario3: 200 nodes with 1, 2, 4 and 8 concentrators (with separate PLC link for each concentrator)

Scenario4: 100 nodes with 1, 2 and 4 concentrators (with separate PLC link for each concentrator)

Scenario5: Successful transmission rate (defined under Section 6.2.3) vs. number of concentrators for 100, 200 and 400 nodes

Scenario6: Transmission time vs. varying request data sizes for 100 nodes with 1 concentrator

6.2 Results and Performance Analysis

Using the test-bed described in the previous section, several simulation tests were carried out to evaluate the performance of the smart metering infrastructure based on different performance parameters, such as transmission time, successful transmission rate, etc., by varying the number of nodes (smart meters), request data size and number of concentrators. The results were analysed under separate scenarios to highlight the key findings and performance of the test-bed. The terms ‘nodes’ and ‘smart meters’ are used interchangeably throughout this chapter.

6.2.1 Transmission Time vs. Number of Nodes

The number of nodes (smart meters) was varied from 10 to 400 and the transmission time to send all the data from the smart meters to the concentrator was recorded. The maximum request data size (145888 bytes) and the minimum request data size (100 bytes) were considered under this section to evaluate the performance of the smart metering infrastructure.

Scenario1: Transmission time vs. number of nodes (10, 20, 40, 60, 80, 100, 200 and 400) for 145888 bytes (maximum data size) with 1 concentrator

Figure 6.2 shows the transmission time variation for different number of nodes with 1 concentrator. Three statistical measures (maximum, average and minimum) were considered to identify the upper, middle and lower transmission time values for the varying number of nodes where the maximum, average and minimum transmission times are denoted by MaximumTT, AverageTT and MinimumTT respectively.

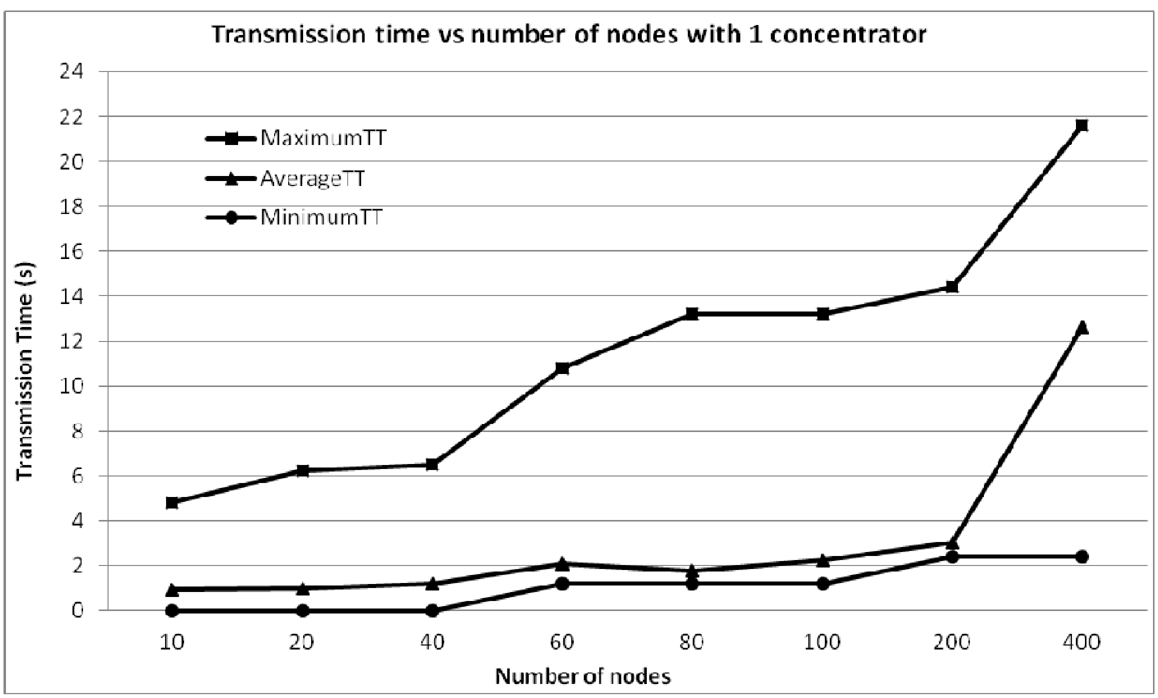

Figure 6.2: Transmission time vs. number of smart meters (145888 bytes)

When the number of nodes was increased from 10 to 400 there was an increase in the transmission time required for sending all the data from the nodes as seen in Figure 6.2. The request data size was fixed to 145888 bytes (ENA worst case scenario) and the number of nodes was increased from 10 to 400. The MaximumTT line provides the information regarding the maximal transmission time required for all the data to be delivered to the concentrator/control centre. It can be seen from Figure 6.2 that when he number of nodes is 10, all the smart meters managed to send all the data within the 5 seconds time limit (this time limit is the lowest response time specified in the ENA document [6])

Transmission time vs. number of nodes (10, 20, 40, 60, 80, 100, 200 and 400) for 100 bytes (minimum data size) with 1 concentrator

A data size of 100 bytes was used to evaluate the transmission time against varying number of nodes (10 to 400) as shown Figure 6.3.

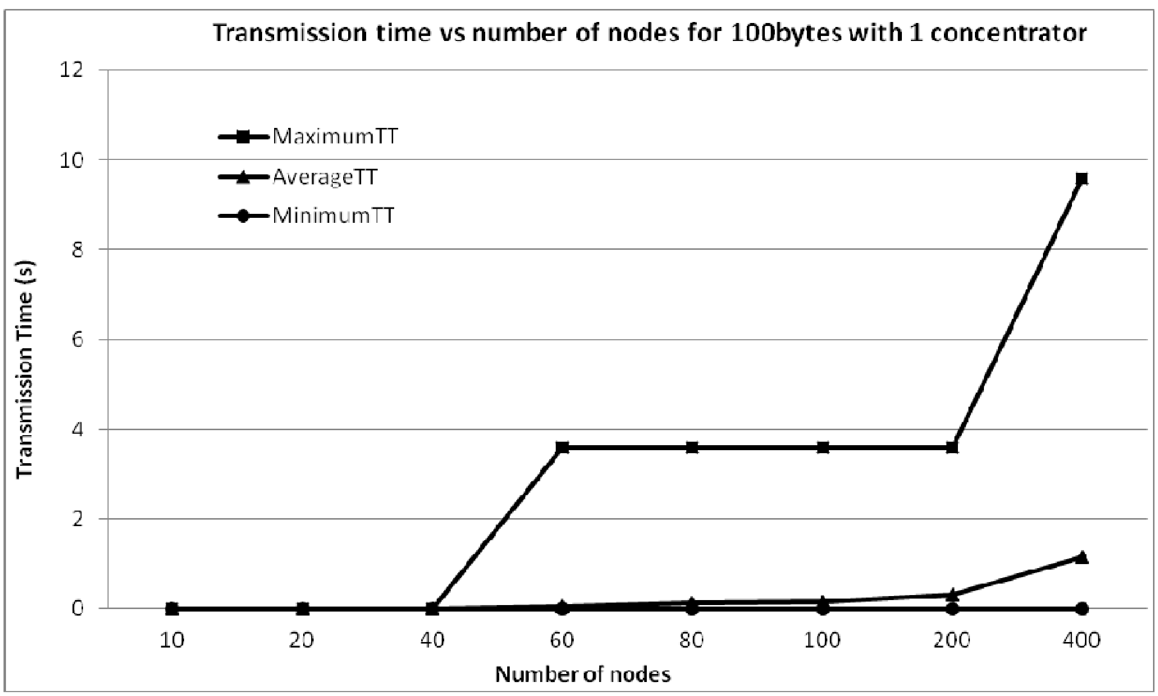

Figure 6.3: Transmission time vs. number of smart meters (100 bytes)

If the successful transmission time is set to 5 seconds, only few nodes will exceed this time limit under this scenario. But the average transmission time for 400 nodes is less 2 seconds. Under Scenario1, it can be noticed that only less than 20 nodes managed to send all the data within 5 seconds time limit when the data size was 145888 bytes (maximum data size case). However, under Scenario 2 less than 200 nodes managed to send all the data within the 5 seconds time limit. Therefore, it will be beneficial for DNOs to consider several scenarios with varying data sizes and varying number of nodes to find out optimum values for these two parameters. It will eventually result in low-cost solution when deploying smart meters and concentrators for LV network. But, it should also be carefully considered that the future requirements from the DNO may result in expanding or even totally installing new network components in the LV network to accommodate the tsunami of data from the smart meters or MV/LV network devices (such as IEDs). This will add further or unexpected cost to DNO. Therefore, rigorous studies should be carried out to derive optimum communication network and economical solutions.

The large difference between the maximum and the average values are due to most nodes sending all the data within short time and only few of the nodes will send with large transmission time. For example, we can take the maximum and average transmission time values for 100 nodes and they are around 13.2 and 1.2 seconds respectively. The cumulative distribution function of the transmission time for all 100 nodes is given in Figure 6.4. It provides the information about the spread of the transmission time for all the nodes and why there is large difference between the average and maximum transmission times.

From the probability density function, see Figure 6.5, it can be seen that the rest of the nodes sent all the data with different transmission times varying from 0.5 to 13.2 seconds resulting in a sparse distribution of the transmission time. It was the reason behind the large difference between average and maximum transmission times under all the scenarios. Therefore, in the following scenarios this explanation will be used to reason the large difference between average and maximum transmission times and it is not necessary to provide the CDF and PDF functions for each scenario.

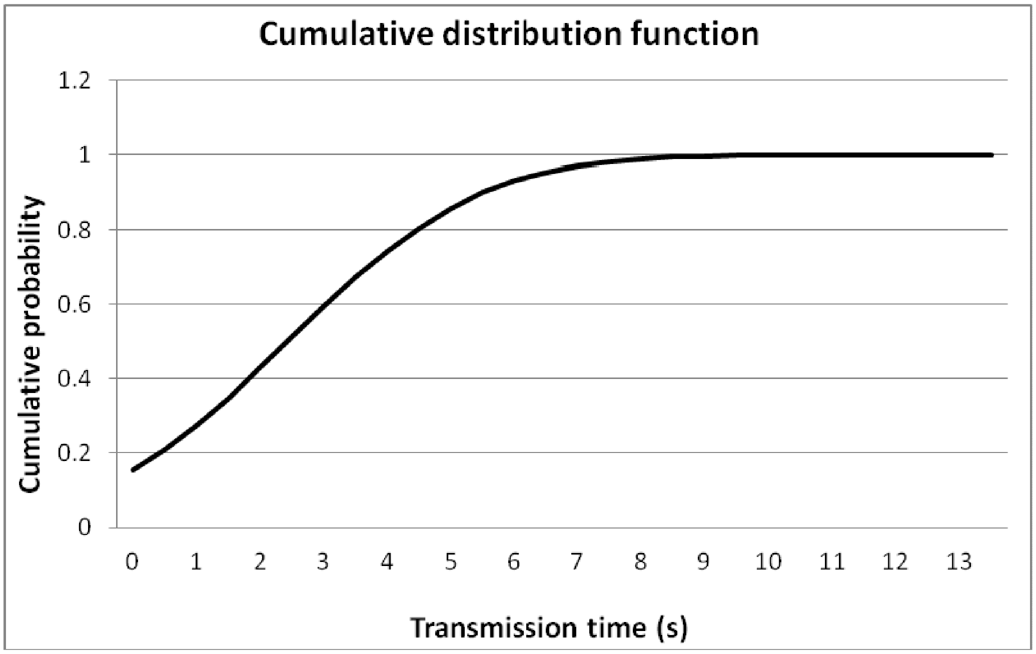

Figure 6.4: Cumulative distribution function for 100 nodes

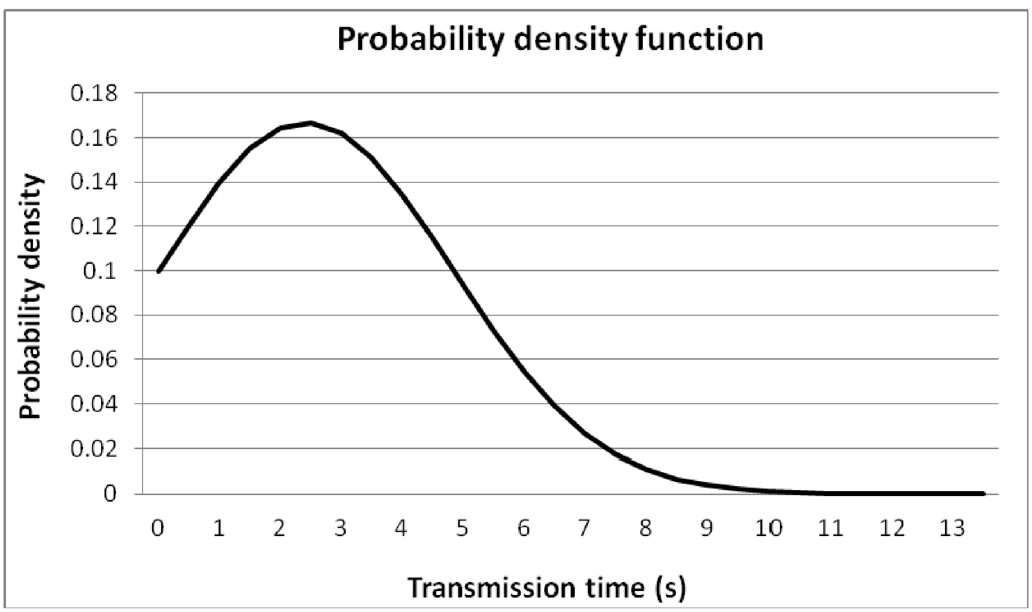

Figure 6.5: Probability density function for 100 nodes

6.2.2 Transmission Time vs. Number of Concentrators

A different set of tests were carried out to evaluate the transmission time performance when the number of concentrators (1, 2, 4, 8 and 16) was varied for different number of nodes (100, 200 and 400). These test results are discussed using different scenarios under this section.

<u>Scenario2: 400 nodes with 1, 2, 4, 8 and 16 concentrators (with separate PLC link for each concentrator)</u>

Figure 6.6 shows the transmission time against varying number of concentrators for 400 nodes. Each concentrator is connected with a separate PLC link. The x-axis shows the number of concentrators (1, 2, 4, 8 and 16) and the y-axis is the transmission time in seconds.

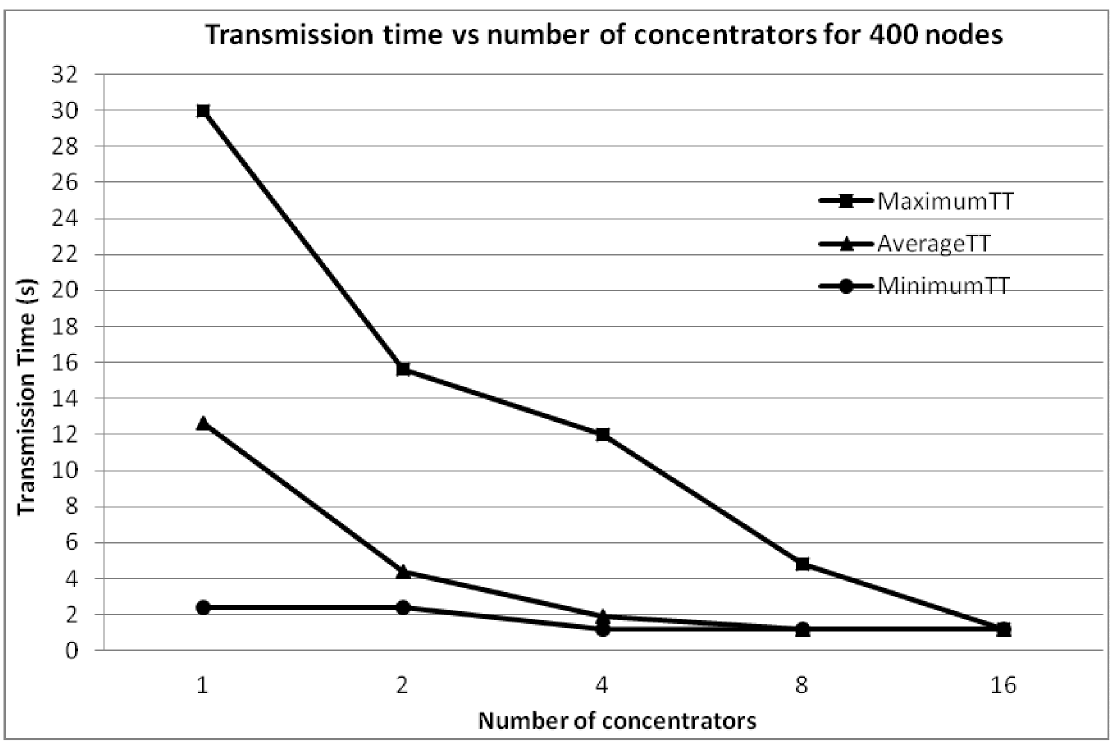

Figure 6.6: Transmission time vs. number of concentrators for 400 nodes

In this scenario the number of concentrators was varied from 1 to 16 for a fixed number of nodes (400 nodes) and the transmission time was recorded. This figure clearly shows that when increasing the number of concentrators the transmission time decreases exponentially. When 8 or 16 concentrators were used the maximum transmission time falls below the 5 seconds time limit. But the average time is below 5 seconds when minimum of 2 concentrators were used.

Scenario3: 200 nodes with 1, 2, 4 and 8 concentrators (with separate PLC link for each concentrator)

Under this scenario, 200 nodes with varying number of concentrators (1, 2, 4 and 8) were tested and the maximum, average and minimum transmission times were plotted as shown in Figure 6.7.

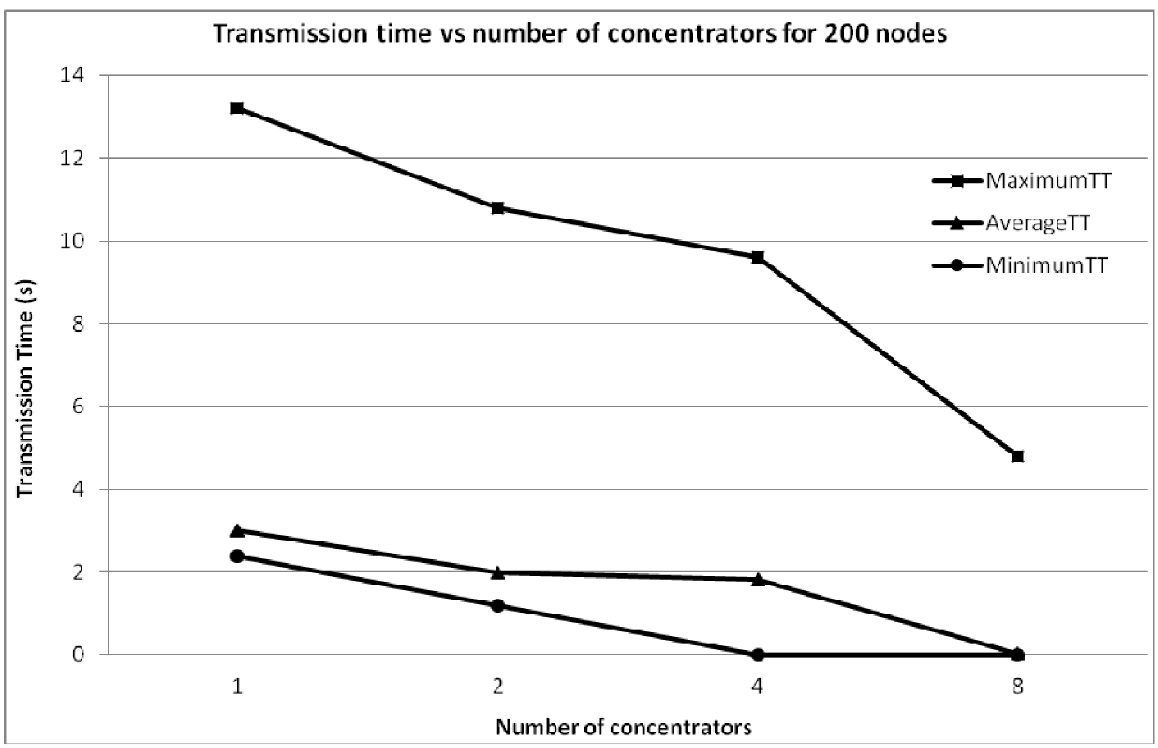

Figure 6.7: Transmission time vs. number of concentrators for 200 nodes

The large difference between the maximum and the average transmission times are due to the reason which was explained under Scenario1. When the number of concentrators was increased to 8 the maximum transmission time falls below the 5 seconds giving 100% successful transmission rate for 200 nodes with 8 concentrators.

Scenario4: 100 nodes with 1, 2 and 4 concentrators (with separate PLC link for each concentrator)

Figure 6.8 shows the transmission time decrease when the number of concentrators was increased from 1 to 4 for 100 nodes. When 4 concentrators were used the transmission time lies below the 5 seconds time limit and this is useful for the DNOs to decide the number of concentrators for this scenario.

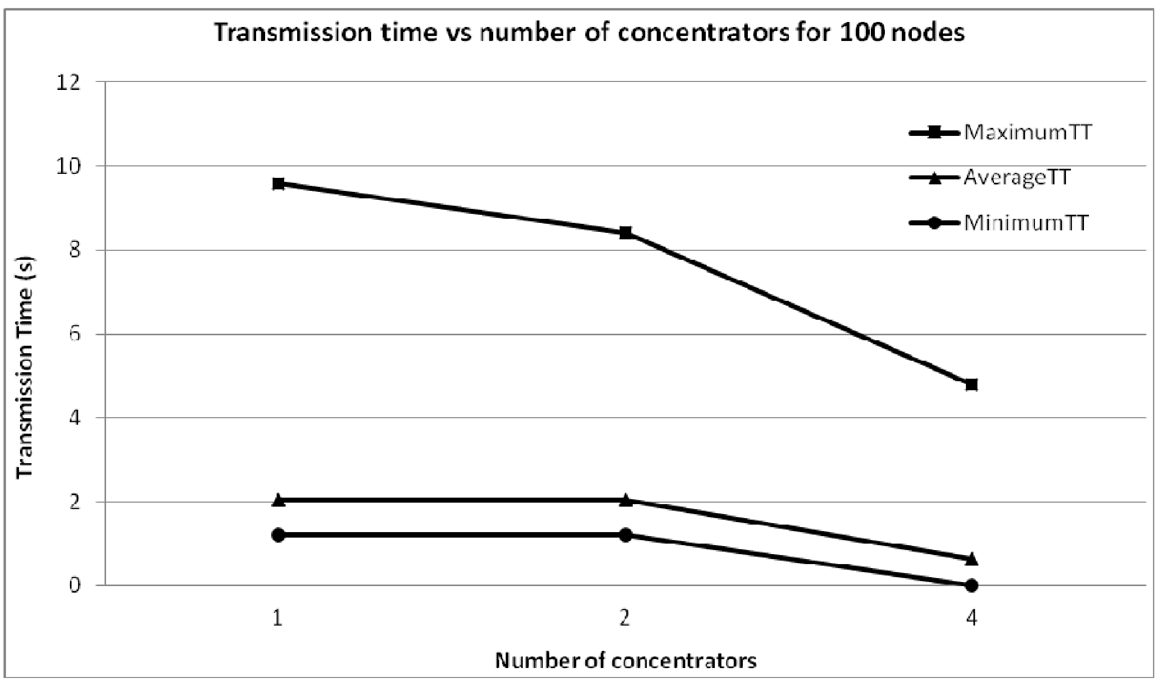

Figure 6.8: Transmission time vs. number of concentrators for 100 nodes

6.2.3 Successful Transmission Rate vs. Number of Concentrators

Under this section, the successful transmission rate against varying number of concentrators was evaluated to decide the minimum number of concentrators required to provide a relevant performance. The successful transmission rate (STR) is calculated based on Eq. (5):

STR = (number of successful nodes/total number of nodes)*100% Eq. (5)

If a particular node manages to send all the data within 5 seconds (the minimum latency considered in the ENA document [6]) that node is considered as a 'successful node'.

<u>Scenario5: Successful transmission rate vs. number of concentrators for 200 nodes with 1 and separate PLC link</u>

Another comparison was carried out to check the successful transmission rate under two cases, with 1 PLC link for all nodes and with separate PLC link for a set of nodes as shown in Figure 6.9.

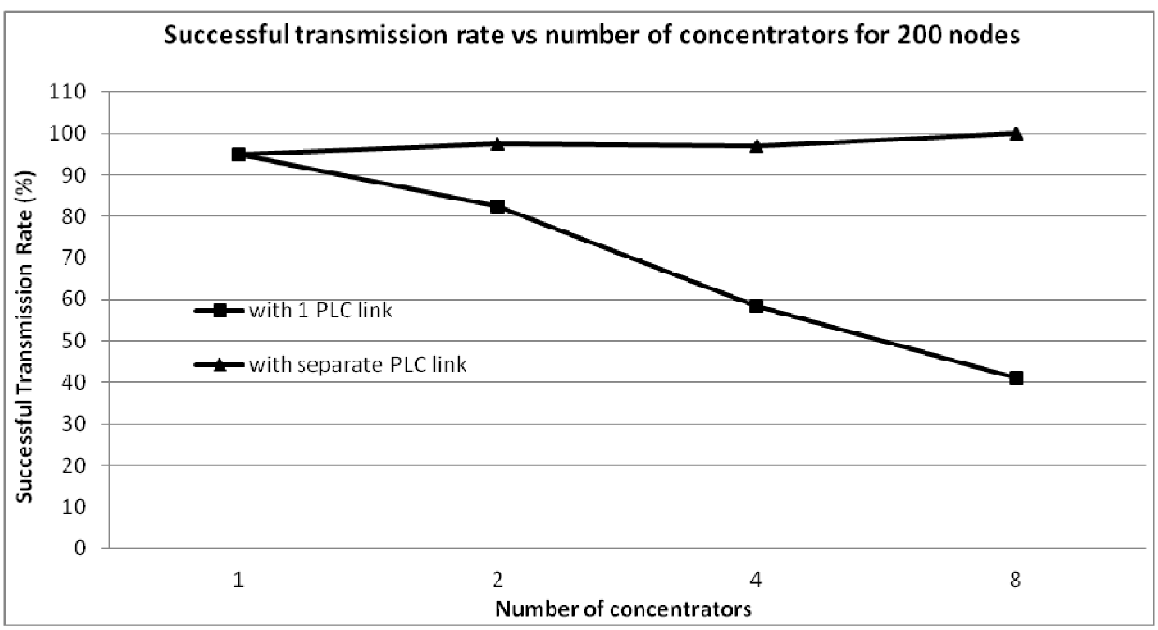

Figure 6.9: STR vs. number of concentrators for 200 nodes

For example, if 4 concentrators were used with separate PLC link then there will be 50 nodes for each PLC link therefore there will be 4 PLC links for all 200 nodes. This is called the separate PLC link case. Then the number of concentrators was varied from 1 to 8 and the transmission time was recorded under each case. All 200 nodes are connected using 1 PLC link and separate PLC link was used to connect each concentrator.

It can be seen from Figure 6.9 that when the number of concentrators increased from 1 to 8 the STR also increased for separate PLC link case and reached 100% for 8 concentrators. But with 1 PLC link case it decreased and reached about 40% for 8 concentrators. Because the actual communication bandwidth is shared among all 200 nodes, increasing the number of concentrators does not increase the success rate. The nodes in the shared PLC medium try to send the data when there are no other nodes sending at that time. If more concentrators are connected to this medium the efficiently in allocating the resource for each node is decreased. This eventually results in longer back-off period hence the transmission time will be higher.

The results proved that using 1 PLC for nodes and increasing the number of concentrator results in adverse effect on the transmission time. Therefore, when using the PLC network for connecting with smart meters separate PLC links should be used to connect a group of smart meters in order to increase the transmission time performance as depicted in the figure with red line. Therefore, in other scenarios separate PLC link was used when increasing the number of concentrator.

Successful transmission rate vs. number of concentrators for 100, 200 and 400 nodes

The successful transmission rate against the number of concentrators for varying number of nodes is shown in Figure 6.10. Three cases, 100, 200 and 400 nodes were plotted (Figure 6.10) to realise the required number of concentrators for each case on the same diagram. It can be noted from Figure 6.10 that all 100 smart meters will send all the data if 4 or more concentrators are used. Even with 1 or 2 concentrators the success rate is around 97%. But for 400 smart meters it is required to have minimum of 8 concentrators for a 100% success rate. It can also be seen from Figure 6.10 that when the number of concentrators was increased to 8 the success rate became 100% for all three cases (100, 200 and 400 nodes). This means that all the smart meters will send all the data within 5 seconds time limit.

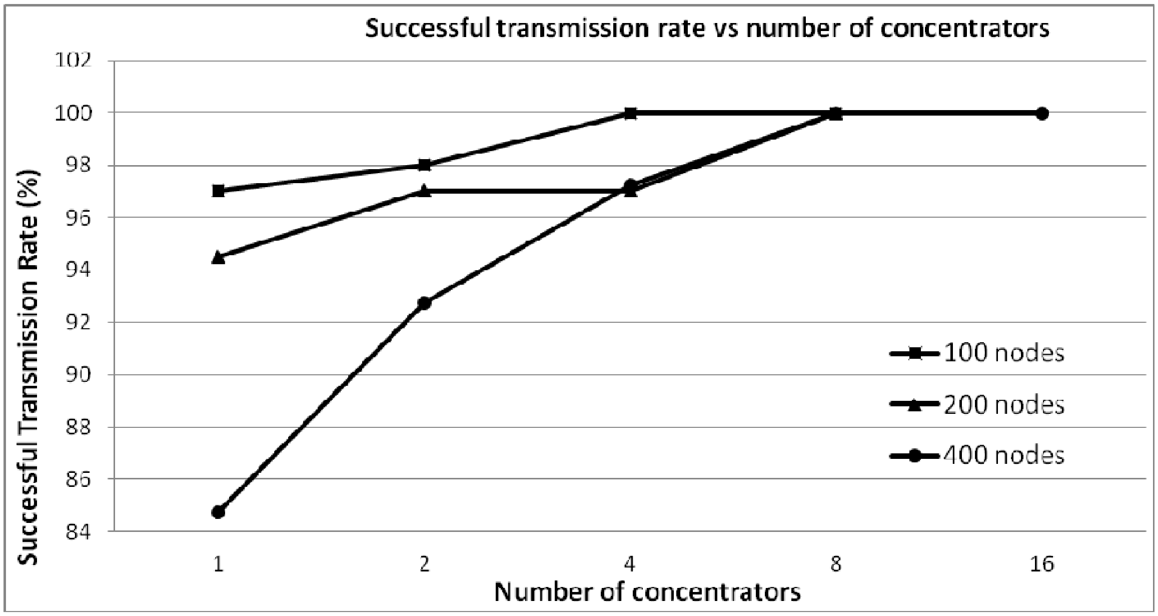

Figure 6.10: STR vs. number of concentrators for 100, 200 and 400 nodes

This comparison is helpful to the DNOs to decide the number of concentrators required to guarantee the relevant success rate. If the response time is irrelevant for the DNO applications and it requires all the data to be delivered to its control centre servers then it can be chosen to have only 2 or 4 concentrators. And this may reduce the cost involved with the number of concentrators.

6.2.4 Transmission Time vs. Request Data Size

Under this section, the performance of transmission time was evaluated by varying the request data size. These tests will reveal the required request data size for a preferred transmission time for varying DNO applications. The DNOs can set either the transmission time (seconds to minutes) or the request data size (10 to 145888 bytes) to achieve the required performance for their applications, depending on the criticality (low or high) of the applications.

Scenario6: Transmission time vs. varying request data sizes for 100 and 200 nodes with 1 concentrator

Simulation tests were carried out for 100 and 200 nodes by varying the request data size from 10 to 145888 bytes and the transmission time was recorded. Figure 6.11 shows the variation of the transmission time against varying request data sizes (from 10 to 145888 bytes).

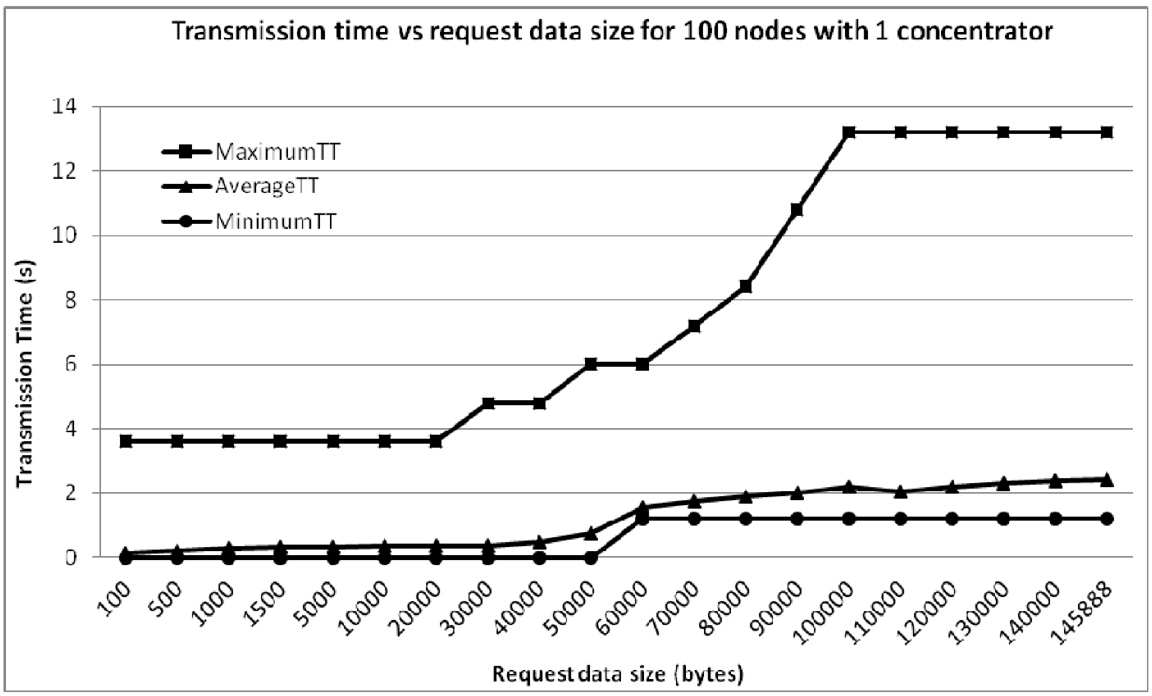

Figure 6.11: Transmission time vs. request data size for 100 nodes

The maximum (145888 bytes) and minimum (100 bytes) data sizes are used as per the specification on the ENA document [6]. In this ENA document it was also discussed that this data size assumption may vary from hundreds of bytes to thousands or tens of thousands of bytes. Therefore, a larger data size range was used during the simulation to evaluate the transmission time effects. The figure illustrates that the average transmission time increased steadily throughout. But with the maximum transmission time there is a steep increase 60000 to 100000 bytes and this is mainly due to the higher bandwidth consumption due to burst data sizes that eventually results in larger back-off time for some nodes in the PLC network. Again, this is only for few nodes but most of them managed to send with a smaller average transmission time.

A similar performance was observed in the following figure when the request data size was varied for 200 nodes with 1 concentrator. The maximum transmission time increased continuously and reached about 22 seconds (much higher compared to the maximum transmission time in 100 nodes case) with the data size of 145888 bytes.

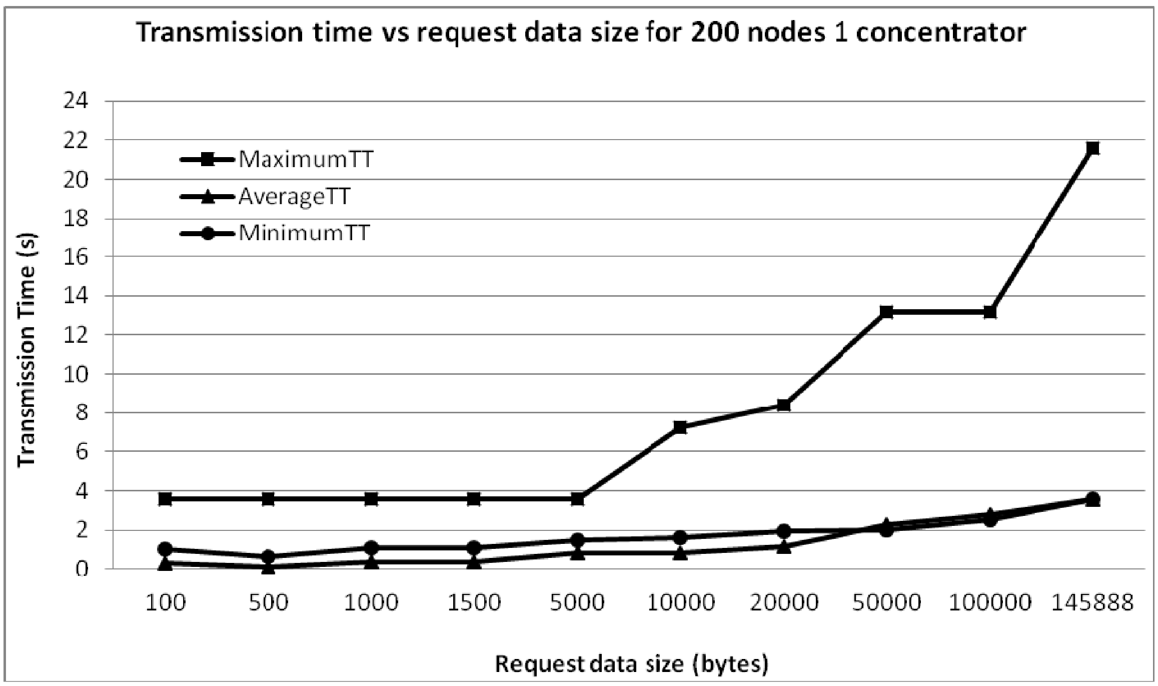

Figure 6.12: Transmission time vs. request data size for 200 nodes

Several other studies can be carried out to study and evaluate the performance of the smart metering infrastructure and the PLC network by varying different parameters. These studies will be valuable for the DNOs during their planning and design stages before deploying smart meters in their LV network. To analyse the distribution of the transmission time for different number of nodes, the cumulative distribution function (CDF) was used. Figure 6.13 shows the distribution of the transmission time for 100, 200 and 400 nodes cases. Different threshold percentage values can be used to identify the resulting transmission time for each case. For example, the 95% threshold value is set as seen in Figure 6.13 and from this the minimum transmission time can be derived from the graph if 95% of the nodes will have to transmit all the data. For 100, 200 and 400 nodes this value is about 10.5 seconds, 12.5 seconds and 21 seconds respectively.

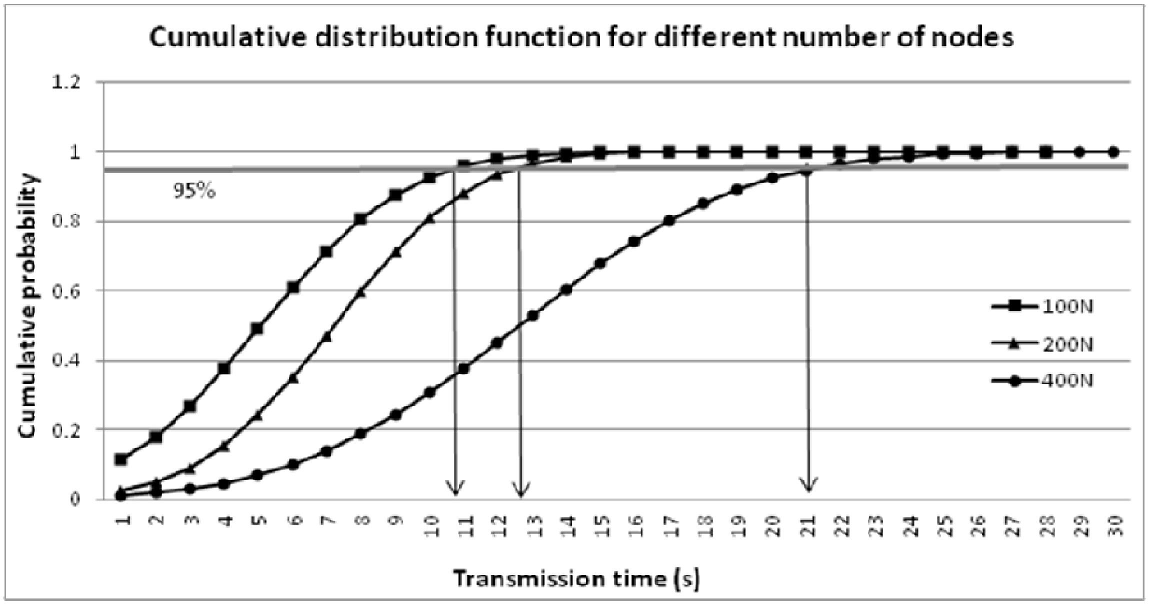

Figure 6.13: CDF of Transmission time for different number of nodes (100, 200 & 400 nodes)

If the DNOs require all the smart meter data to be transmitted to the concentrator and do not require stringent response time guarantees, then this threshold value can be set to 100% and the resulting transmission times can be read from the graph accordingly as shown in Table 6.1.

Table 6.1: Transmission time for different number of nodes

Cumulative Probability	Transmission time (seconds)		
	100 Nodes	200 Nodes	400 Nodes
95%	10.5	12.5	21
100%	14	15	26

The CDF for the transmission time is shown in Figure 6.14 when the number of concentrators was varied from 1 to 16 for 400 nodes. The 95% threshold is set and the resulting transmission times can be read for 1, 2, 4, 8 and 16 concentrator cases and they are about 21, 8.5, 4.5, 2 and 2 respectively. This distribution analysis is useful for the DNOs to decide the number of concentrators required to receive the data from particular percentage of the smart meters. In this example, the transmission times can be read from the graph and 95% of the smart meters managed to send all the data with the different transmission time provided above. These threshold set points can be set at different levels on the graph to derive the number of smart meters and the corresponding transmission times.

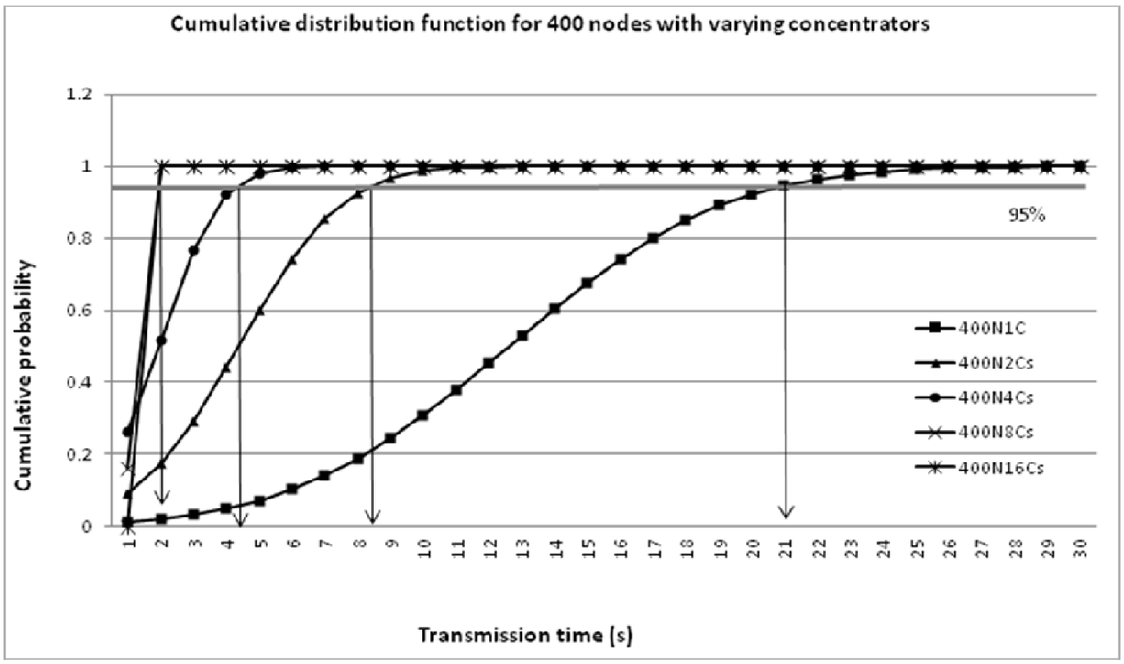

Figure 6.14: CDF of Transmission time for different number of concentrators for 400 nodes

In Figure 6.14 the short notations (400N1C, 400N2Cs, etc) are interpreted as follows:
400N1C – 400 nodes with 1 concentrator where C stands for concentrator
The 95% and 100% threshold values are derived from Figure 6.14 and are shown in Table 6.2 where the increase in transmission time can be noticed when the cumulative probability was increased from 95% to 100%.

Table 6.2: Transmission time for different number of concentrators for 400 nodes

Cumulative Probability	Transmission time (seconds)				
	1C	2Cs	4Cs	8Cs	16Cs
95%	21	8.5	4.5	2	2
100%	28	12	7	2.5	2.5

The short notation '1C' in Table 6.2 stands for 1 concentrator and '2Cs' for 2 concentrators and so on.

6.3 Concluding Remarks

The OPNET based simulation study was carried out to evaluate the performance and scalability of the PLC network for smart metering infrastructure using several scenarios. Under each scenario, the number of concentrators (1, 2, 4, 8 and 16), the number of smart meters (100, 200 and 400), the request data size (10 to 145888 bytes), the data transmission time and the successful transmission rate were discussed.

Several scenarios were used to evaluate the PLC network performance under two main performance parameters, transmission time and successful transmission rate. There was an exponential increase in the transmission when the number of nodes was increased from 10 to 400 under Scenario1. With an order of magnitude increase in the number of nodes the average transmission time almost doubled but the maximum transmission time tripled. For 400 nodes, the average transmission time was 12 times larger than for 40 nodes. When the number of concentrators was increased from 1 to 16 for 400 nodes the maximum transmission time fell from 30 seconds to around 1.2 seconds. This is useful information to the DNOs when deciding how many concentrators will be needed to provide an acceptable transmission time for the smart meters. This information will also contribute towards the cost benefit analysis there the DNO can decide how many concentrators will provide an optimum solution for a particular application. If it is for the control or real-time tariff applications it is important to receive all the data from all the smart meters within a short time (preferably in near to real-time). If all the smart meter data are collected for any other non-critical applications it may not require short response time.

The transmission time behaviour for 200 and 100 nodes cases were discussed under Scenarios 3 and 4 respectively. Maximum of 8 and 4 concentrators were used for 200 and 100 nodes respectively and all the nodes managed to send all the data within 5 seconds limit. Scenario5 evaluated the successful transmission rate for varying number of concentrators. 100% successful transmission rate was achieved for 100, 200 and 400 nodes with minimum of 4, 8 and 8 concentrators respectively. If the DNO require 100% performance from the smart meter data transfer it can decide how many concentrators are needed for different of number of nodes.

Transmission time against varying data size (from 10 to 150000 bytes) was evaluated for 100 nodes with 1 concentrator under Scenario6. There was exponential increase in the transmission time when the data size was increased from 10 bytes to 150000 bytes. This result can be used by the DNO to decide the relevant data size for a required transmission time.

The final scenario, Scenario7, discussed the performance of transmission time against varying number of nodes for minimum data size (100 bytes). The average transmission time was always less than 1 second for all cases. The maximum transmission time exceeded 5 seconds only for 400 nodes case with only few nodes sending all the data outside the 5 seconds. Therefore, if the DNOs require all the smart meters to send all the data within the 5 seconds time limit then the data size can be set to 100 bytes.

Chapter 7 Conclusions and Suggestions for Future Research

The integration of ICT into the existing power grid is a key enabler to meet the targets set out by governments around the world to tackle many challenges faced with the growing energy crisis. Therefore, detailed study has to be carried out to provide low-cost, scalable and secure communication solutions to make the Smart Grid visions a reality. A detailed performance evaluation of different communication media for distribution networks was carried out using simulation and experimental tests in this research project. Several tasks were carried out throughout this project and a number of contributions were made to this research area. They are discussed below under separate sections and the future research or further developments to these areas are also highlighted at the end of this chapter.

7.1 Performance Evaluation of Communication Media

Performance evaluation of different communication technologies is important for distribution network operators because they have access to more than one communication solution. Therefore, providing a low-cost, scalable and reliable solution is beneficial for the DNOs and it helps them to carry out their day-to-day activities efficiently.

Three communication technologies were tested during this research project and their throughput and latency performance was evaluated. Then the experimental test results from the HiPerDNO project were used to verify the simulation test results. A detailed analysis was carried out under different cases such as, different communication technologies (GPRS, UMTS and PLC), different transport layer protocols (UDP and TCP) and, minimum and maximum throughput and latency. The cellular network (GPRS/UMTS) was restricted by its bandwidth therefore applications requiring low bandwidth (57-384 kbps) can utilise this communication medium for data transfer. However, its flexibility on being able to move around places and its capability to connect larger geographical locations make it a suitable candidate for the last mile solutions. The PLC provided higher throughput and low latency over short distance compared to the GPRS/UMTS. However, this technology is accessible in a fixed location and it will experience severe performance degradation if electrical devices are intermittently connected to the network.

The case studies used to analyse the requirements for high speed communication and high performance computing provided useful information to identify some existing and emerging technologies. These studies were based on perspectives from two different countries, UK and Belgium. This initial comparison was useful to identify the required communication performance and storage capacities for varying number of smart meters. It can also be noted that when the smart meters are fully deployed, the estimate data traffic and data storage capacity values will be useful for the DNOs to plan their communication and computing resources to accommodate these huge demands.

The simulation model can be effectively and easily used to test the relevant real network, it was intended to vary different parameters of the network in the simulation environment to evaluate the performance of the underlying communication media. Incorporating several characteristics of these different communication media into the simulation models is important for accurate simulation studies and is useful for the DNOs to study the performance of their communication infrastructure using cost-effective and convenient simulation studies.

7.2 Performance Evaluation of Smart Metering Infrastructure

A simulation based smart metering infrastructure was set-up using the OPNET simulator and the OPNET based PLC communication medium was used to evaluate the performance of the infrastructure using different scenarios (Chapter 6).

Several parameters, such as number of smart meters, number of concentrators, request data size, number of PLC links, etc., were varied to study the transmission time and successful transmission rate performance characteristics. 10 to 400 smart meters were tested to study the transmission time behaviour with the increase in the number of smart meters and it resulted in exponential transmission time increase. The tests were carried out for both maximum request data size of 145888 bytes and the minimum of 100 bytes as specified in the ENA document.

The number of concentrators was varied for 100, 200 and 400 smart meters and the transmission time performance was evaluated. The transmission time decreased with the increase in the number of concentrators as expected and it reached below 5 seconds when 4, 8 and 8 concentrators were used for 100, 200 and 400 smart meters respectively. The successful transmission rate was evaluated for this different number of smart meters to decide how many of them manage to send all the data within a specified time period (5 seconds). Finally, the request data size was varied from 100 bytes (minimum) to 145888 bytes (maximum) to investigate the transmission time response and there was exponential increase in the transmission time when the data size was increased from 100 to 145888 bytes. Further studies were also carried out to verify the results derived from the simulation using the cumulative distribution function and the probability density function at the end of Chapter 6.

7.3 QoS Monitoring Tool for Bandwidth Intensive Applications

A Client/Server based Java program was significantly modified to include a gateway to monitor the performance of the bandwidth intensive application (video streaming). Different QoS parameters were calculated at the gateway and the results were displayed in real-time in a GUI. These parameters were also stored in a file for off-line analysis. This test-bed was then integrated with the LiveGraph [88] tool to display the QoS parameters graphically using different window properties as explained under Chapter 4. Several modifications were made to the test-bed to realise the real network conditions, such as random packet drop, packet delay using different number of hops, packet delays within the gateways, etc.

The performance of the developed test-bed was compared against the well know Wireshark monitoring tool. The proposed monitoring tool outperformed the Wireshark in terms of packet delay and jitter performance as discussed under the results and analysis section in Chapter 4. Different components of this test-bed were combined within a batch file so that the implementation of the test-bed using on any computer was made convenient. The end user does not need to know how the different modules work and should be able to run the software very easily.

7.4 Suggestions for Future Research

This section indicates some possible future works that can be carried out from this research. Different aspects of the communication technologies for the distribution networks were investigated and resulted in many areas to be researched about. Within the duration of this research not all the aspects were implemented therefore some topics need further investigation and future works. These topics are listed in the following section.

- Further studies can be carried out from the simulation models used in Chapter 5 to study the effects under varying network conditions by changing the parameters. These studies will be useful to the DNOs to plan and design solutions for their communication infrastructure to accommodate the future demands from the Smart Grid. Several studies can be carried out to improve the throughput and latency performance for the cellular network (GPRS/UMTS). The effects when the distance between the user equipment and the base station is changed can be evaluated to propose the optimum positioning of the user equipment in the network. Further studies may include the performance analysis of the network when several other bandwidth intensive applications are using the network for data transmission. These studies will reveal the different effects on the throughput and latency performance. The performance degradation of the PLC medium can be evaluated by introducing different types of noise. The scalability of the PLC network can be tested by adding different number of devices to the PLC medium and by evaluating the throughput and the latency performance. An adaptive rate control technique can be used to improve the performance of the PLC. The IEC 61850 GOOSE messaging can be tested using the OPNET simulator and the different characteristics can be evaluated in the simulation environment as discussed under Section 2.2.2.

- The publisher/subscriber model in OPNET was modelled by the MSc students and this model needs further modification to realise the full functionalities of middleware architecture. It can also be modified to include some properties of the InfoBridge middleware and the performance can be compared. The alpha version of the InfoBridge middleware was tested using simple set-up to evaluate the throughput and latency performance as part of the HiPerDNO project. Further studies can be carried out to test different aspects of this middleware and the results can be compared against a similar simulation model in OPNET. The initial publisher/subscriber model in OPNET can be modified to include the characteristics of the InfoBridge middleware. A large scale Smart Grid infrastructure can be set-up in OPNET by integrating different communication models that were developed through this research and a simulation demonstration can be performed.

- The initial smart metering infrastructure set-up can be used to study different other performance characteristics by changing different parameters. The cost benefit analysis can be carried out to provide useful information to the DNOs using the initial smart metering infrastructure testing carried out as part of this research. The initial testing included information regarding the number of smart meters and concentrators for LV network. The scalability of this infrastructure can be tested by increasing the number of smart meters to higher value (500, 1000, etc.). The noise can be introduced to the PLC medium and the performance can be evaluated to see how the noise effects affect the performance of the overall infrastructure.

- The proposed QoS monitoring test-bed can be improved by carrying out further studies and developments as discussed below. Testing this test-bed over different types of networks (WAN, wireless, etc.) to evaluate its scalability and capability to adapt to various network environments. Developing the test-bed to apply for more real time video/audio network applications based on any other protocols, creating databases to store analysis reports during the monitoring of network applications for future analysis, considering the possibility of routing only the RTP packets to specific gateway for QoS analysis hence the delay experienced by other traffic can be significantly reduced while the monitoring is carried out, and integrating this monitoring tool with the electrical distribution networks related management and monitoring activities locally or centrally. This test-bed can also be integrated with the InfoBridge middleware to realise a wide area network communication by including the smart metering data transfer as the bandwidth intensive application.

7.5 List of Publications and Reports

1) "Modelling and Analysis of Noise in Power Line Communication for Smart Metering,"
2) "Evaluation of Throughput and Latency Performance for Medium Voltage and Low Voltage Communication Infrastructures"
3) "Developing Novel Information and Communications Technology based Solutions for Smart Distribution Network Operation"
4) "Evaluation of QoS Parameters for Real-time Rich Media Applications Using a Test-bed Implementation"
5) "Design and Implementation of Roof-top Wind Turbine Monitoring System"

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