Experimental Analysis and Modelling of an Information Embedded Power System

A Thesis

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DOCTOR OF PHILOSOPY

By

Amanullah Maung Than Oo

To

School of Electrical Engineering

Faculty of Health, Engineering and Science

Victoria University
Australia

Declaration of Originality

I, Amanullah Maung Than Oo, declare that the PhD thesis entitled “Experimental Analysis and Modelling of an Information Embedded Power System” is no more than 100,000 words in length, exclusive of tables, figures, appendices and references. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Amanullah Maung Than Oo

To my wonderful wife Habibah Begum

and

Our lovely son Midhad Aman

ABSTRACT

As power industry enters the new century, powerful driving forces, uncertainties and new functions are compelling electric utilities to make dramatic changes in their information communication infrastructure. Expanding network services such as real time measurement and monitoring are also driving the need for more bandwidth in the communication network and reliable communication infrastructure. These needs will grow further as new remote real-time protection and control applications become more feasible and pervasive. Information embedded power system via wide area network (IEPS-W) is the solution to accommodate the growing demand of wide area monitoring, protection and control. IEPS-W is an extension of traditional power systems with added monitoring, control and telecommunications facilities.

Various power system communication protocols are being used within IEPS-W to transmit critical data in real time along with decades old Supervisory Control and Data Acquisition System (SCADA). Most of the protocol in used are not originally developed to use in wide area computer network (WACN) environment. However, protocol developers upgrade their protocols and use it in WACN. This requires experimental investigation of various power system communication protocols before employing it on the power grid.

An experimental platform was set up at Victorian Network Switching Centre owned by SP AusNet PTY LTD (an Australian Transmission and Distribution company based in

Victoria) in order to experimentally analyse the performance characteristic of Distributed Network Protocol (DNP3) over wide area network (WAN). In this experiment, real time data were sent from Intelligent Electronic Devices to utility control center using WAN.

Experimental work reveal that measurement delays associated with DNP3 over WAN is high, as this type of network is much more complex due to the added complexities of routing and switching. This requires further development of DNP3 protocol to be reliably used in IEPS-W. Hence, DNP3 was further developed using Optimized Network Engineering Tools (OPNET). OPNET is the industry's leading simulator specialized for network research and development. Finally, a new protocol has been developed based on DNP3 protocol to reliably and securely transmit power system data for IEPS-W.

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LIST OF ABBREVIATIONS

ACSI	Abstract Communication Service Interface
AGC	Automatic Generation Control
ALP	Application Layer Protocol
ATM	Asynchronous Transfer Mode
CASM	Common Application Service Models
CORBA	Common Object Request Broker Architecture
CRC	Cyclic Redundancy Code
CSMA/CD	Carrier Sense Multiple Access/Collision Detection
DA	Destination Address
DCOM	Distributed Component Object Model
DES	Data Encryption Standard
DMS	Distributed Management System
DNP3	Distributed Network Protocol version 3
DPU	Data Processing Unit
DTS	Dispatcher Training Simulator
EMS	Energy Management Systems
EPRI	Electric Power Research Institute
FACTS	Flexible AC Transmission System
GOMSFE	Generic Object Models for Substation and Feeder Equipment
GOOSE	Generic Object-Oriented Substation Events

ICCP	Inter-control Centre Communications Protocol
ICV	Integrity Check Value
IEC	International Electrotechnical Commission
IEDs	Intelligent Electronic Devices
IEEE	Institute of Electrical and Electronics Engineers
IEPS-W	Information Embedded Power System over Wide Area Network
IETF	Internet Engineering Task Force
IIN	Internal Indications
IKE	Internet Key Exchange
IP	Internet Protocol
IPSec	Internet Protocol Security
IT	Information Technology
LAN	Local Area Network
LPDU	Link Protocol Data Unit
LSDU	Link Service Data Unit
MMS	Manufacturing Message Specification
MTU	Master Terminal Units
NIS	Network Integrated System
NTP	Network Time Protocol
OO	Object Oriented
OPNET	Optimised Network Engineering Tools
OSI	Open Systems Interconnection
PGP	Pretty Good Privacy

PKI	Public Key Infrastructure
PLC	Power Line Carrier
PSTN	Public Switched Telephone Networks
PVC	Permanent Virtual Circuit
RTS	Richmond Terminal Station
RTU	Remote Terminal Unit
SA	Substation Automation
SCADA	Supervisory Control and Data Acquisition System
SCSM	Specific Communication Service Mapping
SDU	Service Data Unit
SEL	Schweitzer Engineering Laboratories
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical Network
SSL/TLS	Secure Sockets Layer / Transport Layer Security
SVC	Switched Virtual Circuit
TCP/IP	Transmission Control Protocol/Internet Protocol
TH	Transport layer Header
TPCI	Transport Protocol Control Information
TPDU	Transport Protocol Data Unit
TSDU	Transport Service Data Unit
UCA	Utility Communication Architecture
UDP	User Datagram Protocol
UDP/IP	User Datagram Protocol/Internet Protocol

VHF/UHF	Very High Frequency / Ultra High Frequency
VNSC	Victoria Network Switching Centre
VOIP	Voice Over Internet Protocol
VON	Virtual Overlay Network
VPN	Virtual Private Network
WAN	Wide Area Network
WACN	Wide Area Computer Network
XML	Extensible Markup Language

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CHAPTER 1

THESIS OVERVIEW

1.0 Introduction

An Information Embedded Power System over wide area network (IEPS-W) is an extension of traditional power systems with added monitoring, control and telecommunication capabilities. In this thesis, information embedded power system refers to transmitting power system data from various Intelligent Electronic Devices (IEDs) or Remote Terminal Units (RTU) to the control centre using Distributed Network Protocol (DNP3) over Wide Area Network (WAN). A simplified illustration of an IEPS-W is shown in Figure 1.1.

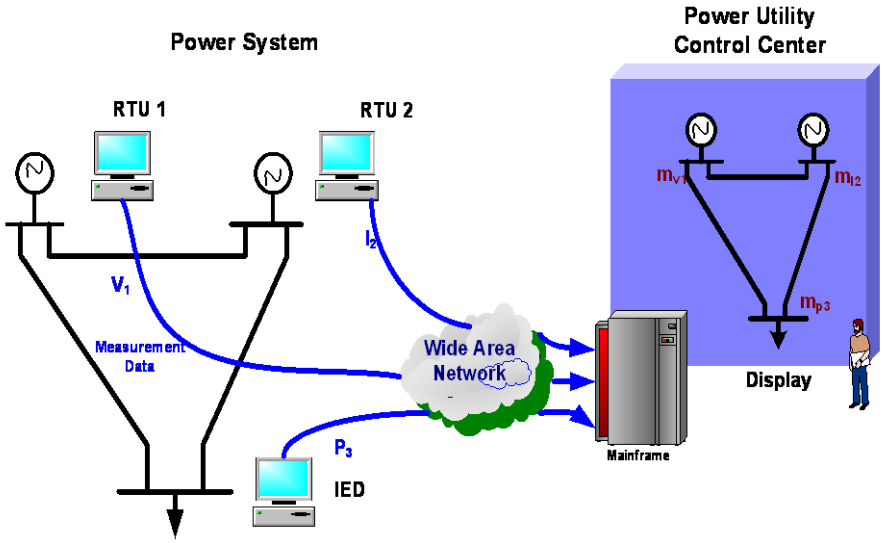


Figure 1.1: Information embedded power system over WAN (IEPS-W)

As seen in the figure, IEPS-W consists of: i) power system hardware ii) the measurement system – which is represented by IEDs or RTUs iii) the communication system representing WAN and iv) the electric utility control centre. In this system, IEDs or RTUs record power system measurements and send them in real time over a wide area computer network to the power control centre using DNP3 protocol. Control centres also send control messages to various IEDs to perform control actions such as opening/closing breakers, relays actions, transformer tap changing and generation control. This thesis investigates the performance accuracy and characteristics of the DNP3 protocol over WAN when data are being sent from IEDs to control room.

Various power system monitoring and observability method has been discussed in references [1-12]. Power utility uses different power system communication protocols to transmit data from field devices to control centre using dedicated proprietary link. Recently, with the advancement of information and communication technology, utility utilizes computer network technology to transmit power system data. However, little research is available showing investigation whether any investigation involving the existing power system protocols are able to deliver the service requirements when power system employs existing protocols over computer network especially over WAN. This thesis is a pioneering step in attempting to investigate the propagation delays associated in DNP3 protocols when power system data are being sent over WAN. Higher propagation delays in the power network due to propagation delay may render parts of the power system unobservable and uncontrollable.

Due to increasing demand of data by various utility, research efforts have begun to make power system communication infrastructure more efficient, reliable and secure. Further research has also been focused on how delays in computer control networks can introduce errors in measurements, when these measurements are sent across the wide area network. Carullo has done a thorough experimental study on measurement delay errors while power system employs local area network (LAN) to transmit power system data [13].

A Matlab simulation study was performed by Lian, Moyne and Tilbury [14] to determine key performance parameters of several types of common direct-link computer networks. These parameters included network utilization, magnitude of expected time delay and characteristics of time delays. Skeie, Johannessen and Brunner [15] investigated whether Ethernet has sufficient performance characteristics to meet real-time demands of substation automation. Luque, Escudero and Perez [16] also develop an analytical model of the relationship between measurement error and delay. They modelled the evolution of magnitudes in electric networks as a first order autoregressive process AR(1). This model assumes measurement error is a function of both the communications delay and the bandwidth of the evolution of the voltage magnitude.

Section 1.2 provides some motivation on the requirement of the performance analysis of currently available power system communication protocols. Research methodologies and techniques are discussed in Section 1.3. Organization of the thesis is presented in Section 1.4. Section 1.5 highlights originality of the thesis.

1.1 Motivation

Information exchange is a vital component in the efficient operation, profitability and growth of a restructuring electric power industry. Commercial and regulatory needs today mandate a variety of advanced utility functions [13], including:

- Real-time calculation/optimisation of total/available transmission and generation
- Contingency assessment and response using live data to feed wide-area protection and islanding algorithms
- Asset and workforce management with constantly updated databases
- Spot market/power exchange energy pricing and delivery
- Demand response, energy efficiency, and customer management through real time pricing, advanced metering and distributed generation
- Outage management, auto-restoration and distribution network optimisation based on up-to-the-minute data from customer premises.

Integrated information systems and telecommunications networks capable of supporting these functions, as well as future capabilities, are critical in the changing utility environment.

Key to facilitating this exchange is adherence to industry standards and specifications and utilisation of established protocols in the design, implementation and operation of electric power and communication systems. For a utility to deploy and maintain an open

and interoperable communications and control environment, standards must shape the architecture and accepted practices of the entire enterprise, especially when it is required to integrate different systems, vendors and technologies.

To improve the efficiency of a power system, it is necessary to develop power system monitoring devices and the system which can integrate and analyse the data from the devices. The system having the function to control the power system property is important, where the data collected with the device will be used as a control input. It is expected that there will be many of communication activities between the devices and the system. Thus designing the efficient communication protocol is very important. For this reason, it is vital that the performance of existing power system communication protocols is experimentally analysed. For example, the distribution of packet delivery times under different network traffic using different protocols may have a large effect on the real-time state estimation solvability or cause unacceptable error magnitudes. Random network traffic may cause delays in delivering metered data to the state estimator in the control centre, which may render many buses in a power system unobservable during one or more calculation intervals [14].

The modern trends towards implementing computer networks for transmitting power system measurements to the power system control centre, have provided a motivation for studying the performance of different protocols when employed in WAN. Up until now, little research has been carried out to experimentally investigate performance analysis of various available power system communication protocols. Furthermore, little

research has been done to analyse how random measurement delays due to WAN traffic can affect the accuracy of power system measurements. Hence, experimental investigation is required to systematically analyse performance characteristic of different power system communication protocols before adopting them into WAN environment.

1.2 Research methodologies and techniques

This research aims to experimentally study the performance of DNP3 protocol over WAN when data are sent from various IEDs to power control centre. The main aim is to develop an efficient power system communication protocol based on DNP3 for an information embedded power system to significantly reduce the propagation delay associated with DNP3. The experimentation was done using real life power system hardware, tools and software own by SP AusNet (a Australian Transmission and Distribution Organisation based in Victoria). Modelling, design, implementation, simulation and development was carried out using appropriate software development and network design tools called Optimized Network Engineering Tools (OPNET). The details of proposed methodology and techniques to achieve the requirements of this research project are as follows:

1.2.1 Analysis of the currently available systems / Literature review

This initial stage of the research program involved searching the state of art in the field of power system monitoring, control and protection by analysing the currently available

systems in order to recognize the weaknesses of the present power system communications protocols which are used in the utility. This step of analysis and research showed that up until now, little research has been performed to experimentally investigate power system communication protocols such as DNP3 when power system data are sent via WAN for efficiently and reliably transmitting power system data for monitoring, control and protection purposes.

1.2.2 Setting-up experimental platform

An experimental platform was set up at Victorian Network Switching Centre owned by SP AusNet Pty LTD in order to experimentally analyse the performance characteristic of DNP3 protocol over WAN when data are sent from IEDs to utility control centre using WAN. More specifically, the experiment was setup to experimentally measure the propagation delay associated with DNP3 over WAN. The experimental platform consists of power system hardware, measurement system, embedded computer network communication system (WAN) and power system control centre as shown in Figure 1.1. After experimental platform had been set up, power system data were sent from IEDs to control center via WAN using DNP3 protocol and r the propagation delay recorded. The experimental platform utilises TEKRON precision clock to accommodate the precision timing.

1.2.3 Development and implementation of DNP3 link and transport layer modules

The measurement delays associated with wide area network was very high as this type of network is much more complex due to the added complexities of routing and switching. Hence, based on the experimental data collected and carefully investigating the data, a more efficient and reliable protocol is developed based on DNP3 protocol using OPNET modeller. DNP3 link and transport layer was initially developed to analyse the protocol.

1.2.4 Design and implementation of DNP3 application layer modules

Application layer of DNP3 protocol is vital for critical data communication process. It describes the message format, service and procedures. The application layer responds to complete messages received (and passed up from the transport layer) and builds messages based on the need for or the availability of user data. Once messages are built, they are passed down to the pseudo-transport layer where they are segmented and passed to the data link layer and eventually communicated over the physical layer. After successfully developing the DNP3 link and transport layer, application layer was developed using OPNET technology to fully investigate and simulate the measurement delays involved in DNP3 over WAN.

1.2.5 Development of time efficient information embedded power system

A more reliable and time efficient power system communication is required in order to transmit power system data more reliable and efficiently. After successfully developing

DNP3 in OPNET environment, a more reliable and time efficient IEPS-W has been developed reducing the propagation delay involved in DNP3 over WAN. This allows provide power system to monitor, control and protect more efficiently.

1.2.6 Development of secure information embedded power system

Modern power utility faces significant security threat when they employ internet technology to transmit the power system critical and non-critical data. A more secure and reliable communication system is essential to avoid catastrophic disaster from major information attack. Hence, a more secure and reliable information embedded power system has been developed for the modern utility based on DNP3 protocol for IEPS-W.

1.3 Organization of the Thesis

This thesis contains eight chapters and is organized as follows:

Chapter 1 provides basic introduction about the research as well as the motivation behind this research. This chapter also includes the research methodologies and techniques and the contribution of this research to the knowledge of science and engineering.

Chapter 2 presents literature review of power system communications, recent developments and the use of protocols and future power system information needs. It further discusses the power system communication requirements in deregulated power industry highlighting the importance of efficient communication requirement in the deregulated power industry.

An overview of information embedded power system over wide area network has been presented in Chapter 3. It also details discussion on power system communication protocols and wide area computer network together with an overview of energy control centre. Chapter 4 presents detailed experimental analysis of DNP3 protocol over WAN for an IEPS-W. It includes detailed experimental set up and procedure carried out to investigate performance of DNP3. Experimental results and data have also been included.

Chapter 5 presents modelling of information embedded power system. A brief overview of OPNET modeller which was used for simulation, design and development of DNP3 protocol has been discussed. The design and implementation details of each layer of DNP3 have been presented. Chapter 6 elaborates on the development of time efficient information embedded power system together with requirement of time critical infrastructure for power system. The implementation and development of secure information embedded power system is presented in Chapter 7. The conclusions and future scope for this research are discussed in Chapter 8.

1.4 Originality of the Thesis

This research will contribute to the knowledge in information embedded power system as it addresses major issues in efficient and reliable power system communication. The experimental analysis and development of IEPS-W is one of the pioneering attempts in power system communication.

This research will contribute to knowledge in the following specific areas:

(1) Contributes to the knowledge by identifying the requirement of performance analysis for different power system communication protocols. The proposed research will be immensely beneficial to power protection and control engineers since it further enhances the understanding of the different power system communications protocols.

(2) Contributes to the knowledge by conducting experiment to study the performance of DNP3 over WAN for an information embedded power system, identifying the critical issues behind the development and design of a specific communication service aimed at providing all sorts of communication mechanisms to DNP3 based applications running within power network.

(3) The proposed research is significant since it develops DNP3 protocol using OPNET modeller which will be very useful for future research and development.

(4) Contributes to knowledge since it develops a more reliable and efficient power system communication protocol based on DNP3 protocol.

(5) Further contributes to knowledge since it looks at the most critical issues of power system which is power system security. The developed power system security will enhance the vulnerability of power system communication.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The purpose of this chapter is to provide the necessary background required to understand the concepts that relate to power system communications, recent developments and the use of protocols for an information embedded power system.

Power supply is one of the most essential resources to the human society development. The cost of power outage is on the order of billions of dollars [17, 18]. In addition, power system can become vulnerable in the face of possible system abnormalities such as control, protection or communication system failures, disturbances and human operation errors. Therefore, to keep power supply stable and reliable is a very critical issue for future power system design.

Computer networks and data communication play important roles in power systems [19]. Applications from Supervisory Control and Data Acquisition System (SCADA) [20], remote measurement [21, 22], to monitoring and control [23], and protection [24] are critical to the proper operation of power system in order to maintain system reliability and stability. The massive power break-ups in the last ten years cost billions of dollars in direct and indirect losses to the power industry worldwide. These critical incidents

clearly demonstrated the essential adoption of real time information coordination for the control system strategy design. Most communication technologies currently employed in the power system only allow local, narrowly focus, control actions [25] at the substation or line level due to lack of efficient, high speed, high bandwidth and reliable communication infrastructure.

As the electric power industry enters the new century, powerful driving forces, uncertainties and new services are compelling electric utilities to make dramatic changes in the power system information infrastructure design [26, 27]. The increasing incorporation of digital devices throughout the enterprise as well as the forces of deregulation is driving utility communications into new realms [28]. Expanding network services such as real time monitoring are also compelling the need for more increasing bandwidth in the communication network backbone. These needs will grow further as new remote real-time protection and control applications [29, 30] become more feasible and pervasive. Reliable communication capability with reliable communication protocol must exist both within a utility and with government emergency service respondent and other stakeholders to effect rapid recovery operations during a major disruption in the power system [31].

To highlight these, this chapter is arranged to provide deeper understanding of wide area power system communication issues and the importance of power system communication in modern power system. Section 2.1 elaborates on wide area power system monitoring, protection and control including impact of the information technology

on power system. A broader literature review portion of this thesis is discussed in Section 2.1 which covers deregulated utility communications requirements. In this section, importance of real time information in power system along with future power system information needs has also been discussed. A detailed elaboration on current power system data communication media has been presented in Section 2.3. Section 2.4 discussed various power system communication protocols used by power utility. A more integral part of power system communication is discussed in Section 2.5 as SCADA system design for electric utilities. Conclusion remark is made in Section 2.6.

2.1 Wide area power system monitoring, protection and control

The electric utility industry is going through significant changes caused by deregulation, distributed generation, increased competition and requirements for continuous improvement in the quality of power supplied to the users. At the same time, the use of the internet is growing, and more and more utilities are using WAN for their communications.

A WAN enabled monitoring, protection and control system is necessary to provide a complete pre-engineered and cost effective solution. While traditional SCADA systems are the main backbone of today's electric utility system for remote monitoring and control, the internet along with power system communication protocols provide an alternative vehicle for data communications and control for today's IEDs within the wide

area power network [32]. Power system communication protocols such as DNP3 and International Electrotechnical Commission 61850 (IEC 61850) play significant role couple with SCADA ensuring the effective and reliable monitoring of modern power system network.

The prerequisite is an efficient communication link not only for SCADA and energy management systems (EMS) but also for providing the protection, maintenance and planning departments with direct access from remote to information from the substation primary and secondary equipment [33]. Thus, WAN based monitoring has become a very significant part of the power system monitoring, protection and control.

2.1.1 Impact of the information technology on power system

2.1.1.1 Data Acquisition

With computing power making its way into the primary equipment, more and more equipment internal data can be made available to the outside at virtually no extra cost. Interfaces to acquire such internal data were previously not provided for cost reasons. Data that will be accessible includes, but is not restricted to:

- Switching counters
- Thermal information
- Quality of isolation media
- Entire timing curves of switching operations

- Switching currents
- Manufacturing data
- Original value of key performance criteria.

This kind of data can be the source of valuable condition information and exploited for building condition monitoring systems for those assets that exhibit the highest failure rates and/or cause unacceptable power interruption impact. Without doubt the transformers and circuit breakers are the prime candidates for these kinds of monitoring systems.

The second trend within the data acquisition falls into the category of IED, i.e. secondary equipment like protection terminals. Besides their primary functions, they host more and more additional functionality, which increase their attractiveness compared with dedicated single function units. Many of these additional functions provide a sound foundation for basic monitoring systems, cost-efficient and perfectly suited for medium and distribution voltage level IEDs for protection or control may comprise:

- Disturbance recorders
- Event recorders
- Statistical value recording (peak current indicators, number of starts/trips, current at tripping, etc.)
- Power quality analysers

- General purpose programming capabilities that allow to write and run customer specific applications on the IEDs
- Detective maintenance, i.e. to detect hidden failures by means of special functional checks and diagnostics.

The type of maintenance policy to select for specific equipment for transmission and distribution depends on reliability and on economic and customers' business related availability considerations, which take the consequences of failures into account [34].

2.1.1.2 Information Technology

There are three areas where advanced information technology (IT) applications can contribute significant benefits in terms of better power system performance and reduction of operating and maintenance costs:

1. Advanced power system management, which results in higher reliability of power supply
2. Intelligent substation automation which assures higher availability
3. On-line power system monitoring.

In comparison with the traditional way of communication in power system industry, the adoption of WAN technology to monitor, protect and control power system brings key benefits such as:

Mobility: In this context is the ability of a user of the system to access data without requiring physical configuration changes to the system to do so.

Simple Network Management Protocol (SNMP) Diagnostics: Remote diagnostics dealt primarily with the control and protection systems and not with the infrastructure that communicated the data. The SNMP protocol can be used to manage the complete network from Switches and Routers, Servers and Client PC's, Protection and Control devices to Printers. Using a network management system the health and performance of the network can be monitored in addition to allowing for the configuration of devices from a single point in the network. Bottlenecks in the system may be identified (where traffic is at its highest) and the routing or topology may be modified to alleviate any problems.

Scalability: Naturally the ability to add services must not adversely affect the existing system so hand in hand with this goes scalability. If an interface is too slow then simply add in or reconfigure the interface to a faster one. If fibre optic interfaces are used it is possible to scale from 100Mb to 1 or 10 Gb over the same fibres.

Voice over Internet Protocol (VOIP): As the WAN structure supports many protocols simultaneously it is simple to add voice communication to the bays and substations. No additional cabling is required. In fact some industrial users are considering VOIP as an alternative to their existing telephone system as they pay rental on the telephone wires even across their own site.

Video: In the same vein, the WAN can mediate video streams. These can be used for remote guidance in fault finding if site personnel are unfamiliar with the equipment or if the manufacturer needs to become involved. Web cams are cheap items and could be used freely. Specialist security/surveillance cameras can also be integrated into the system with facilities such as remote control and recording.

Remote Diagnostics: Performance data is collected and stored on each network devices and may be retrieved, stored and printed either using a diagnostic toolbox or by interrogation using SNMP. Remote diagnostics provide the ability to access this data from any point whilst not requiring any physical modification to the system. If any fault cannot be determined by local staff then external specialists can dial in to the system and perform more detailed analysis.

Tunnelling Protocols – Virtual Wire: Tunnelling allows a protocol to be transmitted as the data of another protocol. If serial protocol cannot be mediated over Ethernet and Transmission Control Protocol/Internet Protocol (TCP/IP) then it can be encapsulated as data in a protocol that can be. This offers reduced complexity and engineering and improves the overall diagnostics.

Robustness: An industrial application requires that it be resilient to failure within the system. A single point of failure should not adversely affect the system. To this end a ring of industrial Ethernet switches provide the backbone of the network over which all

communications occur. Failure of a single switch or fiber would be detected and rectified within 500ms by internal reconfiguration of the topology.

(Extension) Scalability: Due to the evolving nature of electrical networks, control and monitoring systems need to be scalable in both network structure and bandwidth. Network based technologies allow the addition of independent networks (subnets) to their structure. Furthermore, they can later be integrated into corporate networks.

(End of equipment life) Multi-Source Kit: As TCP/IP and Ethernet are ubiquitous one is not forced to use a single source for software or hardware in the network. Application software can reuse the infrastructure if replaced, without penalty.

(Bandwidth Changes) Faster Kit: As new equipment becomes available it is possible to upgrade the infrastructure without hindrance to faster devices when required.

Time Synchronization: A fast WAN topology allows for more accurate time synchronization than in tradition serial topologies. Network Time Protocol (NTP) is an adaptive time synchronisation protocol that can adjust and choose between multiple time sources. Propagation delays over the network can be accommodated [35].

2.1.2. Obstacles to technology

Robust, consistent computer networks for critical applications and infrastructures such as power system are still under development despite many years of research and

development in the area of trusted networked computer systems. The vulnerability of any network computing system increases with the number of network access points enabled within that system [36]. Thus, a wide-area network for electric power monitoring, protection and control suffer from the same obstacles seen in creating wide-area trusted computing networks such as:

- Lack of a wide-area based critical data communications infrastructure
- Vulnerability of the internet technology
- Lack of network quality of service guarantees
- Immaturity, fragility and lack of interoperability in trust frameworks
- The variety of control station and substation communications protocols and their lack of interoperability
- Socio-economic and political resistance to regularity controls.

The reliability demands and time-critical nature of electric power systems place additional burdens on quality of service guarantees and high-speed authentication and trusted communications. Although it is assumed that the same technologies for mitigating risk and implementing interoperability in computer networks could be used for control and protection in electric power systems. The above-mentioned barriers have now been elaborated.

2.1.2.1. Lack of wide area based critical data communications infrastructure

Birman in reference [37] states that in order to run mission-critical applications across wide spatial areas, there is a need to develop a Virtual Overlay Network (VON) separate from any next generation internet network that may evolve. In addition, Electric Power Research Institute (EPRI) has proposed the Inter-control Centre Communications Protocol (ICCP) as the base of an inter-regional communications infrastructure. The literal intent behind VON and ICCP is to segregate infrastructure related critical data communications (e.g., power system protection) from non-critical communications like e-commerce.

2.1.2.2. Vulnerability of Internet technology

As an alternative to a separate protection-level communications structure, several utilities and engineering services have experimented with using the Internet for access to control station data and substation equipment. While Internet access is sufficient for casual observation and maintenance planning, it is unsuitable for real-time protection. The internet is characterized by “best-effort” non-deterministic delivery via unsecure dynamic routing and is vulnerable to snooping, hacking and deliberate overloading. These weaknesses prevent its use for any aspect of time-critical control applications. Other telecommunications infrastructures include the Public Switched Telephone Networks (PSTN) and leased lines forming Asynchronous Transfer Mode (ATM) networks, Frame Relay Permanent Virtual Circuits (PVCs) and Frame Relay Switched Virtual Circuits (SVCs). The ATM and PVC solutions have reliability and quality of service suitable for critical applications and are discussed in the next subsection. PSTN and SVC solutions have reliability and quality of service concerns, respectively, that

create questions about their use in real-time applications. Therefore, internet access without any specialized protocol is unsuitable for real time protection; however it access is sufficient for casual observation and maintenance planning.

2.1.2.3. Lack of Network Quality of Service

There are a few mechanisms for ensuring the quality of service over a network such as packet prioritisation. Ethernet network prioritisation is still a research topic though packet prioritisation has been implemented on proprietary networks. Several companies and organisations have implemented Ethernet TCP packets over leased ATM. Fortunately, these two communication mechanisms do provide quality of service guarantees suitable for time critical applications. Unfortunately, the end-to-end TCP flow-control necessary for quality of service implementation can interfere with ATM and Frame-Relay packet construction, thereby causing an indeterminate degradation in service quality. Further work is needed to better define quality of service mechanisms within ATM and Frame-Relay packets.

2.1.2.4. Immature, Fragile Trust Frameworks

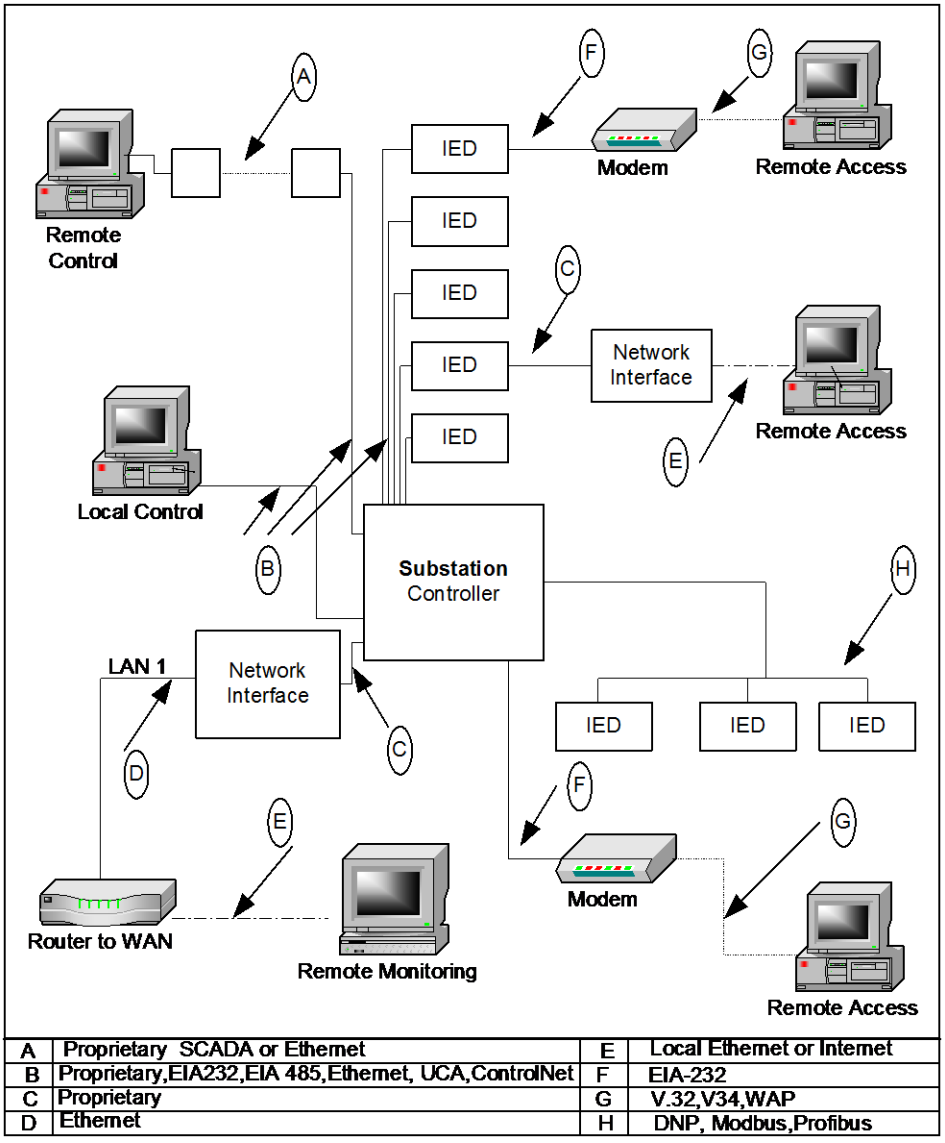
Communicating anomalies and disturbances across spatial, economic and governing boundaries will be the main criteria for the wide area early warning system. Trusted communication between sender and receiver is a vital prerequisite before initiating any control or protective action.

There are a few frameworks for establishing trusted interconnections between computing systems: Internet Protocol Security (IPSec) and Public Key Infrastructure (PKI). IPSec is an effort of the Internet Engineering Task Force (IETF) to add security mechanisms to the TCP/IP layers within the Ethernet protocol. PKI is an attempt to create a world-wide infrastructure for secure communications based on asymmetric public-key cryptography. As an alternative to PKI, the Pretty Good Privacy (PGP) group has implemented and advocates an informal “web of trust” where trusted users vouch for and include others in formalised lists of who to trust. Other mechanism for establishing trust levels and trust frameworks are being explored, but all of these efforts are focused on e-commerce and are not sufficiently robust for electric power control systems.

2.1.2.5. Control and Substation Protocols with Minimal Interoperability

There are many communications protocols including a multitude of proprietary protocols as well as: EIA-232, EIA-485, Ethernet, Utility Communications Architecture (UCA), DNP3, Modbus and Modbus-Plus, Profibus, Foundation Fieldbus and ControlNet. These protocols are used to connect the protection equipment such as breakers, reclosers, relays and IEDs to control equipment like RTUs, Data Processing Units (DPUs), communications controllers, local workstations and SCADA devices. Figure 2.1 [38] shows an example of substation configuration with varying communication protocols within and external to the station.

The diversity and lack of interoperability in these communication protocols create obstacles for anyone attempting to retrieve disturbance data (trip, near-trip, critical, or near-critical) from the station.



A	Proprietary SCADA or Ethernet	E	Local Ethernet or Internet
B	Proprietary,EIA232,EIA 485,Ethernet, UCA,ControlNet	F	EIA-232
C	Proprietary	G	V.32,V34,WAP
D	Ethernet	H	DNP, Modbus,Profibus

Figure 2 .1: Substation communication protocols [38]

2.1.2.6 Socio-economic and political resistance to regularity controls

Despite the calls for centralized control structures and increased regulatory requirements, it is doubtful whether today's socio-economic and political climate would support such actions. The failed deregulation attempt in California have slowed but not stopped similar efforts in other parts of the world. Thus, it seems that the electric power industry will undergo the same deregulatory actions and influences experienced by U.S. telephone, railroad, and airline industries. It remains questionable, however, if a keystone critical infrastructure like the electric power grid should be stressed and jeopardised by deregulatory machinations.

2.1.3. Possible solutions to technology obstacles

After classifying the obstacles, new technologies now identified from computer networking and electric power system protection that might be used to overcome obstacles and foster development for such system:

- Recognition for and the development of information infrastructures
- Investigations into improved quality of service WAN parameters and service level agreements
- Tunnelling utility protocols within Ethernet's TCP/IP layers
- Improvements in hardware for authentication and secure network tunnelling

- Research in trusted third-party infrastructures
- Revisiting the issue of Deregulation
- Next generation FACTS and IEDs.

2.1.3.1. The development of information infrastructures

There have been several calls for a WAN based critical data information infrastructure that could be used for electric power management. Bakken, Evje and Bose [39] are working to further develop GridStat, an information infrastructure for gathering and disseminating electric power grid status information. Similarly, Stahlkopf and Wilhelm [40] propose a Wide- Area Measurement System (WAMS) consisting of GPS based phasor measuring instruments, power system monitors and Flexible AC Transmission System (FACTS) devices all combined with substation data via ICCP. They suggest that such an early warning system could have prevented the 1996 West Coast (US) cascading blackout by giving California operators sufficient time to bring auxiliary generators on-line in the time between the initial faults occurring in Oregon and the subsequent loss of the North-South inter-tie in Northern California roughly 6 minutes later. In that particular case, a virtual overlay network early warning system may have given operators in Southern California sufficient time to shed load or increase generation prior to the separation of the North- South inter-tie. The figure shows how an independent protection-level communication infrastructure might be overlaid on the Western U.S. power grid with inter-loop gateways and access paths to key control

stations and cutpoints. Advances in fiber-optics (e.g., Synchronous Optical Network (SONET)) make this type of network feasible today.

2.1.3.2. Improved WAN quality and service level agreements

There is a growing recognition of the need for quality of service parameters on the internet in general, and over time-critical WANs in particular. For example, Dixit and Ye [38] looked into quality of service implementations over TCP/IP stacks and concluded that the need for ultra-high speed data-centric networks was just around the corner. Advancements in robustness and quality of service over leased lines (e.g., ATM and Frame Relay) can already be witness. The Frame Relay Forum and the ATM Forum have combined to form a task group investigating mechanisms for increased interoperability and higher levels of service.

2.1.3.3. Tunnelling utility protocols within Ethernet's TCP/IP layer

There are several success stories of implementing utility protocols over Ethernet's TCP/IP and User Datagram Protocol/Internet Protocol (UDP/IP) stacks. For example, Schweitzer Engineering Laboratories (SEL) implemented the Utility Communication Architecture Generic Object-Oriented Substation Events (UCA GOOSE) and Generic Object Models for Substation and Feeder Equipment (GOMSFE) models over TCP/IP.

Analysis of those implementations with respect to IEC 834 standards for power systems' teleprotection show that for closed-LAN communications tunneling the UCA protocols under TCP are more than adequate to meet the time-critical needs for substation protection events [41]. Other efforts by SEL and various protective relay manufacturers are having success implementing utility protocols over TCP/IP and UDP/IP. Thus, it seems that Ethernet has provided us with a common protocol for most, if not all, LAN-based substation equipment data communication.

2.1.3.4. Improvements in hardware for authentication and secure tunnelling

Advances in hardware and cryptographic authentication devices have been well proven in large financial transactions and military applications and can be directly implemented in the electric power control and monitoring domain. Microcontrollers and Abstract Communication Service Interface (ASIC) for cryptographically secured communications are now available from a variety of commercial vendors. Intel, for instance, is now marketing a network interface card with an onboard crypto-chip that boasts 113 Mbps throughput while running a 168-bit Triple encryption algorithm on all I/O. Integration and automation engineers are starting to recognize the value of these turn-key commercial solutions.

2.1.3.5. Research in trusted third-party Infrastructures

Because of the boom in cyber-hacking activity targeted against e-commerce and military computer installations there has been much attention focused on developing trust levels and flexible trust frameworks within computer networks. For example, Vogt et al [42] suggest a framework for exchange protocols that increase in trust and expense as the importance of the exchange heightens.

Wichert, Ingham and Caughey [43] show how a non-repudiation scheme could be implemented in Common Object Request Broker Architecture (CORBA) middleware using an Extensible Markup Language (XML) document format based on the Internet Engineering Task Force's (IETF's) digital signature standard. When combined with hardware authentication devices like SmartCards, digital signatures may provide the extra layer of authentication and non-repudiation necessary for critical applications.

2.1.3.6. Revisiting the issue of deregulation

Lessons have been learned from the California deregulation fiasco. Other regions have slowed or adapted their deregulation efforts, politicians are calling for increased production and conservation, and engineers are looking for better, more efficient solutions to bulk power transfers. As part of this last effort, on-line stability analysis and modelling, state estimation functions, and adaptive algorithms for inter-tie cut-sets will have to be developed. Together with post-emergency balancing procedures, these are the issues that Grudinin and Roytelman [44] identified in 1997 as missing components to an improved wide-area automatic control system. Thus, it would be ironic if failed

deregulation efforts were the impetus for adopting a centralized scheme for inter-regional load balancing and protection.

2.1.3.7. Next generation FACTS and intelligent electronic devices

Technologies specific to electric power system management are also evolving into next generation devices that will help enable a wide-area monitoring and protection. FACTS devices are using new sensor technologies and better algorithms for faster power transfers across wider control areas. This helps optimize power transmission and distribution. Similar advances are being made in microprocessor controlled protective relays and IEDs. Today's IEDs are nominally capable of measuring and storing 960 voltage, current, and phasor samples per second, and state-of-the-art devices are being released with nearly 10 times that capability. Combined with this faster/larger sampling are improved techniques for device-to-device communications and LAN interconnections. Analyses and experiments at SEL show that multi-device protection schemes can be optimized for sensitivity, security and operational time. Analyses and experiments at SEL show that multi-device protection schemes can be optimized for sensitivity, security and operational time [45]. For instance, SPI PowerNet (now SP AusNet) has developed Substation Control and Information Management System (SCIMS) as shown in Figure 2.2. It brings real-time terminal station monitoring and control under one digital system providing an integrated substation automation system [46].

2.2 Deregulated utility communications requirements

In recent times, interconnected power networks have become much more complex. As a result of this increasing complexity, maintaining the security of the power system has become more difficult. Deregulation has also served to further complicate the operation of power systems.

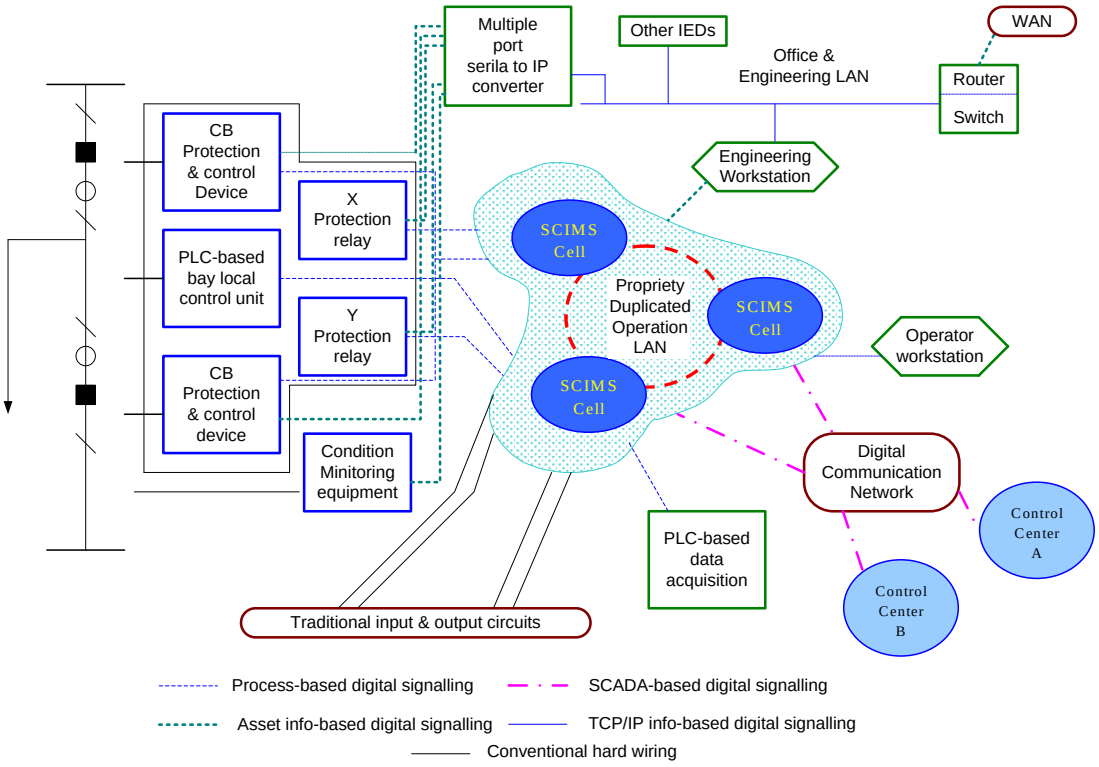


Figure 2.2: SCIMS - base architecture [46]

In the new deregulated environment, the pattern of power flows in the network is less predictable than it is in the vertically integrated systems, in view of the new possibilities

associated with open access and the operation of the transmission network under energy market rules [47]. The goal of modern power utilities, in the presence of new competitive markets, is to provide services to customers aiming at high reliability with the lowest cost. Before the days of deregulation, utilities performed both power network and marketing functions but were not motivated to use tools that required accurate real-time network models such as optimal power flows and available transfer capability determination. These practices are starting to change in the emerging competitive environment.

Modern power utilities are now starting to install more advanced SCADA systems and modern data communication networks in order to implement real-time network models, which allow for faster “snapshots” (or sampling rate) of the states of the power system. Although reliability remains a central issue, the need for the real-time network models and faster telecommunication systems becomes more important than before due to new energy market related functions in EMS. These models are based on the results yielded by state estimation and are used in network applications such as optimal power flow, available transfer capability, voltage and transient stability [48].

The traditional communication architecture for power systems, which has been successfully implemented in the industry for decades, is point-to-point (e.g. phone modems, Radio frequency transmitters, etc.). The expanding physical sizes and modern power control schemes are pushing the limits of point-to-point architecture. Hence, a traditional point-to-point SCADA system is no longer suitable to meet new requirements

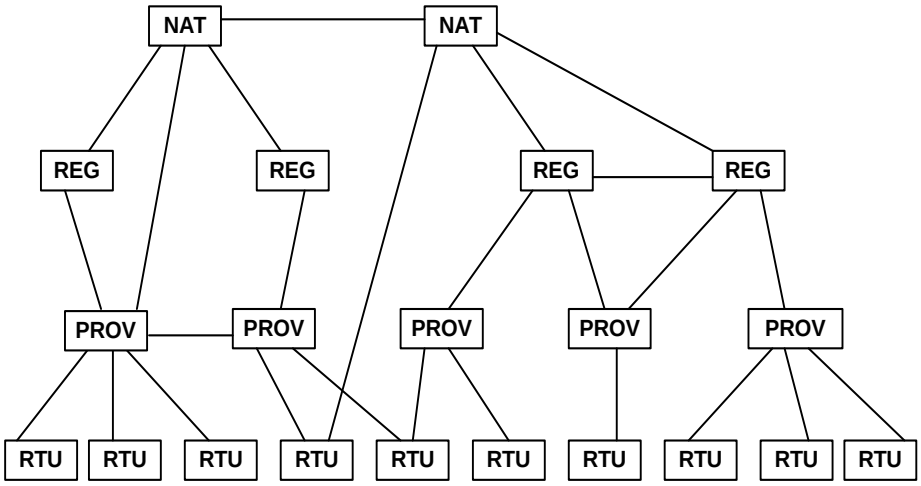
such as modularity, centralization of control, integrated diagnostics, quick and easy maintenance and low cost. Many different computer networks types, with common bus architectures, have been promoted for use in power systems. There has been much effort over the last decade towards the standardisation of communication protocols used by electric power utilities.

The motivation for this standardization is to ease the integration process for inter-company data sharing. In 1990, EPRI launched a concept known as the UCA. The main purpose of the UCA was to identify a suite of existing communication protocols that could be easily mixed and matched, provide the foundation for the functionality required to solve the utility enterprise communication issues and be extensible for the future [48].

As mentioned earlier, worldwide electric utility deregulation is expanding and creating demands to integrate, consolidate and disseminate information quickly and accurately between and within utilities. Utilities spend an ever-increasing amount - estimated $ 2 billion to $ 5 billion dollars a year in the USA only-for voice and data communication. There are strong needs to find ways of reducing operating costs to improve utility earnings.

In the deregulated power industry, it is necessary to have global vision of the network situation. That is, the measures acquired locally in the RTUs should be transmitted to a provincial control centre. The information from these provisional control centres is transmitted to a control centre of higher level such as regional in which a more global

vision of electric network can be obtained. In a similar way, the information from the regional control centres can be transmitted to a national control centres in which one obtains a general vision of the network. This results in a hierarchy of control centres with several levels, from the RTU until the general (national) network control centre. In addition, information is frequently exchanged among control centres of the same hierarchical level or different levels as shown in Figure 2.3 [49].



RTU=Remote Terminal Unit, **PROV** = Provincial Control Centres

REG= Regional Control Centres, **NAT**=National Control Centres

Figure 2.3: Computer network controlling the electric network with a tree topology [49]

The increasing incorporation of digital devices throughout the utility enterprise as well as the forces of deregulation are driving utility communication into new realms with new requirements and paradigms. Deregulation places new requirement on the

communication of data and information throughout the utility enterprise. With the current advancement in IT, utility can meet the present data sharing in broader perspective. The time has come to fully employ WAN technology in the power system industry.

Conventional SCADA network designs rely on the predictable nature of connection-oriented services using fixed audio bandwidth links, analogue modems and specific protocols. Setting up and maintaining these networks require specialised skills. Reconfigurations involve hardware rewiring, are time consuming and costly. Bandwidth is limited to 3 kHz, which is adequate for current RTUs but potentially limiting business move towards the use of substation automation and remote management. As the world moves to digital communications, the support of analogue modems is becoming increasingly difficult.

Changing to utilising WAN technology will enable the management of SCADA networks to be integrated into a system common to the corporate data network. Reconfigurations will be simplified to keyboard commands rather than rewiring at multiple points. Bandwidth can be allocated as required and RTUs themselves remotely managed. In addition, the advantages of WAN networking include: worldwide adoption, very well developed hardware and software market, simplicity and choice of application layer protocols, inherent resilience of the IP routing concept and strong network management, including remote control and monitoring. Furthermore, WAN presents the opportunity to migrate to a single network for both operational and non-operational requirements. Applications will include SCADA data, business data, and video

monitoring, which are integrated with Network Integrated System (NIS), Energy Management System (EMS) and Human Machine Interface (HMI) as shown in Figure 2.4 [50].

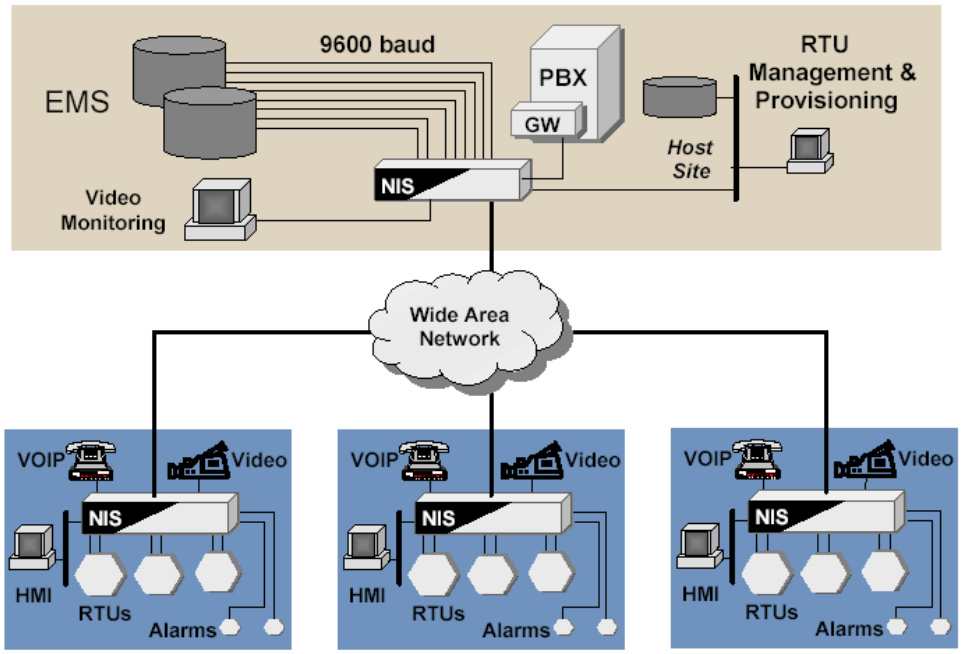


Figure 2.4: Integrated WAN communication network [50]

The electric utility deregulation is gearing in full speed throughout the world. As a result, the integration, consolidation and dissemination of information both inter and intra utilities have become a critical piece of the deregulation picture. Information traditionally used only within a given utility now becomes desired by many players. The general trend in the industry has been toward the use of the Internet for the transfer of data such as:

- Available Transmission Capacity
- Available Transmission Capacity
- Rate Schedules
- Scheduling (especially inter-company)
- Operating Constraints
- Interruption Criteria.

Beyond data sharing, new mandates are being placed on the transmission and distribution utilities to minimise outage times, provide rate alternatives (for example, through Demand Side Management), maintain operating data archives, and in general, push more power through existing power lines. On the financial side, deregulation introduces the need for sharing of accounting data among utilities, metering firms, billing firms, and Independent Power Producers. Inter-utility billing must be correct and standardized. Standard accounting and record keeping topics to track include:

- Revenues
- Costs
- Liabilities
- Assets

Another fall-out of deregulation is the merger and consolidation of many of the existing utilities. Mergers will require the establishment of intra-company communication and the integration of data from companies control centres, power plants and substations.

Implementing this integration with different data models and communication protocols will add considerable time and money to the process. The possibility and inevitability of the need to perform this integration process should drive all utilities toward the standardization of data models and communication protocols.

The increasing connectivity of interactive networks including the electric power grid poses new challenges for robust control, management and secure operation of these complex interconnected systems. These networks are characterized by many points of interaction among a variety of participants; a local change anywhere can have immediate impact everywhere. The increasing complexity of electric power networks and interconnections to other infrastructures, vulnerabilities to cascading failures, interactive and large-scale nature of these networks, coupled with advances in modelling, computational methods, software technologies, simulations, control of networks and economic aspects, have stimulated the interest of the control community in this area. With the advent of deregulation, unbundling, and competition in the electric power industry, new ways are being sought to improve the efficiency of that network without seriously diminishing its reliability. Hence, power system communication protocols will play significant roles in the overall monitoring of power system. Therefore, more robust protocol is required to monitor modern power system network infrastructure.

2.2.1 Importance of real time information in power system

Real time data is highly important for automatic control to maintain system stability; it can also be used as a guide to immediate operating decisions in support of system recovery and for extensive analysis [51]. Research shows that major blackout that occurred during the last ten years could have been avoided. It demonstrates that wide-area, comprehensive and real-time information exchange is becoming a critical factor for the future power system reliability and stability. Figure 2.5 shows the illustration of the relationship between measurement, information and decision-making. The real time data applications range from very rapid control function to the very slow functions such as expansion planning. With high-speed real time measurement, proper protection and control actions could be taken to ensure the reliability of power system when event occurs.

Due to power system deregulation [52], the nature of communication has changed such that it results in information consolidation and open access, and pushes for more extensive internal and external utility information exchange, integration and dissemination. Therefore, fast, real time and comprehensive information acquisition and transmission are the key to wide area power system operation optimisation and control [53-55]. To sustain such data communications, the communication architecture, communication protocols and technologies must be able to deliver operational data and dynamic real time information to the required ends. Generally, the communication infrastructure must have criteria such as:

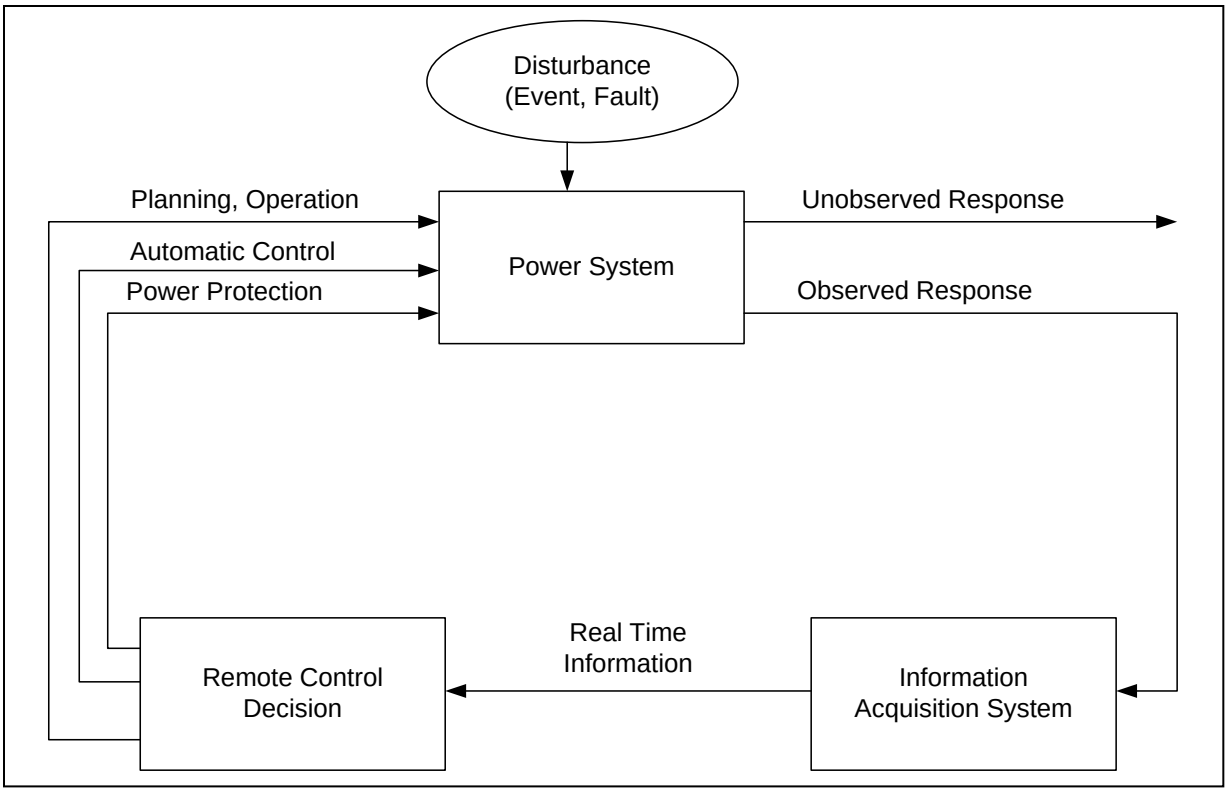


Figure 2.5: The circle of measurement, information and decision making

- It should have high bandwidth to support large volume power system monitoring and measurement information transmission
- It should have low latency to support local area and wide area real time control and protection.

As discussed earlier, the future power system information exchange requirements have changed. Currently existing power system communication media [56] such as power line carrier, radio frequency and microwave cannot fulfil the future power system information needs. The future power system needs more feature-rich services. Fibre

optic network will be the ultimate choice to meet power system real time control, protection and monitoring application requirements due to its high bandwidth, low latency, better security and QoS (Quality of Service) features. Furthermore, the time has come for inter-company communication and integration of data from various control centres, power plants and substations. SCADA systems are essential parts of the Distributed Management System (DMS) and EMS that employ a wide range of computer and communication technologies. However, existing SCADA information management systems [57] cannot fulfil the new challenges as more and faster information has now become desirable by many users and players. Advancement in IT with innovative networking devices available have made it possible to develop low cost real time communication system for accessing real time power system information over digital network. High performance fibre optic network brings great opportunities for the power system real time applications.

Power system frequency [58, 59] is one of the most critical parameters for understanding and controlling power system dynamics. However, frequency instability scenario can be initiated by a large mismatch between generation and load [60, 61]. Such a scenario can result in a cascaded loss of generation through under/or frequency related operation that would eventually lead to a blackout. However, recent technology advances in networking and communication as well as in power system design have opened the door for fast and accurate load shedding system design.

2.2.2 Future power system information needs

Future power system requires for bandwidth with reliable network for the transmission of real time data. From high-speed substation control and protection data communication [62-64] to wide area power system monitoring [65,66] and measurement data transmission, the increasing incorporation of computer network throughout the utility as well as the forces of deregulation are compelling power system communications into new realms with new requirements and challenges. Expanding network services such as real time wide area control [67, 68] and Flexible AC Transmission System (FACTS) device coordination [69, 70] are also driving the need for evermore bandwidth in the network backbone. These needs will grow further as new real-time service, protection and control applications become more feasible and pervasive. Electric utilities often employ several types of communication media for different functions. With more and more bandwidth required by the power system data communication, the current transmission media cannot meet all the high capacity and quality of service requirement. Fibre optic provides the ideal alternative for the future power system communication infrastructure design. Although fast response is always desirable, different functions could have different time latency requirements. Clearance of a transmission line grounded fault requires millisecond of time delay, while several hours are reasonable for power system restoring. In the power system, various applications response time could range from few cycles to hours or even years. The large span of time scale for various power grid control and operation tasks greatly complicates modelling, analysis, simulation, control and operation.

As illustrated in Figure 2.6, fast, real time and comprehensive information acquisition and transmission are the keys to the power system operation. The real time information can be used for power system control, protection, monitoring or even for the system maintenance. This section highlights some typical applications, which can be greatly improved by using real time information.

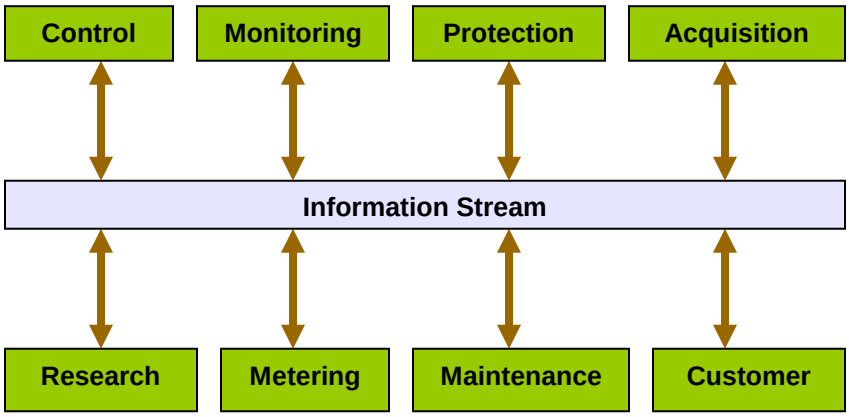


Figure 2.6: Future power system information needs

2.3 Current power system communication media

Power system communications have changed due to the deregulation of power industry. Wide area real time monitoring has become the norm. This requires high bandwidth network backbone to meet the real time data on demand. These needs will grow further as new remote real-time protection and control applications become more feasible and pervasive. Electric utilities often use several types of communication media [71-74] for different functions. With more and more bandwidth required by the power system data communication, fibre optic will be the ideal choice for the future power

system communication infrastructure. This section discusses some commonly used communication media in the power system.

Power Line Carrier (PLC)

PLC operates by transmitting radio band of frequency signals between 10 kHz to 490 kHz over the transmission lines. PLC with power output of order 150 W can be used up to 241 km. Normally, PLC carriers only one channel of 4 kHz bandwidth. The frequency range is limited by government regulations. However, it has some disadvantage such as bandwidth limit. It is subject to lightening, switching surges, and networks reconfiguration. This medium does not offer a reliable solution for wide area data transmission. Communication with remote sites cannot be maintained during a disturbance. Therefore, its effectiveness for wide area data transmission is limited.

Dedicated Links

Dedicated links [73, 74] are employed by many SCADA systems to communicate between control centre and substation RTUs. The main advantage of dedicated link is its capability to provide high data rate. Dedicated links are impractical for controlling medium voltage grids due to lack of connectivity in remote areas. Installation of private lines on electric poles is expensive. Public networks are dependent on third party providers and are subject to service charges.

Radio Systems

Different radio systems, such as conventional radio, trunked radio or spread spectrum are suitable for wide area data transmission [75]. They are based either on licensed channels or over non-licensed frequencies.

However, many countries suffer from a shortage of available frequencies in the Very High Frequency / Ultra High Frequency (VHF/UHF) bands. Besides, due to over-utilisation of these unlicensed frequencies by mass consumer applications, their reliability for commercial and industrial uses are questionable. It is important to note that using line protocols over radio results in unreliable communication and poor utilization of airtime.

Microwave

Microwave operates in the 150 MHz to 20 GHz frequency range. This bandwidth can carry a lot of communication channels for a variety of information. Microwave is the radio signal operating in the 150 MHz to 20 GHz frequency range. The disadvantage of the microwave is that the transmission length is limited to a line of sight path between antennas. Microwave is subject to atmospheric attenuation and distortion. The combined latency using modem plus analog microwave is around 100 milliseconds between two adjacent antennas.

Wireless

Wireless is one of the modern methods of communication. Low orbit satellite communication system provides an existing option to transmit information covering a very large range. The delay is a problem, which depends on the distance. For example, the latency for low orbit satellite at 10 km above the earth is about 300 ms one-way. Another disadvantage is the cost of installation.

Fibre

Fibre is now considered the most reliable media of communication. Single fibre cable can carry up to 8000 channels. In addition to the capacity, the fibre has no interference with other electric systems. The only disadvantage is the cost of the cable and cost of the construction. Fibre optic communication has the smallest latency in all media of the communication.

2.4 Power system communication protocols

There are literally thousands of combinations of protocol agreements that can be created with the large domain of existing pieces. The main protocols that have found widespread use in the substation environment are [76]:

- MODBUS: A popular master-slave protocol with industrial users, which has become popular in substations. It issues simple READ/WRITE commands to addresses inside an IED.
- DNP: An increasingly popular master-slave protocol mainly used in North America. DNP can run over multiple media, such as RS-232 and RS-485 and can issue multiple types of READ/WRITE messages to an IED.
- IEC-870-5-101: is considered as the European partner to DNP. It differentiates itself from DNP with its slightly different messaging structure and the ability to access object information from the IED.

A protocol is basically a set of rules that must be obeyed for orderly communication between two or more communicating parties [77]. The International Standards Organisation (ISO) has divided the communication process into seven basic layers as shown in Figure 2.7, which is commonly referred to as the Open Systems Interconnection (OSI) model [77-79].

Each level operates independently of the others and has a certain function to perform. However, the successful operation of one level is mandatory for the successful operation of the next level. These layers define how data flows from one end of a communication network to another and vice versa. Two devices can only communicate if each layer in the model at the sending device matches with each layer in the model at the receiving device.

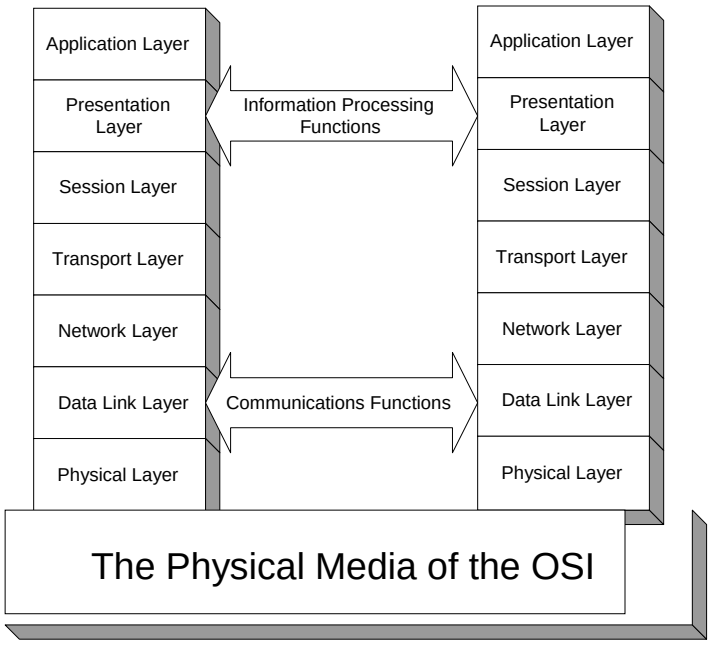


Figure 2.7: The OSI reference model

Communication between data processing systems from different manufacturers has often been particularly difficult due to the fact that there has been separate development of data processing and data communication techniques, often resulting in complex and expensive interfaces.

2.4.1 The Ethernet protocol

The Ethernet protocol [80, 81], a network concept illustrated in Figure 2.8, is one of the most widely used data link layer protocols designed for carrying blocks of data called frames as described by the IEEE 802.3 standard.

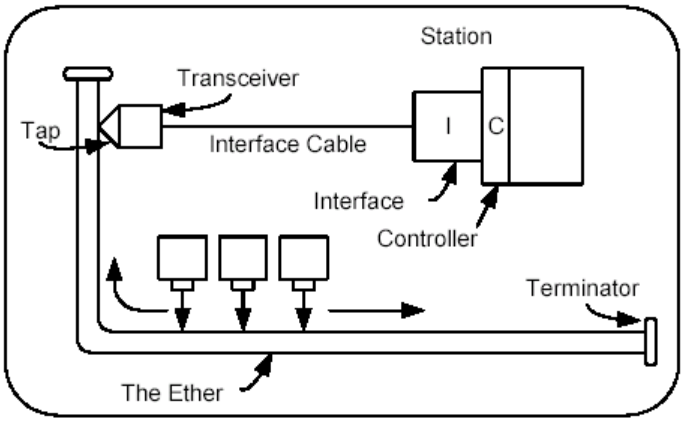


Figure 2.8: The Ethernet network concept [80]

Ethernet uses an access method called Carrier Sense Multiple Access/Collision Detection (CSMA/CD) [82], which is a system where each host listens to the medium before transmitting any data to the network. If the network is clear, the host will transmit. However, if some other node is transmitting, it will wait and try again when the network becomes clear. Collisions occur when two hosts try to transmit at the same instant forcing each other to back off and wait a random amount of time before attempting to re-transmit. Ethernet allows for the transmission of data from a speed of 10 Mbps to 1000 Mbps [83].

2.4.2 The TCP/IP Internet protocol suite

The Internet Protocol (IP) is a network layer protocol, which uses datagram to communicate over a packet-switched network [84, 85]. It provides datagram services for transport layer protocols such as Transmission Control Protocol (TCP) and User

Datagram Protocol (UDP). It is one of the subset protocols of the TCP/IP suite as illustrated in Figure 2.9. The IP forms a computer network by connecting computers assigning each one a unique IP address [86]. Each IP packet carries an IP address [87], which consists of two parts: a destination address and a host address.

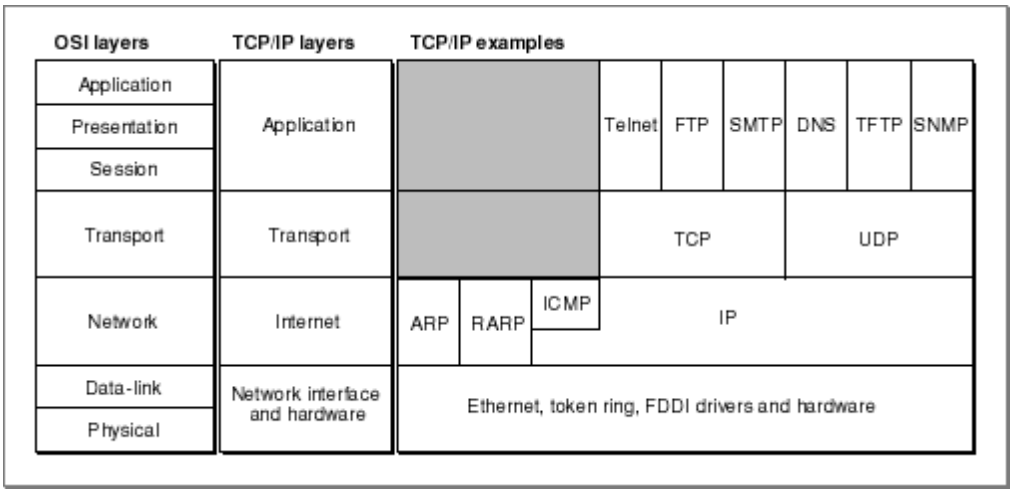


Figure 2.9: TCP/IP protocols and functional layers [26]

The host address is the IP address of the sending computer, whereas the destination address is the address of the recipient or recipients of the packet. Routers, switches make use of the destination address when forwarding packets across interconnected networks.

The major concern with IP is that it makes no attempts to determine if packets reach their destination or to take corrective action if they do not. Therefore IP does not provide guaranteed delivery. This problem can be avoided in some applications where a transport protocol that carries out such a function is used. The best example for the latter is TCP [88], which makes up for IP's deficiencies by providing reliable, stream-

oriented connections that hide most of IP's shortcomings. However, other applications requiring best effort services (faster transmission times) usually use UDP [89], which is a simple connection-less transport layer protocol without any real mechanisms for reliable delivery. UDP packets are delivered the same as the IP packets and may even be discarded before reaching their destinations.

Although the transmission of data requires the best-effort service in some substation applications, reliability is also a major concern. The best effort service requires the use of UDP, which has no support whatsoever for reliable transmission. This implies that certain primitives need to be implemented to achieve higher reliability in cases where IP is to be used alongside UDP. This is one of the major concerns being looked at in this research with a model being proposed in this thesis to solve this problem.

2.5 SCADA system design for electric utilities

The American National Standards Institute defines SCADA [90] as a “system operation with coded signals over communication channels so as to provide control of remote equipment. The supervisory system may be combined with a data acquisition system, by adding the use of coded signals over communication channels to acquire information about the status of the remote equipment for display and for recording functions.” SCADA systems within the electric utility industry provide monitoring and remote control of substations and generating facilities.

RTUs act as the front end for SCADA systems. RTUs typically include data processing and communication subsystems, but may include much more as shown in Figure 2.11. Some other possible subsystems are self diagnostics, control processing, and database maintenance. The data processing subsystem consists of collecting and reporting the field data. Digital data may come from switches, breaker contacts, or other electronic devices. Analog data usually comes from transducers. For information regarding the other subsystems shown in Figure 2.10 refer to reference [91].

Almost all RTUs currently used in the electric utility industry are based on either embedded microprocessor designs or programmable logic controllers. However, personal computers are a viable alternative to the above technologies, because of the reduced cost, greater functionality, and dramatic increase in the processing power of personal computers (PCs) over the last decade [92].

Along with hardware capabilities, software production methods today are rapidly changing. This change is being driven by:

(i) Emerging technologies of client/server based computing

(ii) Stronger software standards and protocols and

(iii) The emergence of object-oriented software design [93].

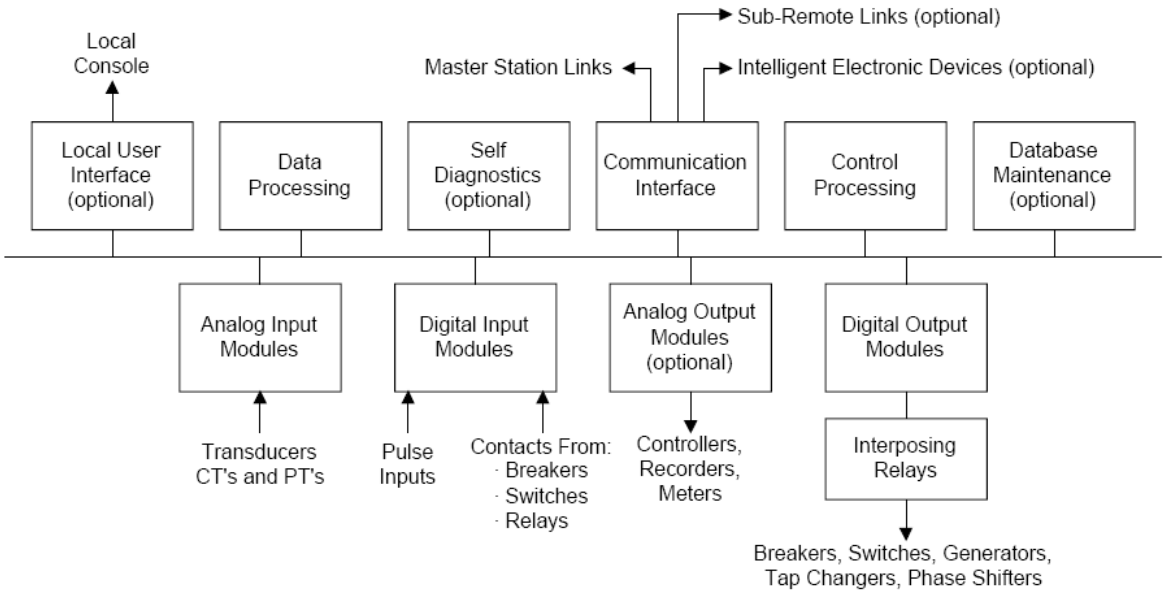


Figure 2.10: RTU components [91]

These three emerging technologies provide a way to decouple tasks into separately running pieces of software often produced by different companies. Most SCADA software currently produced is constructed from tightly coupled and interdependent modules. However, new inter-program communication protocols now allow separately manufactured software components to be combined into a seamless operational whole.

Electric utility RTU devices typically deliver real-time measurement data over a communication system to a control center. This allows for unification of all control elements of the power control board and electrical system into a centralised location and provides a single cohesive and comprehensive view of the entire electrical system. There are two main categories of real-time measurements that the RTUs send to the energy control center:

(i) Analog measurements, which include bus voltages, real and reactive power injections, and real and reactive power flows

(ii) Status measurements consisting of switch and breaker positions.

Analog data usually originate from transducers. Status data may come from switches, breaker contacts, or other electronic devices.

2.6 Conclusion

With the advances in the development of IT and digital broadband communication, more sophisticated systems can be developed in the field of wide area power system control and protection. An era is approaching in which electric power system anomalies can be modelled in real-time using data from disturbances, near-critical conditions and near-trip events. System wide disturbances in power systems are a challenging problem for the utility industry because of the large scale and the complexity of power system. When a major power system disturbance occurs, protection and control actions are required to stop the power system degradation, restore the system to a normal state, and minimise the impact of the disturbance. The present control actions are not necessarily designed for a fast developing disturbance and thus may prove ineffective. With the increased availability of sophisticated computer, communication and measurement technologies, more intelligent equipment can be used at the local level to improve the overall emergency response.

The advanced protection is a concept of using system-wide information together with distributed local intelligence and communicating selected information between separate locations to counteract propagation of the major disturbances in the power system. A great potential exists for advanced wide area protection and control systems, based on powerful, flexible and reliable system protection terminals and high speed communication with reliable power system communication protocol. More specific research and experimental work is required to model wide area time critical communication infrastructure for power system control, protection and monitoring.

CHAPTER 3

AN OVERVIEW OF MODERN INFORMATION EMBEDDED POWER SYSTEMS

3.0 Introduction

The power grid is a highly complex and non-linear dynamic system. It requires very stable, efficient, reliable and secure communication platform to transmit power system data in real time to the control centre. Information has become a vital component to the efficient operation and growth of a restructuring electric utility. Utility operations and commercial needs mandate the use of systems and technologies that are capable of providing for many traditional SCADA and EMS functions as well as utility services derived from an energy market or restructured utility. Integrated information systems and telecommunications capable of supporting these functions as well as future capabilities are critical in the changing utility environment. Existing information management systems can not satisfy new challenges as the demand for more and faster information increases. Therefore, information embedded power system via Wide Area Network (IEPS-W) is ideal to fulfil the information gap which required of a modern power system. IEPS-W is discussed in detailed in this chapter.

IEPS-W consists of The SCADA system (measurement system), communication system and energy control center which is discussed in details in Section 3.1. As in line with the main focus of this thesis, more discussion in this Chapter will be on power system communication protocols used in IEPS-W especially on DNP3 over WAN which is presented in Section 3.2. The conclusion remark is in Section 3.3.

3.1 Information embedded power system

As mentioned in Chapter 1, an information embedded power system consists of the actual power system hardware which consists of generators, transmission lines, transformers, etc. Again, it involves the SCADA system for measurement purpose along with the communication system which facilitates transmitting power system data from field devices to the control room utilising power system communication protocols. It also consists of energy control center which monitors entire network and its affiliated devices.

3.1.1 Measurement system

SCADA systems have been widely used in power systems for monitoring, operation and control purposes at electric utilities for decades. Failure of the SCADA system can result in severe consequences such as customer load losses and equipment damage [94].

The American National Standards Institute defines SCADA [95] as a “system operation with coded signals over communication channels so as to provide control of remote equipment. The supervisory system may be combined with a data acquisition system, by adding the use of coded signals over communication channels to acquire information about the status of the remote equipment for display and for recording functions.” SCADA systems within the electric utility industry provide monitoring and remote control of all connected devices within the power network and generating facilities. RTUs or IEDs act as the front end for SCADA systems. RTUs typically include data processing and communication subsystems interface facilities, but may include many more devices.

Electric utility RTUs/IEDs typically deliver real-time measurement data over a communication system to a control center. This allows for unification of all control elements of the power control board and electrical system into a centralised location and provides a single cohesive and comprehensive view of the entire electrical system. There are two main categories of real-time measurements that the RTUs send to the energy control center:

(i) Analog measurements, which include bus voltages, real and reactive power injections, and real and reactive power flows and

(ii) Status measurements consisting of switch and breaker positions.

Analog data usually originate from transducers. Status data may come from switches, breaker contacts, or other electronic devices. Traditional SCADA systems for electricity

utilities rely on data transmission over fixed analogue circuits and modems. This method has been satisfactory over the years but it is becoming obsolete and unsuited to today's requirements. The use of TCP/IP technology can overcome the limitations of analogue communications, allow the network to be more flexible in terms of expansion and reconfiguration, and have higher bandwidth potential whilst retaining the qualities essential for SCADA operations. In order to support SCADA data transmission, a communication network is essential. SCADA communication networking requirements typically include [96-101]:

Control centre: The location of the SCADA master station, which requires a telecommunication service to transport and deliver real-time data on the power network.

Functionality: SCADA systems require a direct link from the master station to every RTU. This link is often provided by a radial branching communication network with the hub at the control centre.

Connectivity: Most electricity utilities have all their grid substations and power plants served by RTUs. Secure redundant data communication routing into the control centre is often required.

Availability: Because of the operational nature of the data, a SCADA system should be continuously available and is often self-monitoring. Typical systems require availability of at least 99.995% in the communication links between master station and RTUs.

Environmental: Communication equipment should be immune to severe electromagnetic disturbances. Fibre-optic links are often specified as the only medium that will deliver the required noise-immune bandwidth.

3.1.2 Communication system

Data communications have always played a large role in the operation and control of utility power systems. Applications of data communications in power systems range from relay-communications to “inter-control center” data sharing. This thesis is mostly concerned with WAN to deliver real-time measurements from IEDs to an energy control centre. In particular, this thesis focuses discussion on WAN along with Ethernet technology used. WAN is widely used in modern power grid to connect multiple centres with field devices such as IEDs and RTUs.

3.1.2.a Wide Area Network

A WAN is a computer network that spans a relatively large geographical area. Typically, a WAN consists of two or more local-area networks (LANs). Computers connected to a wide-area network are often connected through public networks, such as the telephone systems. They can also be connected through leased lines or satellites. The largest WAN in existence today is the Internet.

3.1.2.b Ethernet Technology

Ethernet is easily the most successful local area networking technology of the last 20 years. Ethernet is a CSMA/CD local area network technology. As indicated by the CSMA name, Ethernet is a multiple access network, meaning that a set of hosts send and receive frames over a shared link.

Therefore, Ethernet can be viewed as a bus with multiple hosts connected to it. The “carrier sense” in CSMA/CD means that all hosts can distinguish between an idle and a busy link. The “collision detect” means that a host listens as it transmits and can therefore detect when a frame it is transmitting has interfered (collided) with a frame transmitted by another host.

An Ethernet segment is typically implemented on “*10 BASE-T*” technology, where the “10” means that the network operates at 10-Mbps, “Base” refers to the fact that the cable is used in a baseband system, and the “T” stands for twisted pair. The bits are encoded using a Manchester encoding scheme. The Ethernet standard has recently been extended to include a 100-Mbps version called Fast Ethernet, and a 1000-Mbps version called Gigabit Ethernet. Both 100-Mbps and 1000Mbps Ethernets are designed to be used in full-duplex, point-to-point configurations, which means that they are typically used in switched networks.

Ethernet has been around for many years and is very popular. Ethernet is extremely easy to administer and maintain. There are no switches that can fail, there are no routing tables to update, and it is easy to expand the number of hosts. It is also very inexpensive to implement. Research on Ethernet has shown that it works best under

lightly loaded conditions [102]. Fast Ethernet or "*100BASE-T"* provides transmission speeds up to 100 megabits per second and is typically used for LAN backbone systems, supporting workstations with 10BASE-T cards. Gigabit Ethernet provides an even higher level of backbone support at 1000 megabits per second (1 Gigabit or 1 billion bits per second). 10-Gigabit Ethernet provides up to 10 billion bits per second.

3.1.3 Energy control centre

The nature of power system monitoring, control and protection has changed in the modern era. Power system are more interconnected than before in order to obtained more realistic view of broader system to avoid catastrophic failures. To help meet the needs of modern power systems and avoid major system failures, electric utilities are starting to install more extensive SCADA systems [103]. As the data from the SCADA system is telemetered to the energy control center, a real-time database is created within the control center to support several application programs. These programs perform power system state estimation, ensure economic system operation, and assess the security of the system in the event of equipment failures and transmission line outages. A block diagram of energy control center can be seen in Figure 3.1. This figure shows how measurements are sent from RTU across the communication system to the control center. The incoming analog measurements of generator output must be directly used by the Automatic Generation Control (AGC) program. All other incoming data needs to be processed by the state estimator before being used by other programs. The result of state estimation forms the basis for all real-time security analysis functions in a power system.

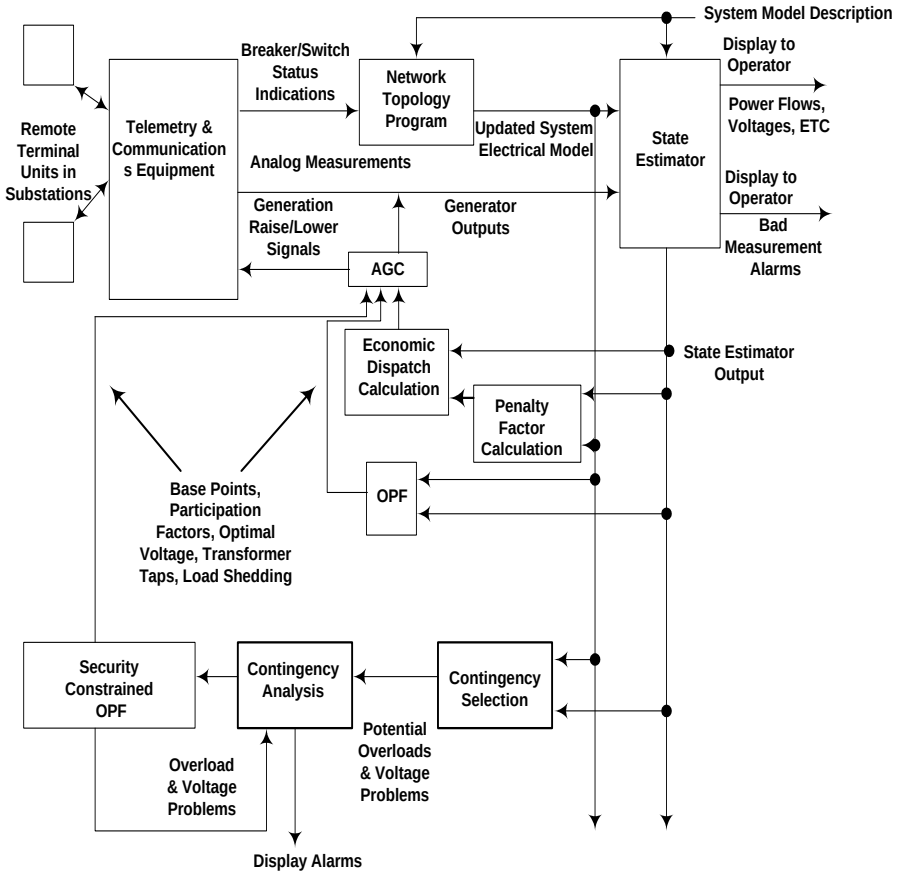


Figure 3.1: Energy control centre [103]

Within the control center, state estimation is the key function for building a real time model of the power system.

As seen in Figure 3.1, the output of the network topology program is sent to the state estimator program along with the other measurements. State estimation is a technique that estimates the state of a power system by utilising a set of real-time, redundant measurements recorded from the power system. There are three main categories of real-time measurements used for state estimation:

(i) analog measurements, which include bus voltages, real and reactive power injections, and real and reactive power flows;

(ii) status measurements consisting of switch and breaker positions; and

(iii) psuedo measurements consisting of forecasted bus loads and generations.

Modern power system control centre has the following attributes [104]:

- Open system architecture based on **the Institute of Electrical and Electronics Engineers (**IEEE) standards to satisfy changing control needs and have lower life cycle costs
- Distributed system across multiple servers built over a redundant, high speed network
- Multi-protocol environment to support communications with existing and future RTU and control centres providing flexibility to install new protocols, if needed
- Capability to operate autonomously, insuring the retransmission (“relaying”) of data necessary to the operation
- Interface to a database according to the model defined by the EPRI Common Information Model
- Full-graphics User Interface based on Windows
- Fault-tolerant configuration with no single point of hardware failure performing critical functions
- Intrusion protection (firewall) among Control Centres

- SCADA functions including data acquisition and exchange, data processing and monitoring, sequence of events, supervisory control and tagging, historical information system and post-disturbance analysis
- EMS functions encompassing:
    - Generation Control: Performance monitoring, generation reserve monitoring
    - Automatic Voltage Control
    - Real-time Network Analysis: Network Topology Processor, State Estimator, Parameter Adaptation, Network Reduction, and Contingency Analysis
    - Study Mode Network Analysis: Network Topology Processor, Dispatcher Load Flow, Network Reduction, and Contingency Analysis, and Optimal Power Flow.

- Dispatcher Training Simulator (DTS) completely integrated and with capacity for simulating:
    - Generation and voltage control
    - Load variation according to pre-defined models
    - Load sensibility to voltage and frequency
    - Long-term dynamic models for generating units, turbine control and voltage regulators with static and dynamic limitations of active/reactive power loading
    - Reconnection and synchronism verification operations

  - Fault effects on the power system and random disturbances on measurements.

- Planning, Pre-Operation and Post-Operation support the following:
  - Automatic transfer of operating schedules from the utility Corporate Network to the Real-time environment
  - Automatic transfer of future data to the utility Corporate Network for pre-operation purposes
  - Automatic transfer of historical data to the utility Corporate Network for post-operation analysis.

3.2 Power system communication protocols

As stated earlier, there are many power system communication protocols employed by power utilities. Some of the most common ones are discussed in the following sections.

3.2.1 Distributed Network Protocol (DNP3)

DNP3 [105] is a SCADA protocol that permits data to be sent between a slave device (such as a RTU or IED) and a master device (such as a computer at a control center). The slave device will respond to requests for data that are issued by the master, but may also be configured to send data in response to a field event without that data

having been requested by the master. It has been used primarily by electric utilities like the electric companies, but it operates suitably in other areas.

Figure 3.2 shows common system architecture in use today. At the top of the figure is a simple one-on-one system having one master station and one slave.

The second type of system is known as a multi-drop design. One master station communicates with multiple slave devices. The master requests data from the first slave, then moves onto the next slave for its data and continually interrogates each slave in a round robin order. The middle row in Figure 3.2 shows hierarchical type system where the device in the middle is a server to the client at the left and is a client with respect to the server on the right.

Both lines at the bottom of Figure 3.2 shows that data concentrator applications and protocol converters. A device may gather data from multiple servers on the right side of the figure and store this data in its database where it is retrievable by a master station client on the left side of the figure. This design is often seen in substations where the data concentrator collects information from local intelligent devices for transmission to the master station. In recent years, several vendors have used TCP/IP to transport DNP3 messages. This approach has enabled DNP3 to take advantage of Internet Technology and permitted economical data collection and control between widely separated devices.

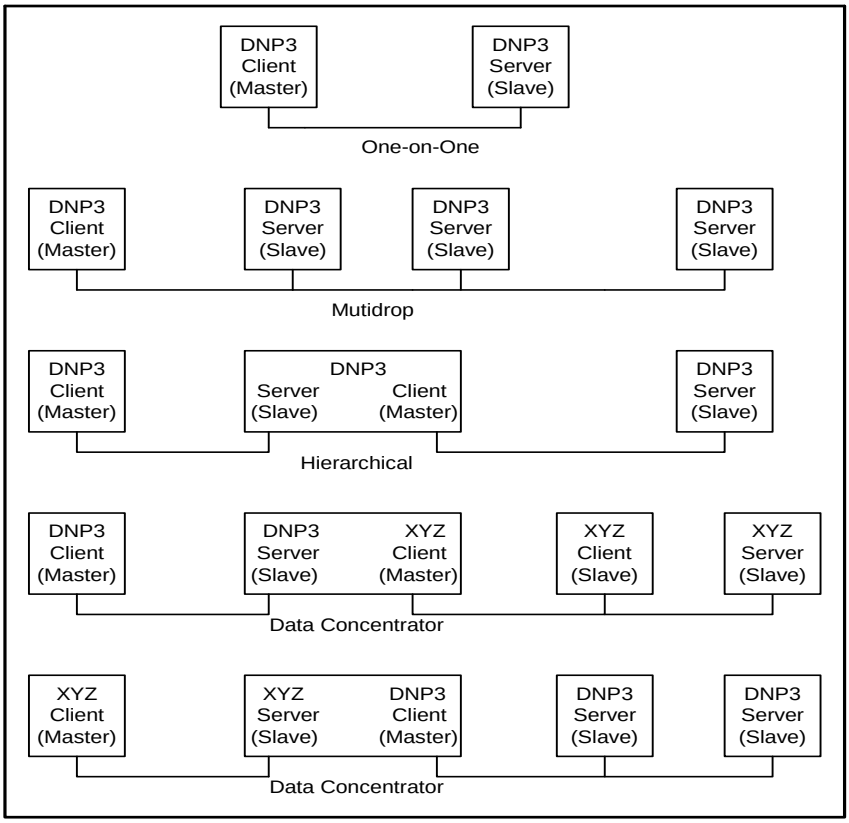


Figure 3.2: DNP3 common system architecture [105]

The DNP3 software is layered to provide reliable data transmission and to effect an organized approach to the transmission of data and commands. Figure 3.3 shows the layering that was not shown in Figure 3.2.

The link layer has the responsibility of making the physical link reliable. It does this by providing error detection and duplicate frame detection. The link layer sends and receives packets, which in DNP3 terminology are called frames.

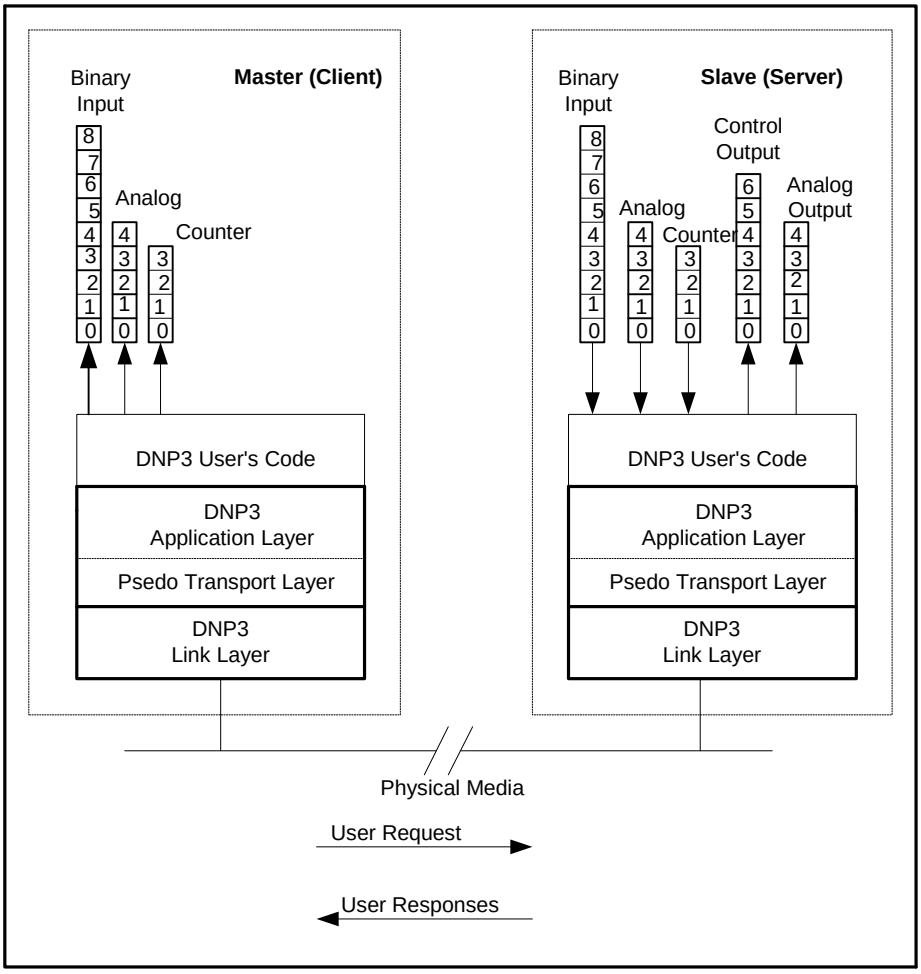
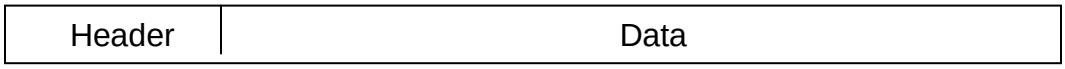


Figure 3.3: Client and server relationship [105]

Sometimes transmission of more than one frame is necessary to transport all of the information from one device to another. A DNP3 frame consists of a header and data section as shown Figure 3.4. The header specifies the frame size, which DNP3 station should receive the frame, which DNP3 device sent the frame and data link control information. The data section is commonly called the payload and contains the data passed down from the layers above.

DNP3



Header

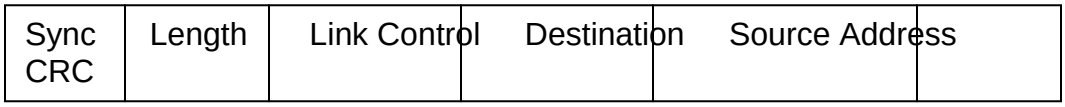


Figure 3.4: DNP3 frame

Every frame begins with two synchronous bytes that help the receivers determine where the frame begins. The length specifies the number of octets in the remainder of the frame, not including Cyclic Redundancy Code (CRC) check octets. The link control octet is used between sending and receiving link layers to coordinate their activities.

A destination address specifies which DNP3 device should process the data, and the source address identifies which DNP3 device sent the message. Having both destination and source addresses satisfies at least one requirement for peer-to-peer communications because the receiver knows where to direct its responses.

It is the responsibility of the transport layer to break long messages into smaller frames sized for the link layer to transmit, or when receiving, to reassemble frames into the longer messages. In DNP3 the transport layer is incorporated into the application layer.

Application layer messages are broken into fragments. Fragment size is determined by the size of the receiving device's buffer. It normally falls between 2048 and 4096 bytes. A message that is larger than a one fragment requires multiple fragments. Fragmenting messages is the responsibility of the application layer.

The application layer works together with the transport and link layers to enable reliable communications. It provides standardised functions and data formatting with which the user layer above can interact. In DNP3, the term static is used with data and refers to the current value.

DNP3 goes a step further by classifying events into three classes. When DNP3 was conceived, class 1 events were considered as having higher priority than class 2 events, and class 2 were higher than class 3 events. The user layer can request the application layer to poll for class 1, 2 or 3 events or any combination of them.

The DNP3 organisation recognises that supporting every feature of DNP3 is not necessary for every device. Some devices are limited in memory and speed and do not need specific features, while other devices must have the more advanced features to accomplish their task. DNP3 organises complexity into three levels. At the lowest level, i.e. level 1, only very basic functions must be provided and all others are optional. Level 2 handles more functions, objects and variations, and level 3 is even more sophisticated. Within each level only certain combinations of request and response formats are required. This was done to limit software code in clients and servers while

still assuring interoperability. It should be apparent by now that DNP3 is a protocol that fits well into the data acquisition world. It transports data as generic values, has a rich set of functions, and was designed to work in a wide area communications network. The standardised approach of objects and variations, and link, transport and application layers, plus public availability makes DNP3 a protocol to be regarded. The most attractive reasons for choosing the internet protocol suite as a transport mechanism for DNP3 are:

- Seamless integration of the substation LAN to the corporate WAN utility
- Leverage existing equipment and standard.

The internet protocol suite and DNP use the OSI layering paradigm; each piece of the protocol stack in one station logically communicates with the corresponding piece in the other station(s). It is therefore easy to build DNP on top of the internet protocol suite since the internet layers appear transparent to the DNP layers as shown in Figure 3.5.

3.2.1.1 Physical, Link and Network layers

Ethernet is recommended to use for the link and physical layers because of the ubiquity and it provides the necessary bandwidth and physical media for substation and control centre LANs. Ethernet wiring and equipment is well understood and standardized. IP forms the basis for the internet protocol suite and therefore recommended network layer

protocol. IP provides a connectionless, best effort datagram delivery service to the transport layer protocols.

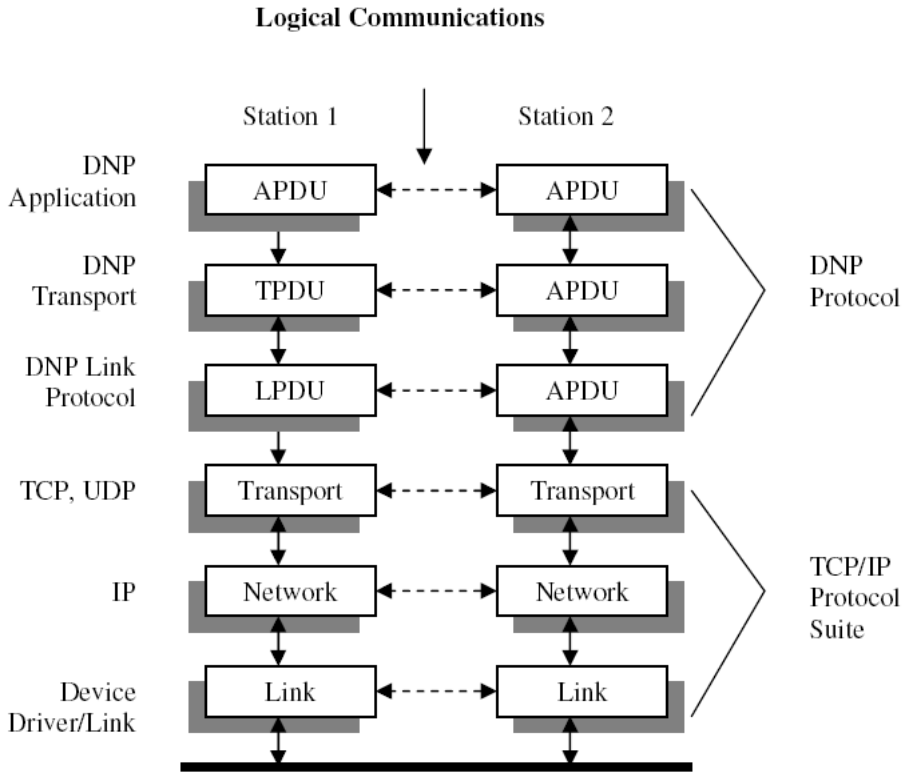


Figure 3.5: DNP3Protocol stack [105]

3.2.1.1 Transport layer

The Transport layer of the internet protocol suite consists of two distinct services: UDP and TCP. TCP shall be the primary transport service for DNP messages because of its reliability; UDP can be used on a high-reliability single-segment LAN and in specific cases where small pieces of non-critical data need to be sent or when broadcasting is

required. UDP cannot be used if the DNP messages must be routed over the utility enterprise or wide area network. A network topology is shown in Figure 3.6.

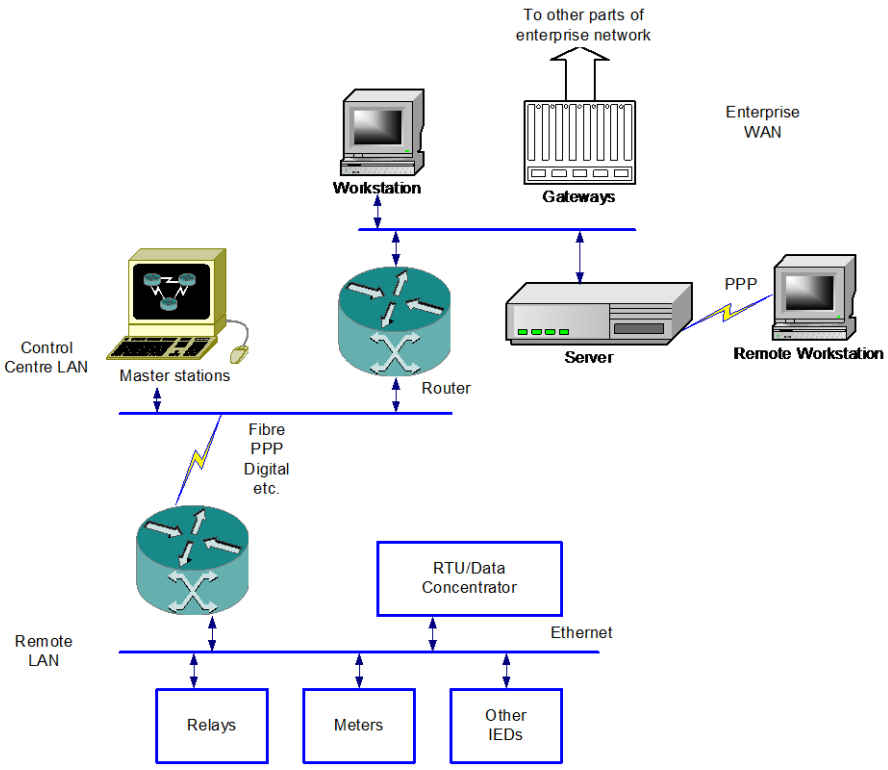


Figure 3.6: Network Topology [105]

3.2.2 IEC 61850

International Electrotechnical Commission (IEC) IEC 61850 is based on the need and the opportunity for developing standard communication protocols to permit interoperability of IEDs from different manufacturers.

Utilities also require IED interchangeability, which is the ability to replace a device supplied by one manufacturer with a device supplied by another manufacturer, without making changes to other elements in the system. IEC 61850 makes use of existing standards and commonly accepted communication principles, which allows for the free exchange of information between IEDs.

Hence IEC 61850 provides a neutral interface between application objects and the related application services allowing a compatible exchange of data among components of a substation automation (SA) system [106-107]. The IEC61850 abstract communication service interface (ACSI) Models are abstract definitions of common utility communication functions in field devices mainly describing communications between clients and remote servers.

It aims for common utility functions to be performed consistently across all field devices provided that standardised mappings of these abstract services to the IEC61850 application layer protocol are defined [108]. Accordingly, ACSI defines Substation-specific information models such as common DATA classes and Substation-specific information exchange service models. Figure 3.7 shows how these two models are interwoven with each other.

ACSI specifies the basic layout for the information models and the information exchange service models. Nevertheless, the implementation of the objects and the modelling issues are left to the user.

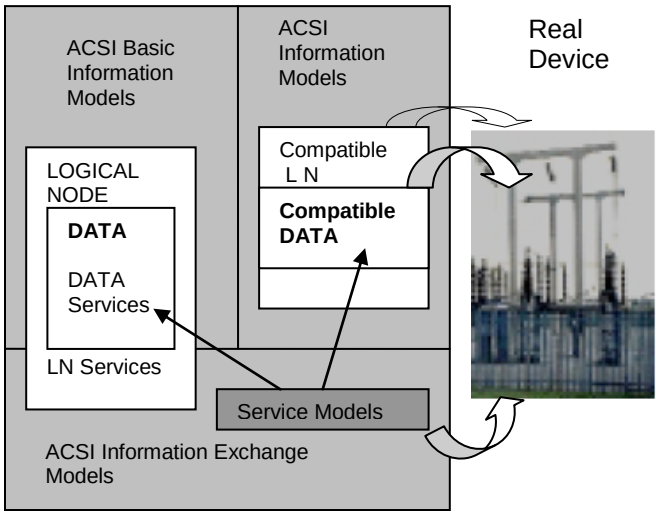


Figure 3.7: ACSI conceptual model

A representation of physical object can be referred to as an object model. For instance, the measurements of voltage, current and power in a relay can easily be grouped together to form the "measurement model". Once standardised, it is possible to request information from devices without having to know any information about the manufacturer of the device. Thus, Object Oriented Modelling techniques are used to define ACSI models. However, it should also be noted that some vendor specific objects within the IED will be left unstandardised and will take some part of the total object space.

The logical node is primarily a composition of Data and DataSet plus some other services where Data is a composition of DataAttributeType (DAType), Functional Components (FC) and Trigger Conditions. The smallest entities for information exchange are the LOGICAL-NODEs such as XCBR. The LOGICAL NODEs are then

used to build the LOGICAL- DEVICES. In turn, several LOGICAL DEVICEs are then used to build up the IEDs [109].

Each of the classes comprising the LOGICAL NODE consists of a number of building blocks. Even though ACSI allows discrete devices to share data and services, it is only an abstract application layer protocol without any real procedure for sending and receiving data. It can only be usable when it is mapped to a specific communication service such as Manufacturing Message Specification (MMS) protocol, Distributed Component Object Model (DCOM) or Common Object Request Broker Architecture (CORBA). The Specific Communication Service Mapping (SCSM) describes the implementation details of services and models using a specific communication stack [110].

3.2.3 Other commonly used power system communication protocols

As stated earlier, there are various power system communications protocols developed by various vendors. Apart from DNP3 and IEC61850, there are few more commonly used protocols which will be discussed briefly. One of the popular ones beside DNP3 is Modbus Protocol. It is a messaging structure developed by Modicon in 1979. It is used to establish master-slave/client-server communication between intelligent devices. It is a de facto standard, truly open and the most widely used network protocol in the industrial manufacturing environment. It has been implemented by hundreds of vendors on thousands of different devices to transfer discrete/analog I/O and register data between

control devices. It's a lingua franca or common denominator between different manufacturers. One report called it the "de facto standard in multi-vendor integration". Industry analysts have reported over 7 million Modbus nodes in North America and Europe alone. Modbus is used in multiple master-slave applications to monitor and program devices; to communicate between intelligent devices and sensors and instruments; to monitor field devices using PCs and HMIs. Modbus is also an ideal protocol for RTU applications where wireless communication is required. For this reason, it is used in innumerable gas and oil and substation applications. UCA is another standardisation communication protocols. The UCA is comprised of data object models, service interfaces to these models and communication profiles as illustrated in Figure 3.8 [113]. Data object models are at the highest level, i.e. at the application layer. Service interfaces include operations such as defining, retrieving and logging of process data.

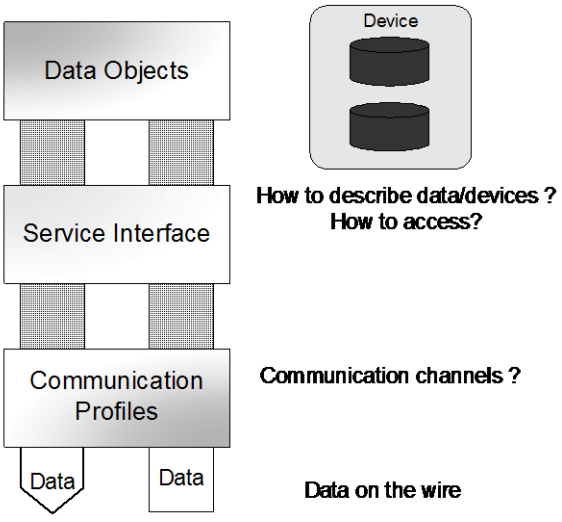


Figure 3.8 Three levels of UCA [113]

Within the UCA framework, a device object model is referred to as the definition of data and control functions made available by the device along with the associated algorithms and capabilities [113]. Device models describe the communication related behaviour of devices by making use of a common set of services. The detailed interoperable structure for utility field devices can be fully specified by mapping these services onto the UCA Application Layer Protocol (ALP) when used in conjunction with the device models. The services and their mappings to the MMS are defined in UCA Common Application Service Models (CASM). Device models can be specified independent of the underlying protocol. Active participation of groups outside the UCA activities has been encouraged due to this feature of protocol independence, which also simplifies migration through the construction of getaways to older existing protocols [114].

UCA targets to reduce the engineering, monitoring, operation and maintenance costs while increasing the agility of the whole life cycle of a substation by improving device data integration into the information and automation technology [111]. Many relay and IED manufacturing companies showed their interest in UCA work and joined in the effort to define and demonstrate a communication network stack [108]. With continued EPRI support, vendors have built UCA-compliant versions of their products. The equipment makers continue to modify and update the implementations in each of the products. Many US and overseas utilities have signed up to demonstrate UCA substation systems. The users can see an impressive and elaborate demonstration of interoperability amongst a broad variety of equipment from competing manufacturers in meetings held several times a year. The importance of achieving interoperable

communication has forced collegial cooperation among competitors, who see the individual-product features and performance as the proper ground for competition [112].

3.3 Conclusion

This chapter has presented broader understanding of information embedded power system over wide area network. An elaborate discussion was given on each component of information embedded power system with major emphasis in measurement system and communication system. A detailed discussion was also presented for various power systems communication protocols in particular to DNP3 and IEC61850. These two protocols are the two major industry protocol employed in power industry.

CHAPTER 4

EXPERIMENTAL ANALYSIS OF DNP3 PROTOCOL FOR AN IEPS-W

4.0 Introduction

An overview of IEPS-W has been presented in the previous chapter. This research was carried out into two major streams. The first part is to experimentally analyse the performance and propagation delays associated in DNP3 protocol. In this experiment, power system data were sent from RTUs/IEDs to control centre via WAN using DNP3 protocol. The second part of this research is to develop more efficient, secure and robust power system communication platform for critical data transmission based on the experimental result which will be discussed in Chapters 6 and 7. The new developed model will enable the power system fault to be found more accurately with time tag of occurrence of system events which will eventually save considerable time when investigating system incidents.

The main focus of this chapter is to discuss the detailed experimental analysis which was carried out at SP AusNet. Section 4.1 provides in elaboration on experimental setup while experimental procedure is discussed in Section 4.2. The experimental result

has been presented in section 4.3. Finally, conclusion remarks have been provided in Section 4.4.

4.1 Experimental setup

An experimental analysis is required for any available power system communication protocols before deploying it into power grid to ensure the employed protocol suits the particular power system infrastructure. A real life experimental platform was created at SP AusNet in order to experimentally measure and characterise measurement delay errors in a scaled down version of a real time information embedded power system when power system data are being sent over WAN using DNP3 protocol as shown in Figure 4.1. This setup allows for measuring delays in sending a typical set of power system bus measurements from RTUs to an energy control center. The contemporary digital RTU50 has been used to transmit data via WAN to the control centre.

The WAN in this experiment involves four routers, three switches and two firewalls that make the communication backbone for data transmission. The SCADA switches are CISCO 4003 and the SCADA routers are CISCO 3640. The corporate network to SCADA firewall is a CISCOPIX 520. There are CISCO 7206 core routers, CISCO 3550-24 switches, PIX 535 firewalls at Richmond Terminal Station (RTS), and CISCO 7206 outside routers to connect to the WAN links on the Richmond side. At the terminal stations, there are CISCO 2620 routers and CISCO 3550-24 switches which were

connected to the test RTUs. The communication link is a 2 Mega bytes link with 8 terminal stations connected in a ring communicating from the two outside routers.

Real time data are being sent from RTU to the control centre via WAN in different stages of network utilisation. The RTU is located at Richmond Terminal Station and the control centre was positioned at Victoria Network Switching Centre (VNSC). Other features and characteristics involved in this experiment are summarised in Table 4.1. The RTUs in this experiment have been configured to accommodate DNP3 and communicate via WAN. Experimental set is depicted in Figure 4.1.

Table 4.1: Summary of experimental features and characteristics involved in DNP3-WAN (TCP/IP) experiment

Protocol use	DNP3 over WAN
Repeat count	10000
Datagram size	18024 bytes
Communication link type	Fast Ethernet 10/100
Transport mode	TCP/IP
Timing Clock	TEKRON precision clock

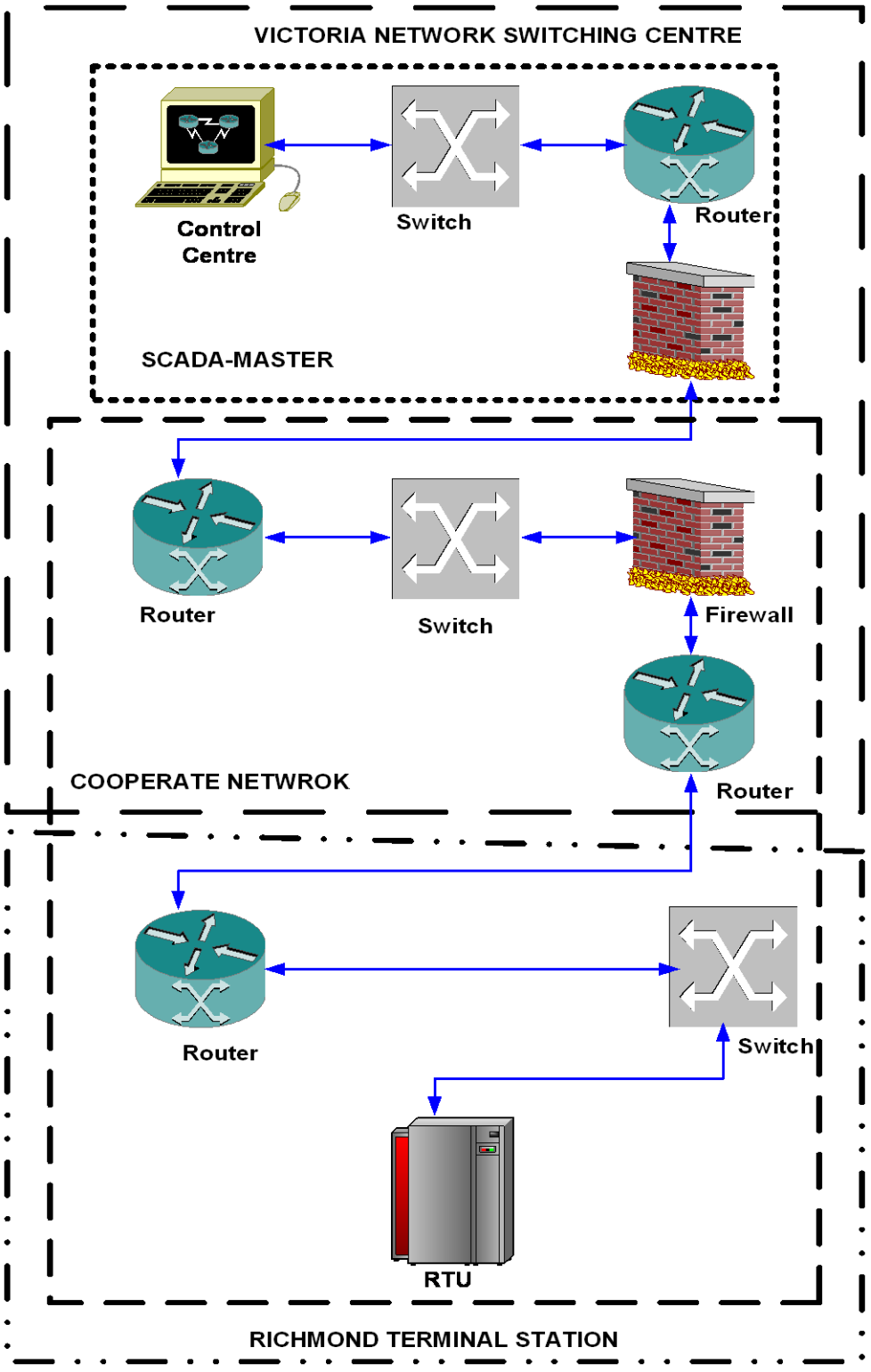


Figure 4.1: Experimental set-up

ASE2000 communication test set developed by Applied System Engineering, Inc was used to simulate the experiment and collect the data. The experiment has run several times in different network utilisation. Data are sent in every 2-second from RTU to control centre while power system uses DNP3 over WAN as its communication backbone.

The ASE2000 is a computer based Communication Test Set that supports a large number of RTU/IED protocols. The ASE2000 is the latest in the ASE Test Set series and offers some significant improvements over earlier versions.

The ASE2000 has been completely re-engineered as a windows application and incorporates many new features that have been requested as desirable additions over earlier Test Set versions. Some of the more significant ones are:

- The Line Monitor view is now divided into two panes with raw data on the left and interpreted data on the right. Either pane can be viewed separately or the two viewed side-by-side. This layout improves readability since raw and interpreted data is no longer interspersed.
- An Input Point view has been added that displays input point data (analog, digital, pulse) in a tabular format. If just input point data values are of interest and not other communication line message information, then this provides an excellent view of the data. The view shows RTU ID, point ID, and point value, time tags, as well as quality code information for applicable protocols (DNP

3.0). Engineering units conversion coefficients, digital state names, high/low alarms limits, and point and RTU names can be entered to provide a more "operational" viewing presentation of the data.

- The Analog Control and Digital Control views are shortcuts for configuring control output request sequences. This provides the ability to sequence control output commands (e.g., trip/close) and values to a set of output points.
- For timing analysis and troubleshooting certain timing problems, the Line Analyser view can be used to plot data and carrier signals on both lines (to RTU, to Master) with millisecond resolution.

In addition to the new features described above, the ASE2000 supports the same basic Test Set modes:

1. Monitor Mode - Monitor, in a passive mode, communication between a master and slave device (data from both the Master to RTU and RTU to Master are displayed).
2. Master Simulation Mode - Communicate directly to an RTU by issuing data, control, and other requests
3. RTU Simulation Mode - Respond directly to the master by simulating one or more RTUs on a single line; each response can additionally simulate analog, digital and pulse accumulator point changes.

4.2 Experimental procedures

DNP3 protocol was not default protocol in use at SP AusNet SCADA network at the time when the experiment was conducted, hence, it was challenging to create a platform to conduct the experiment with data feeding in real time from transmission system to RTS where IEDs/RTUs are located. A new purpose built platform was created to conduct the experiment in which real time data are fed to the control centre from RTS. After setting up the equipments and communications facilities, there were major difficulties in establishing initial communication between RTUs and other communication devices at the control centre. After several weeks of dedicated efforts, communication link was established between RTS and control centre using DNP3 protocol over WAN. Once communication was established, different properties of ASE2000 communication Test Set have been set to initiate the experiment. As depicted in Figure 4.2, one master unit and 2 RTU slave units have been selected for this experiment.

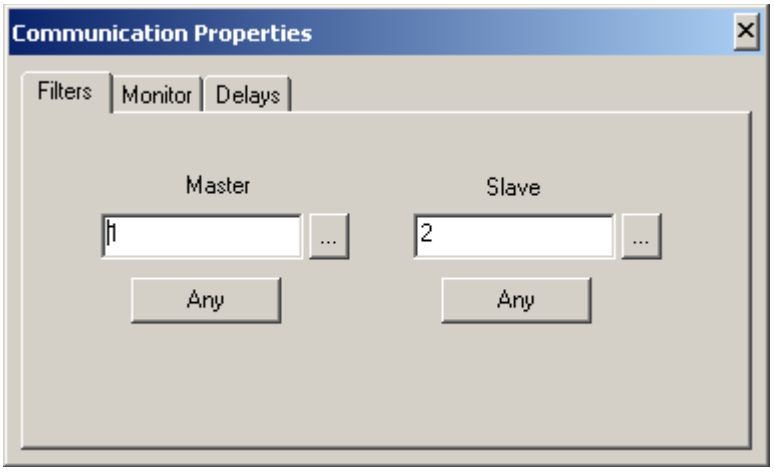


Figure 4.2: Control room (master) and slaves (RTUs) setting

However, one slave RTU was used during the experiment. Master Unit was located at VNSC while RTUs were positioned at RTS. Figure 4.3 shows the time interval chosen for the data to be sent. As seen in the figure, data were sent in every 2 seconds from RTU to the control centre SCADA system.

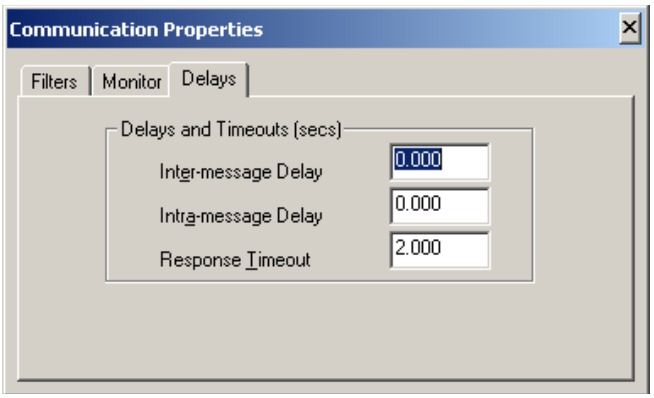


Figure 4.3: Time interval setting

he performance analysis of DNP3-WAN was carried out with extreme precision since the experiment investigates at millisecond accuracy. The experiment was set to record data transmission rate in millisecond as depicted in Figure 4.4.

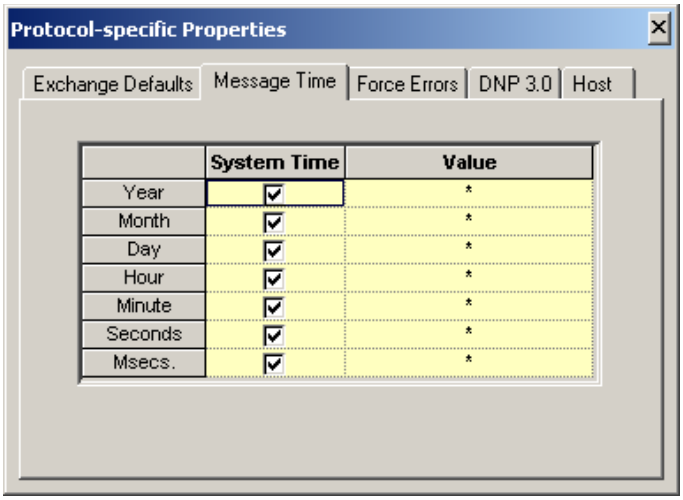


Figure 4.4: Time setting up to milliseconds

DNP3 involves three different classes of data along with many other features which can be incorporated. The details 'Class features' is discussed in chapter 5. For this experiment, Class 1, Class 2 and Class 3 data type to be transmitted have been set as shown in Figure 4.5. Furthermore, the property is set to accommodate unsolicited data in this experiment.

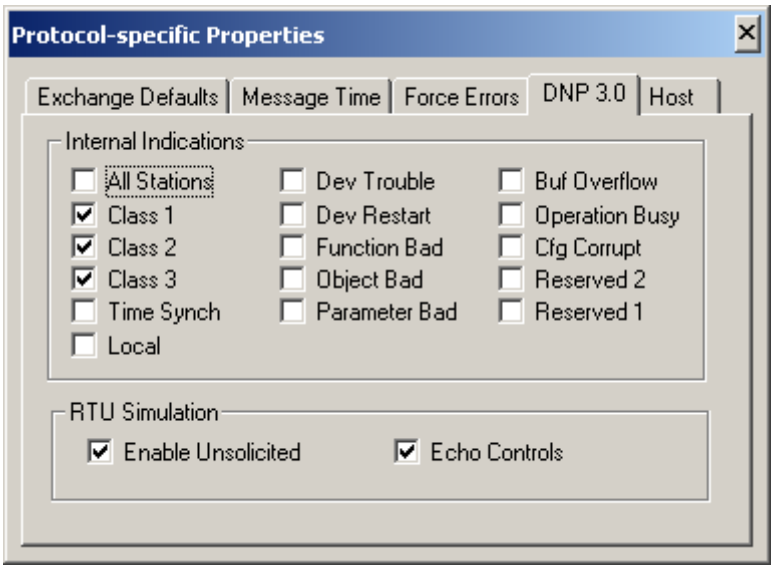


Figure 4.5: DNP3 Classes

As mentioned before, UDP is not suitable to adopt in DNP3-WAN. Hence, TCP/IP was chosen as shown in Figure 4.6 as mode of transport since it guarantees data transmission which is vital in power system. There were many other properties which were required to be set up that have not been shown in this thesis. Figure 4.7 shows ASE2000 communication Test Set activity timeline view for DNP3 -WAN after setting all the required parameters and properties as mentioned above.

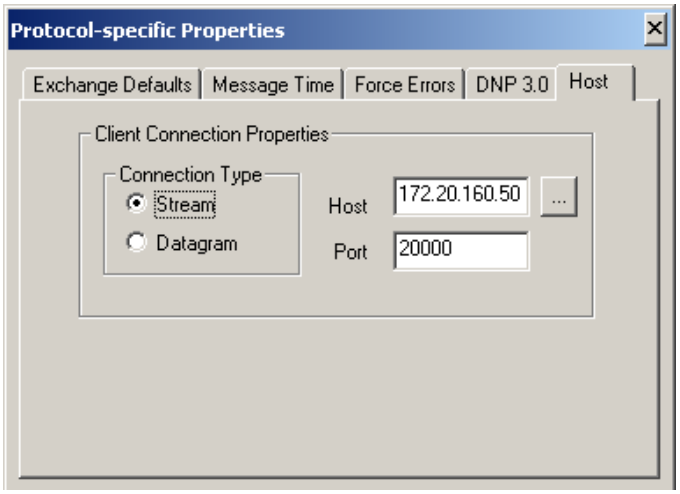


Figure 4.6: ASE2000 communication Test Set: TCP as transport mode

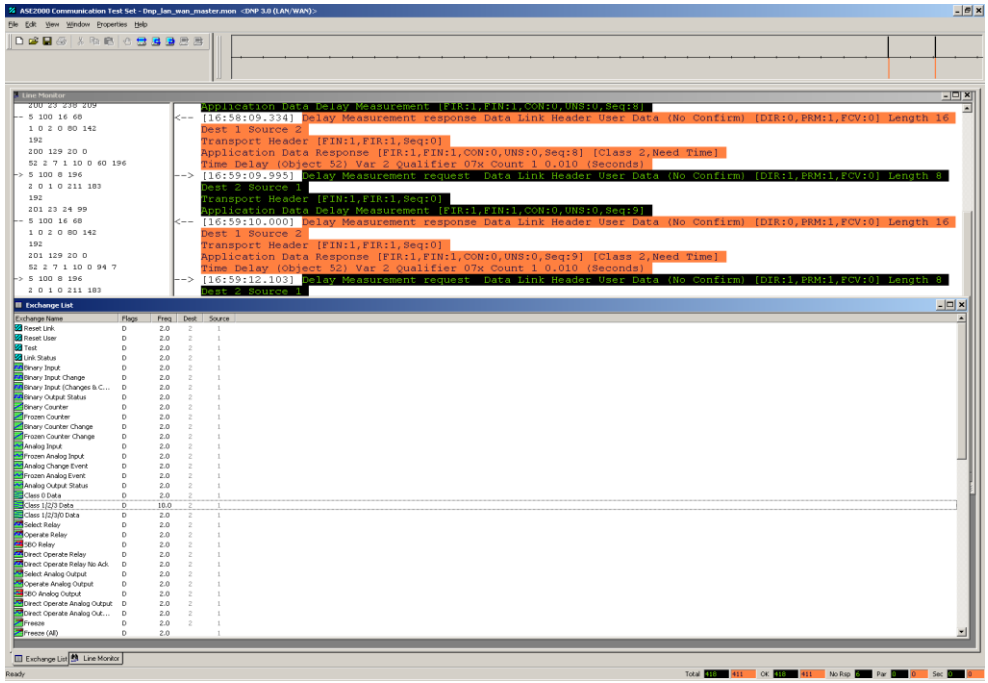


Figure 4.7: Activity timeline for DNP3-LAN/WAN (TCP/IP)

The communication was successfully established and the experiment was successfully run for several weeks to observe performance of DNP3 over WAN.

The activity Timeline is displayed in the upper right-hand corner of the Test Set window. This time-scaled view shows communication line activity and carrier signals. Data is presented as a solid bar, while carrier signals is plotted as a line above and below the data bars.

4.3 Experimental results

The experimental setup in Figure 4.1 was used to measure propagation delay associated in IEPS-W when data are sent from RTUs to control room using DNP3 over WAN. The experiment was carried out in different data traffic and carefully observed the performance characteristic of data traffic. For each experimental run, a group of 10,000 measurement packets were sent from RTU to the control center. Experiments were run using TCP transport protocols as UDP is not suitable in DNP3 over WAN as UDP does not provide message guarantee services.

The RTU response time was set to record the delay in milliseconds as hh:mm: ss: ms since the experiment was conducted to investigate into millisecond precision. Table 4.2 shows the representation of experimental data for 10% data traffic while 10000 measurement packets were sent from RTU to the control center using DNP3 over WAN. The data sent and received shown in the table are in hour, minute, second and millisecond format. The details experimental data can be found in Appendix A.

Table 4.2: Propagation delay with 10% data traffic

Data sent from RTU	Data Received at Control Centre	Propagation delay (ms)
11:47:18.130	11:47:18.138	0:00:00.008
11:47:20.239	11:47:20.248	0:00:00.009
11:47:22.348	11:47:22.359	0:00:00.011
11:47:24.457	11:47:24.463	0:00:00.006
11:47:26.566	11:47:26.578	0:00:00.012
11:47:28.672	11:47:28.683	0:00:00.011
11:47:30.781	11:47:30.794	0:00:00.013
11:47:32.888	11:47:32.904	0:00:00.016
11:47:34.997	11:47:35.010	0:00:00.013
11:47:37.105	11:47:37.117	0:00:00.012

The experimental results involving propagation delays obtained in DNP3-WAN (TCP/IP) is depicted in graphical form in Figure 4.8.

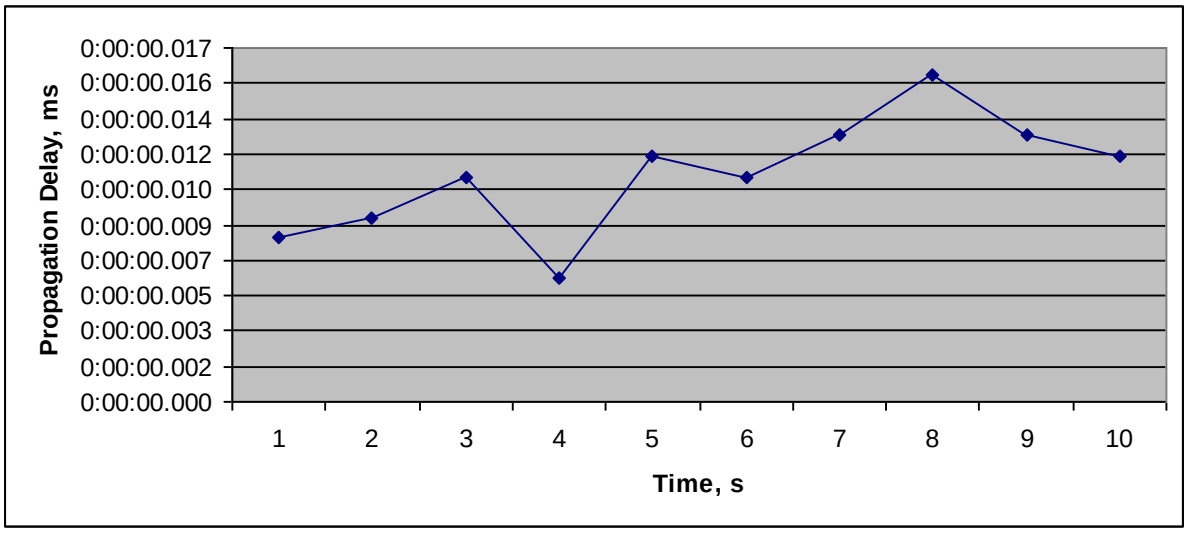


Figure 4.8: Propagation delay with 10% data traffic in DNP3-WAN (TCP/IP)

It can be observed that propagation delay involve in this instance is between 6 -16 ms. The result obtained are based on less traffic in the network. However, as data traffic to be transmitted from RTU to control room is increased, the propagation delay appears to be significantly highly. Table 4.3 presents data with 20% increase in traffic from the initial case.

Table 4.3: Propagation delay with 20% increased data traffic

Data sent from RTU	Data Received at Control Centre	Propagation delay (ms)
15:21:47.454	15:21:47.478	0:00:00.024
15:21:49.564	15:21:49.585	0:00:00.021
15:21:51.673	15:21:51.696	0:00:00.023
15:21:53.783	15:21:53.804	0:00:00.021
15:21:55.893	15:21:55.913	0:00:00.020
15:21:58.001	15:21:58.019	0:00:00.018
15:22:00.110	15:22:00.134	0:00:00.024
15:22:02.220	15:22:02.236	0:00:00.016
15:22:04.330	15:22:04.339	0:00:00.009
15:22:06.440	15:22:06.461	0:00:00.021

As expected, propagation delay has increased when network traffic is increased to 20% as shown in Figure 4.9. The minimum delay in this case is 9 ms while the maximum propagation delay rises 24 ms.

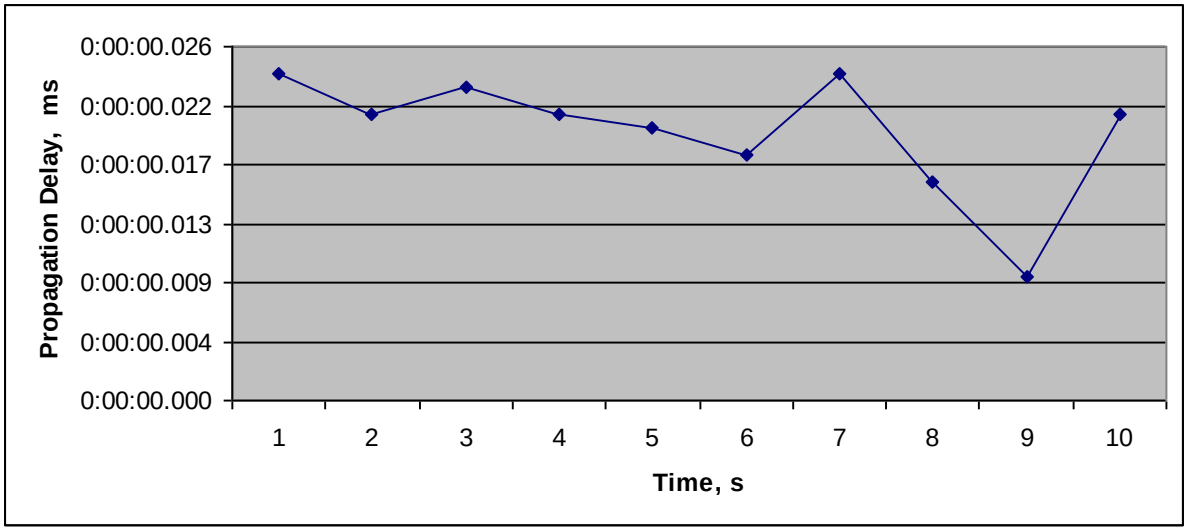


Figure 4.9: Propagation delay in DNP3-WAN (TCP/IP) with 20% traffic increase

As data is increased in the network, the propagation delay also increases substantially. Table 4.4 gives performance result when network traffic is increased to 40%.

Table 4.4: Propagation delay with 40% increased data traffic

Data sent from RTU	Data Received at Control Centre	Propagation delay (ms)
11:36:02.357	11:36:02.379	0:00:00.022
11:36:04.624	11:36:04.647	0:00:00.023
11:36:06.890	11:36:06.914	0:00:00.024
11:36:09.156	11:36:09.182	0:00:00.026
11:36:11.423	11:36:11.444	0:00:00.021
11:36:13.689	11:36:13.707	0:00:00.018
11:36:15.955	11:36:15.976	0:00:00.021
11:36:18.222	11:36:18.238	0:00:00.016
11:36:20.488	11:36:20.507	0:00:00.019
11:36:22.755	11:36:22.774	0:00:00.019

With 40% network traffic, propagation delay grows with minimum delay of 16 ms and while maximum delay is up to 26 ms as shown in Figure 4.10.

When network is loaded with 60 % traffic, the transmission delay has increased to 28 ms as depicted in Table 4.5 which has also been presented in Figure 4.11 as graphical representation.

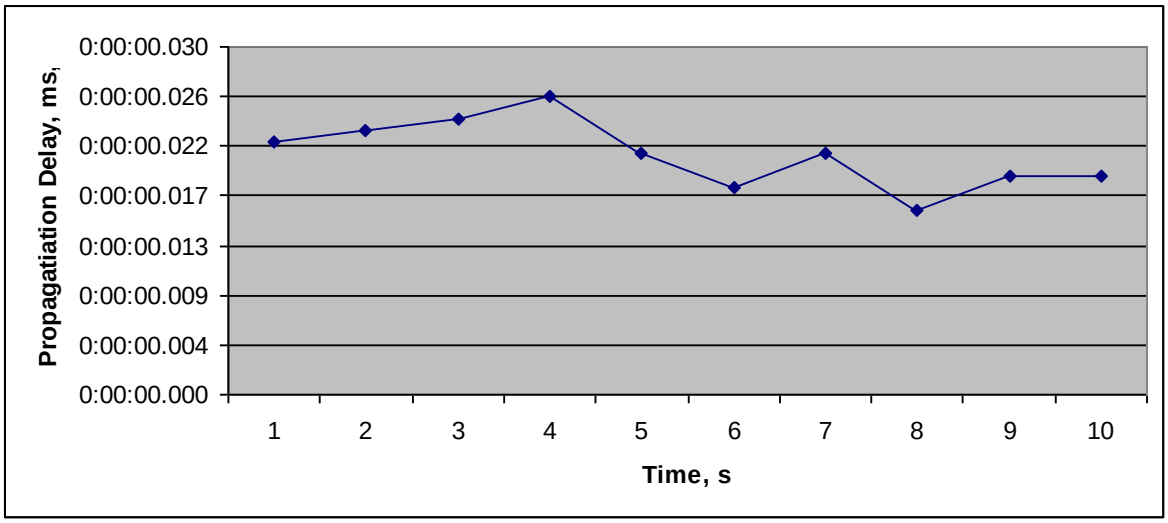


Figure 4.10: Propagation delay in DNP3-WAN (TCP/IP) with 40 % traffic increase

Table 4.5: Propagation delay with 60 % increased data traffic

Data sent from RTU	Data Received at Control Centre	Propagation delay (ms)
13:00:46.080	13:00:46.106	0:00:00.026
13:00:48.347	13:00:48.366	0:00:00.019
13:00:50.613	13:00:50.641	0:00:00.028
13:00:52.880	13:00:52.901	0:00:00.021
13:00:55.146	13:00:55.170	0:00:00.024

13:00:57.412	13:00:57.435	0:00:00.023
13:00:59.679	13:00:59.706	0:00:00.027
13:01:01.945	13:01:01.972	0:00:00.027
13:01:04.212	13:01:04.219	0:00:00.007
13:01:06.478	13:01:06.498	0:00:00.020

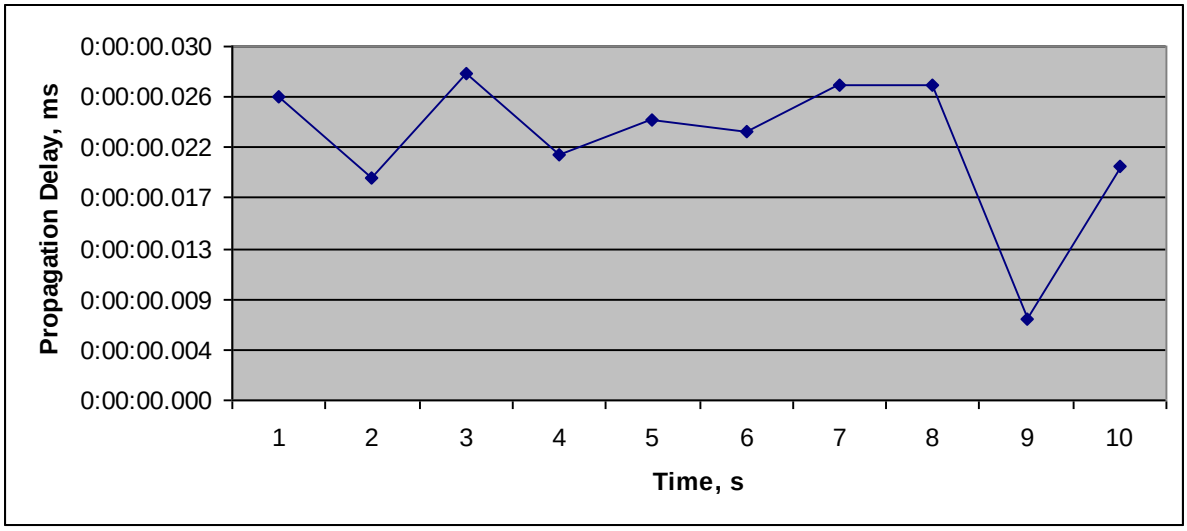


Figure 4.11: Propagation delay in DNP3-WAN (TCP/IP) with 60 % traffic increase

As the network traffic increases with high amount of data passing through the network, the propagation delay significantly increases. Table 4.6 and Figure 4.12 depict the network performance when data are sent with 80% increase in traffic. The minimum delay in this case is 18 ms with a maximum delay of 38 ms.

Table 4.6: Propagation delay with 80 % increased data traffic

Data sent from RTU	Data Received at Control Centre	Propagation delay (ms)
9:41:42.084	9:41:42.111	0:00:00.027
9:41:44.351	9:41:44.374	0:00:00.023
9:41:46.617	9:41:46.638	0:00:00.021
9:41:48.883	9:41:48.921	0:00:00.038
9:41:51.150	9:41:51.180	0:00:00.030
9:41:53.416	9:41:53.438	0:00:00.022
9:41:55.683	9:41:55.703	0:00:00.020
9:41:57.949	9:41:57.970	0:00:00.021
9:42:00.215	9:42:00.234	0:00:00.019
9:42:02.482	9:42:02.500	0:00:00.018

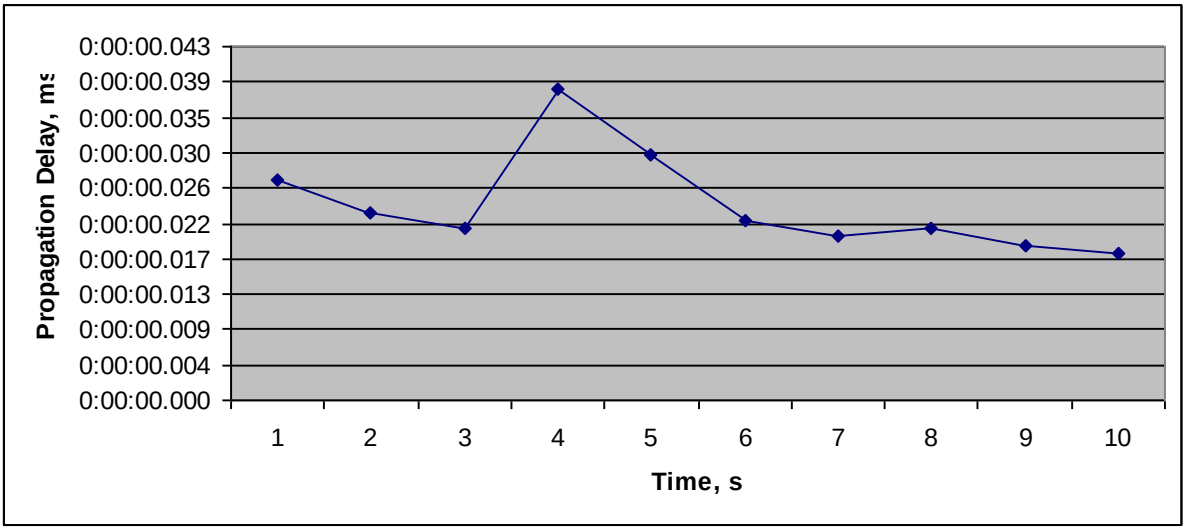


Figure 4.12: Propagation delay in DNP3-WAN (TCP/IP) with 80 % traffic increase

Table 4.7 and Figure 4.13 summarises the performance results of DNP3-WAN (TCP/IP) for an IEPS-W in the form of mean delay. As the data in this experiment suggests propagation delay increases with the increased of network traffic. The mean delay with 10% of network traffic is 11.1 ms while mean delay increases to 23.9 ms when experiment was 80 % data traffic. However, as can be seen in Appendix A, there are occasions when traffic delay increases up to 100 ms or more.

Table 4.7: Summary of Experimental results in different network traffic

Network Traffic (%)	Mean propagation delay (ms)
10	11.1
20	19.7
40	20.9
60	22.9
80	23.9

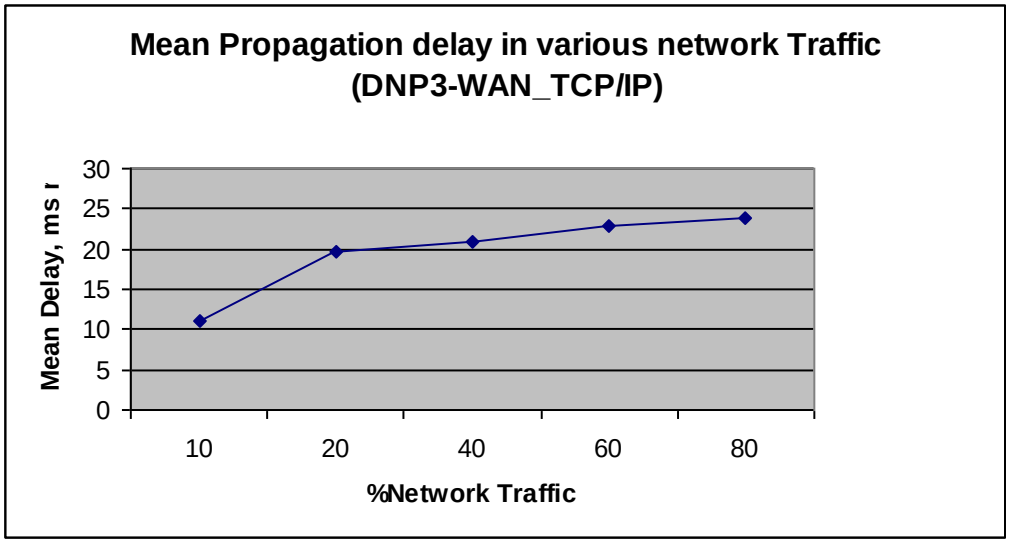


Figure 4.13: Mean propagation delay for DNP3-WAN (TCP/IP)

As stated earlier, there are hundreds of RTUs/IEDs which transmit data consistently to the control room in real time using various power system communication protocols. The data sent in this experimental analysis is only from one RTU. In practical, data will come simultaneously from different IEDs. In such cases, propagation delay could be significantly high failing to transmit critical data on time. This can cause catastrophic failure for power system. Hence, communication protocols must be carefully designed when it is intended to use in the broader communication network.

4.4 Conclusion

An experimental investigation is vital to conduct before employing any protocols to power grid as data are very critical to ensure high reliability of power system. DNP3 was not originally developed to use in WAN environment, hence the experimental investigation carried out in this project has contributed significantly. Details experimental procedures along with experimental setup and experimental result have been presented in this Chapter. Based on the results obtained from the experiment, it is apparent that a more robust communication protocol is required to be used in a wider power system network. The next chapter presents the development of DNP3 protocol in OPNET modeller to further simulate it in order to develop a more effective and reliably communication protocol to be used in IEPS-W.

CHAPTER 5

MODELLING OF DNP3 PROTOCOL FOR AN IEPS-W

5.0 Introduction

A detailed discussion on experimental analysis of the DNP3 over WAN for IEPS-W was presented in Chapter 4 where a significant propagation delay was found while power system data were sent from RTUs to control centre via WAN using DNP3 protocol.

This chapter presents the development and modelling of DNP3 protocol in an OPNET environment. OPNET has been used to develop DNP3 protocol and further analyse it in order to model a better information embedded power system to be used in WAN. Section 5.1 starts with a brief introduction on OPNET modeller which was chosen to develop DNP3 protocol in order to build a more reliable and secure power system communication protocol. OPNET is an Object Oriented (OO) discrete-event network simulator allowing for the modelling, implementation, simulation and performance analysis of communication networks and distributed applications. Section 5.2 then presents the development of data link and transport layer of DNP3 protocol in OPNET environment. A detailed description on the development of application layer of DNP3 is given in Section 5.3. Conclusion is made in Section 5. 4.

5.1 Brief overview of OPNET modeller

OPNET Modeller [115] is the industry's leading simulator specialised for network research and development. It allows to design and study communication networks, devices, protocols and applications with greater flexibility. It provides a graphical editor interface to build models for various network entities from physical layer modulator to application processes. All the components are modelled in an object-oriented approach which gives intuitive easy mapping to the real systems. It gives a flexible platform to test new ideas and solutions with low cost. OPNET is a simulator built on top of a discrete event system. It simulates the system behaviour by modelling each event happening in the system and processes it by user-defined processes. It uses a hierarchical strategy to organise all the models to build a whole network. OPNET also provides programming tools to define any type of packet format to be used in purpose-built protocols. Programming in OPNET includes the following major tasks:

- Define protocol packet format,
- Define the state transition machine for processes running the protocol,
- Define process modules and transceiver modules needed in each device node.

It allows to finally define the network model by connecting the device nodes together using user-defined link models.

5.2 Development and modelling of DNP3 protocol using OPNET modeller

As stated earlier, OPNET platform has been used to develop and model each layer of DNP3 protocol. As discussed in Chapter 3, DNP3 protocol provides the rule for substation IEDs and SCADA devices to communicate data and control commands. It was designed to optimise the transmission of data acquisition information and control commands from one control centre to other IEDs. The internet protocol suite and DNP3 [105] use the OSI layering paradigm. Each part of the protocol stack in one station logically communicates with the corresponding part in the other station(s). Therefore, DNP3 is built on top of the internet protocol suite since the internet layers appear transparent to the DNP layers as shown in Figure 5.1.

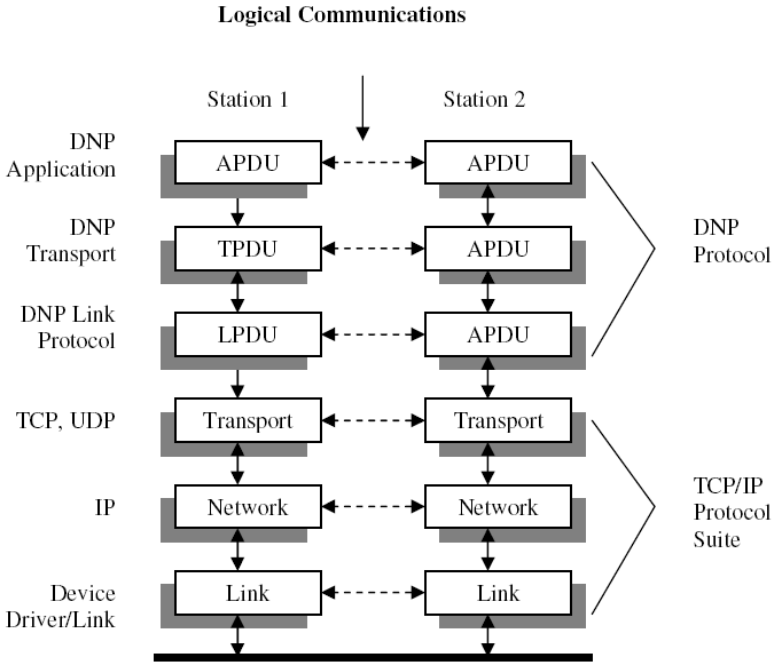


Figure 5.1: DNP3 protocol [105]

As discussed earlier, one of the major components of IEPS-W is control centre or master station in power system. Control centre communicates with outstation field devices such as IEDs or RTUs to monitor and protect modern power system via WAN platform incorporating various power systems communication protocols. A master station representing control centre and an IED have been developed based on DNP3 for an information embedded power system as shown in Figure 5.2 using OPNET Modeler. There are numerous code involved behind this blocks while developing DNP3 protocol.

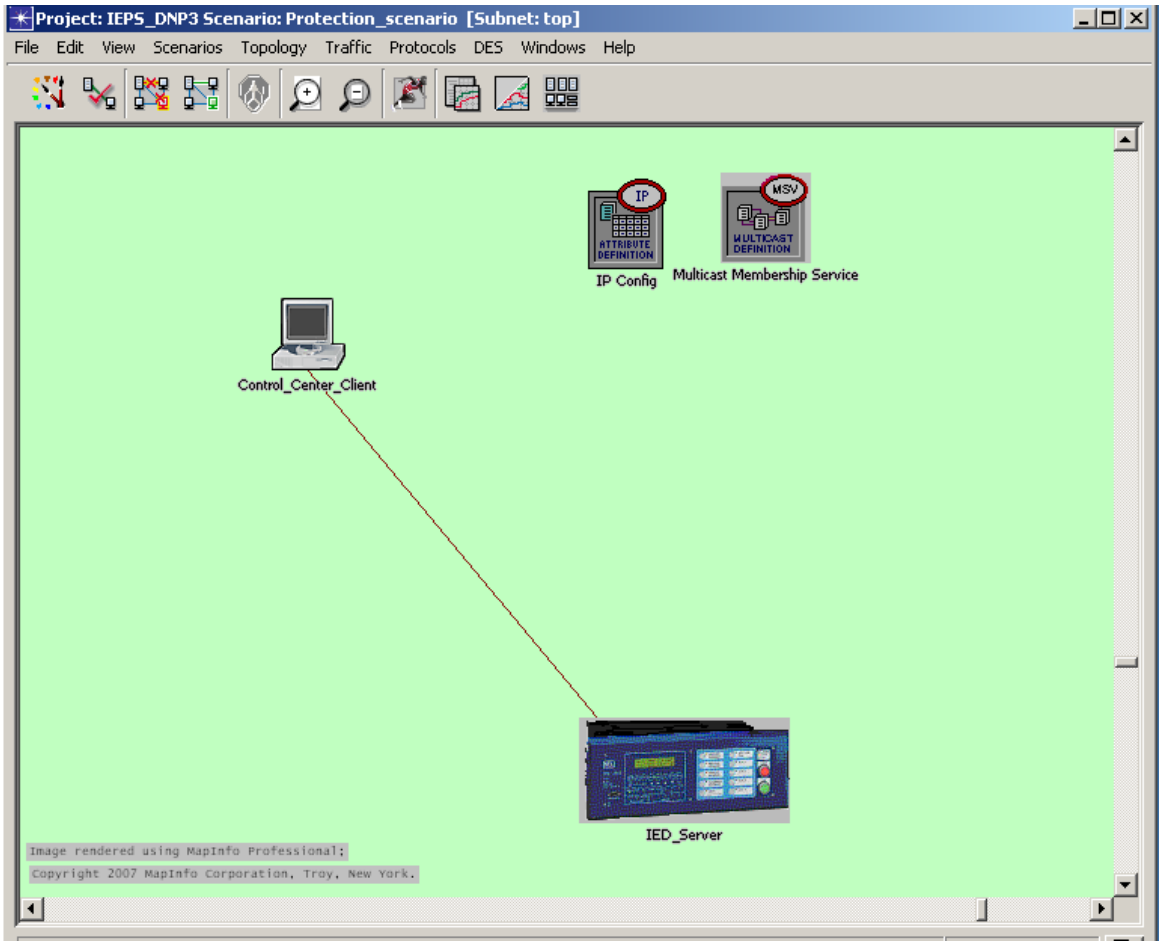


Figure 5.2: Control centre and IED in OPNET platform

As described in Figure 5.1, DNP3 protocol has three layers which are DNP link layer, DNP transport layer and DNP application layer. DNP3 sits on top of TCP/IP protocol suite making it easier to migrate it to Internet Technology. Figure 5.3 shows OPNET representation of Figure 5.1 whereby DNP3 layer sits on top of TCP/IP protocol suite. The detailed discussion on the development of master station (control centre) has been discussed in the following sections. DNP3 protocol has been developed to be used in both Master station and IED using OPNET modeller as shown in Figure 5.3.

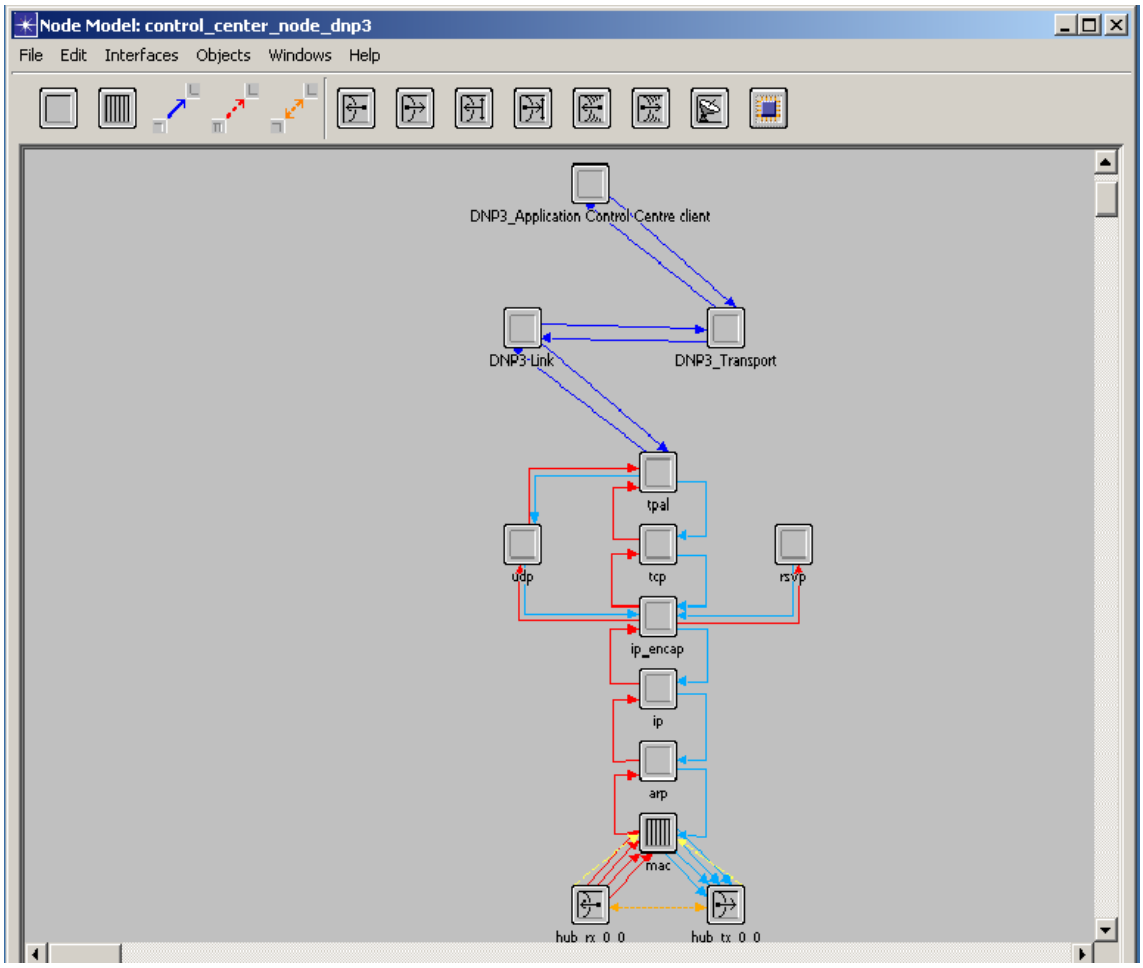


Figure 5.3: DNP3 protocol stack in OPNET environment

5.2.1 Implementation of DNP3 data link layer

The main purpose of the DNP3 data link layer [116] is twofold. It provides transfer of information or Link Service Data Unit (LSDU) across the physical link along with indications of other events such as link status. DNP3 handles both connectionless and connection oriented services. The communication requirements of the network layer and the pseudo-transport layer are satisfied by the data link layer service primitives.

The following data link functions have been executed in developing DNP3 data link layer:

- Performing message retries
- Synchronising and handling of the frame control bit in the control word
- Setting and clearing the data flow control bit based on buffer availability
- Automatically establishing a connection based on the destination parameter in a dial-up environment when a directed service is requested by the user
- Disconnection in a dial-up environment
- Packing user data into the defined frame format and transmitting the data to the physical layer
- Unpacking the frames that are received from the physical layer into user data
- Controlling all aspects of the physical layer
- Performing collision avoidance/detection procedures to ensure the reliable transfer of data across the physical link
- Responding to all valid frames (function codes) received from the physical layer.

The data link is responsible for providing the following services:

- Exchange of Service Data Units (SDUs) between peer DNP data links
- Error notification to data link user
- Sequencing of SDUs
- Prioritised SDU delivery
- Quality SDU delivery.

Priority delivery is set to EXPEDITED or NORMAL to indicate a high or low priority request. Quality delivery is categorised as SEND-NO-REPLY or SEND-CONFIRM to indicate whether or not message acknowledgment is required.

The data link service primitives are illustrated in pseudo code to illustrate the requirements and behaviour in a real implementation and are not intended as an exact interface definition.

Data link request (REQ) services is used after the data link has been initialized and configured by the system as follows.

```
confirm = request_data_link_service (
                SERVICE,
                TIME_SERVICE,
                destination,
                source,
                send_data_buffer,
                send_count,
                retry_flag,
                time_of_transmission
)
```

SERVICE	Service to perform
TIME_SERVICE	Guaranteed time service to perform
destination	Destination address to use in sent message
source	Source address to use in sent message
send_data_buffer	Data to send in message
send_count	Number of octets in message
retry_flag	Instructs data link layer to retry unacknowledged frames or not
time_of_transmission	Time that first bit of first octet of message is to be sent
time_of_transmission	Time that first bit of first octet of message was sent

Data link indications (IND) is set to request by the service user as follows.

indications = request_data_link_indications (
source_address,
destination_address,
received_data_buffer,
received_data_count,
time_of_reception)

source_address	Source address of received message
destination_address	Destination address of received address
received_data_buffer	Received message
received_data_count	Number of octets in message
time_of_reception	Time at which first bit of first octet of message was received

In this layer, a primary station sends a SEND-CONFIRM RESET frame to a secondary station. The secondary station receives the message and respond with an ACK confirm frame. Figure 5.4 shows the implementation of the above rules and functions which was developed using OPNET environment.

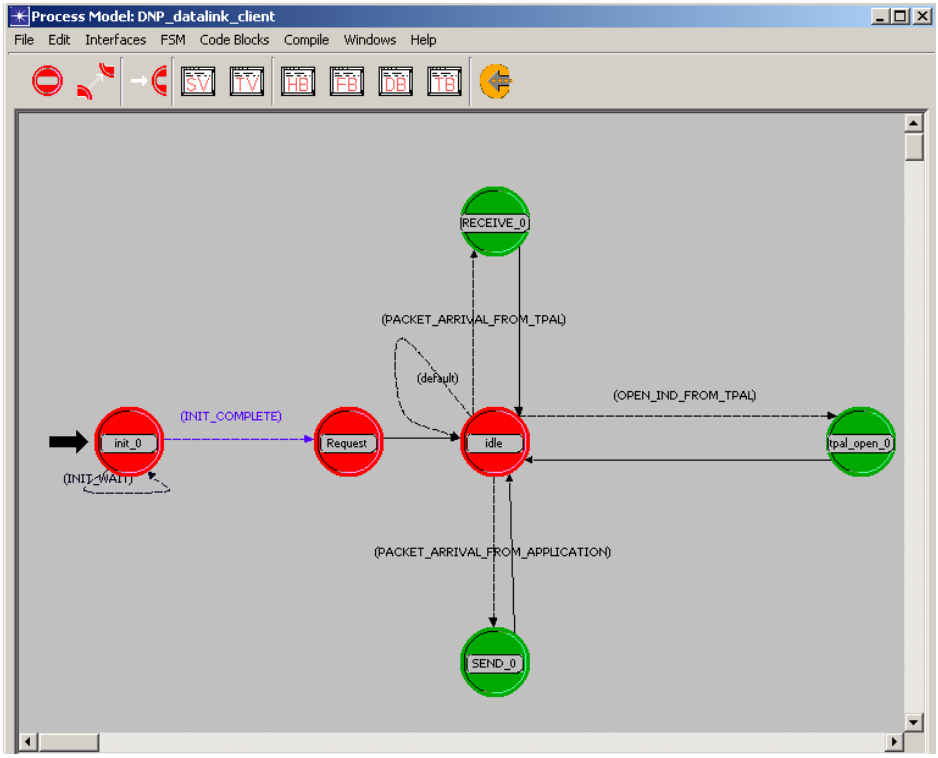


Figure 5.4: DNP3 data link layer in OPNET environment

5.2.2 Implementation of DNP3 transport layer

Master stations, submaster stations and outstations or IEDs use transport functions [117] to pass messages between primary (originating-control centre) stations and secondary (receiving-IEDs) stations. In this protocol, master stations, submaster stations and outstations are both originators (primary stations) and receivers (secondary stations).

The communication requirements of the network layer and the application layer are satisfied by the pseudo-transport layer service primitives.

The following functions have been implemented in pseudo-transport layer of DNP3 protocol:

- Pack user data into multiple frames (more than one) of the defined DNP3 Data Link frame format and use the services of the DNP3 Data Link for transmitting the data
- Unpack multiple frames that are received from the data link into user data
- Control all aspects of the data link excluding data link configuration.

The pseudo-transport layer is designed to provide the following services:

- Exchange of SDUs between peer DNP3 pseudo-transport layers
- Error notification to transport user
- Sequencing of SDUs
- Prioritised SDU delivery
- Quality control of SDU delivery.

The pseudo-transport layer function is specific only for those messages that are larger than one Link Protocol Data Unit (LPDU) between primary and secondary stations. This pseudo-transport layer acts as the DNP data link user in a protocol stack consisting of only the DNP Data Link and DNP Application Layer. This functionality allows the

pseudo-transport layer to disassemble one Transport Service Data Unit (TSDU) into multiple (more than one) Transport Protocol Data Units (TPDUs), or frames and assemble multiple (more than one) TPDUs into one TSDU. The pseudo-transport layer takes one TSDU (user data) and breaks it into several sequenced TPDUs (each with Transport Protocol Control Information (TPCI)). Each TPDU is sent to the data link layer as Link Service Data Unit (LSDU) for transmission. It also works in the reverse fashion. The pseudo-transport layer receives multiple TPDUs from the data link layer and assembles them into one TSDU.

When a primary station transmits a message to a secondary station, the transport functions break the message into LSDUs. These functions add a Transport layer Header (TH) octet at the beginning of the user data fragments that contain the information for the secondary station to reconstruct the complete message. The secondary station checks the TH octet on reception of each LSDU for the correct sequence and builds a TSDU message for higher layers. The TH contains information that can identify the first frame, last frame and give every frame a six-bit sequence number. This information is required to reconstruct a message and also to guard against higher layers from receiving misdirected or incomplete messages.

5.2.2.1 Transport header

After the data link receives a complete frame, the data is presented to the transport.
The TH field is stripped out before the frame is combined with other frames belonging to the same message. Figure 5.5 shows the structure of transport layer message layout.

TH	Transport control octet. One octet in length
USER DATA	1 to 249 octets in length

Figure 5.5: Transport layer message layout

When an application requests the transmission of a long message, the message is broken into fragments small enough to fit in a single DNP3 Data Link frame. The maximum size of a fragment is 249 octets of user data. The TH is added to the head of the fragment and the maximum number of octets to be framed becomes 250 octets. Figure 5.6 defines TH bits in details.

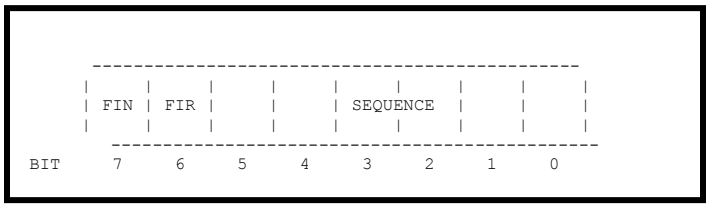


Figure 5.6: TH bit definitions

Where

FIN The final bit indicates that this frame of user data is the last frame of a sequence which compromises a complete user message.

FIN = 0 More frames to follow

1 Final frame of a sequence

FIR The first bit indicates that the frame is the first in a sequence of frame(s) which comprise a complete message. When a secondary station receives a frame with the FIR bit set, all previously received unterminated frame sequences are discarded. If a complete user message is only one frame in length, both the FIR and FIN bits are set.

FIR = 1 First frame of a sequence.

0 Not the first frame of a sequence.

SEQUENCE The sequence number of the frame is used to check that each frame is being received in sequence. It guards against missing or duplicated frames. All user messages start off with a sequence specified in the first frame which has the FIR bit set.

The sequence number increments for each frame sent to or received from the same address belonging to the same message and resets at the beginning of a new message. The sequence number does not have to increment across message boundaries, i.e. any sequence number is valid when the FIR bit is set.

5.2.2.2 Transmission of messages

Figure 5.7 illustrates the transmission of a single-frame message using the SEND - CONFIRM frame service.

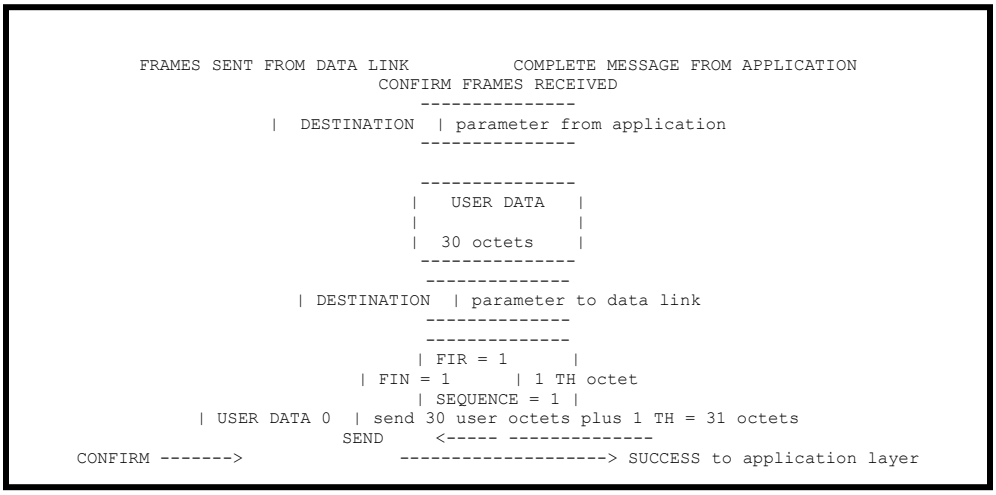


Figure 5.7: Transmission of a single frame message

Figure 5.8 shows DNP3 transport layer in OPNET environment which incorporates all functions and mechanism discussed earlier.

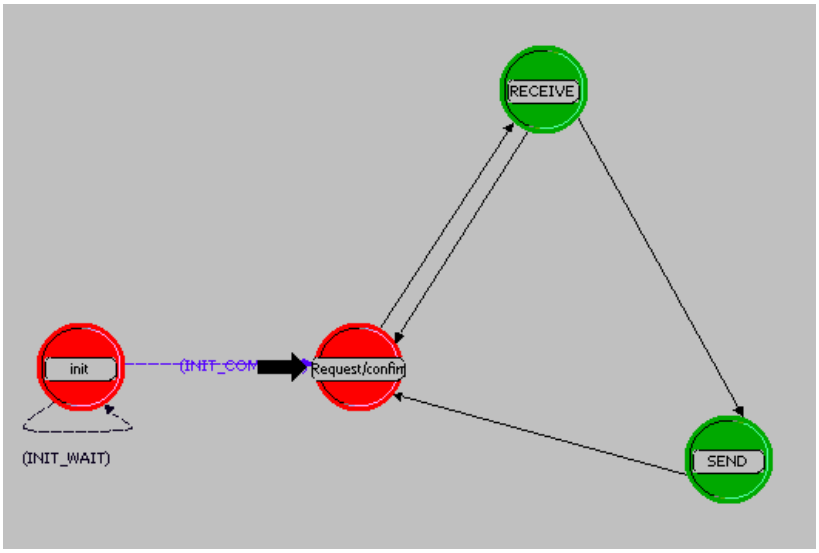


Figure 5.8: DNP3 transport lawyer in OPNET platform

5.3 Development and Implementation of DNP3 application layer

DNP3 Application Layer [118] is the top and main layer which provides standardised functions, data formats and procedures for the efficient transmission of data acquisition values, attributes and control commands as shown in Figure 5.9. DNP3 user's software is the application program that makes a device unique, whether it is a master, Intelligent Electronic Device (IED) or a data concentrator. It makes use of the Application Layer's services to send messages to, and receive messages from another DNP3 device. In this specification, the master station is defined as the station sending a request message and the outstation is the slave device, RTU or IED to which the requested messages is destined. In DNP3, only designated master stations can send Application Layer request messages and only outstations can send Application Layer Response messages. Figure 5.10 shows the sequence of Application Layer messages between one master and one outstation (IED).

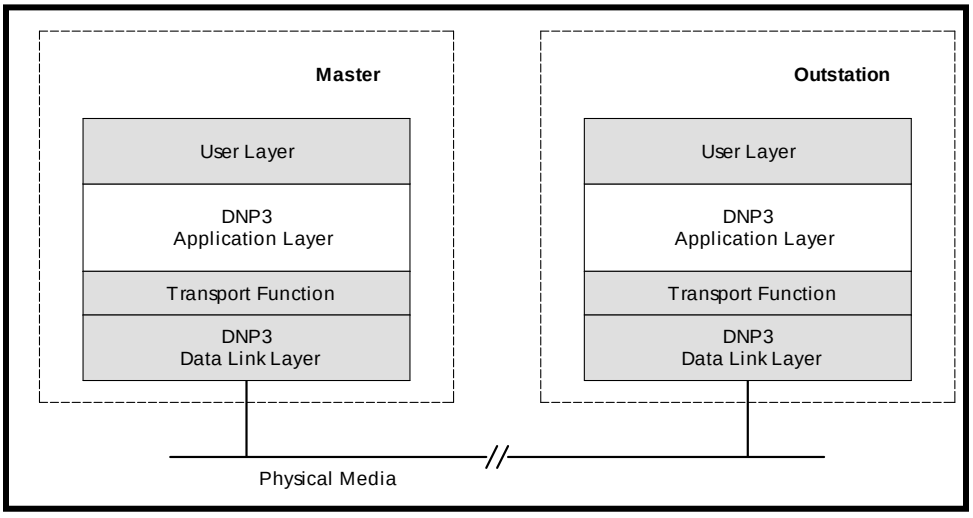


Figure 5.9: DNP3 device interface

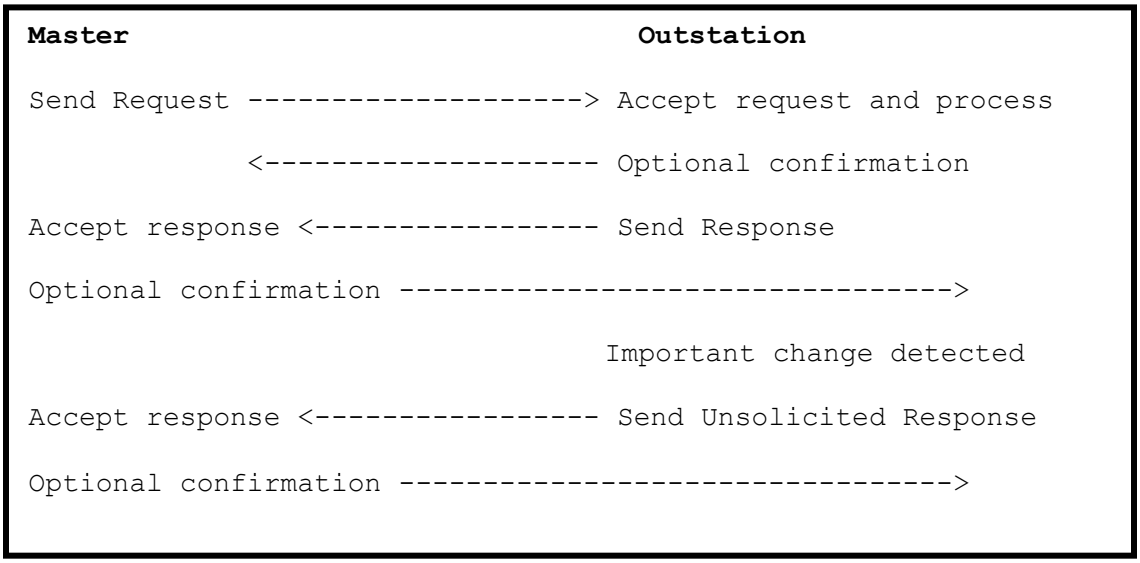


Figure 5.10: Message sequence

As shown in Figure 5.10, the master station sends an Application Layer Request to the outstation which returns an Application Layer Response. The outstation can decide to spontaneously transmit data using an Application Layer Unsolicited Response message. For a master, a request/response transaction with a particular outstation must be completed before another request can be sent to that outstation. A master station may accept unsolicited responses while the request transaction is in progress.

For an outstation, a request/response transaction must be completed before any other requests are accepted or unsolicited responses are sent. Unsolicited responses can be sent before or after the request/response transaction but not during transaction of message.

In addition, each response or request can consist of 1 or more individual fragments. Each fragment however should be digestible (parsable) and therefore executable

(because the function code is part of every fragment). It is advised that devices with limited message storage capabilities should only be sent single fragment message requests when the expected response (from all fragments sent) is larger than one fragment. This is to ensure that devices can process a request and build, and more importantly send a response before the next request is received. Otherwise, multi-fragment messages may require multi-fragment responses which may require more message storage than the device has available.

5.3.1. Message structure

Masters formulate and send request messages for an outstation IED to return data, carry out a command or perform a special activity. Upon receipt, an outstation performs or initiates the requested action, generates an appropriate response message and transmits it back to the master with the data, results or special information.

An application request header is used in requests from masters and has two fields as shown in Figure 5.11. Each field is one octet in length.

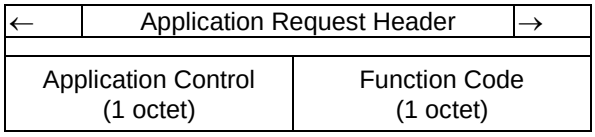


Figure 5.11: Application request header

An application response header is used in responses from outstations IED and has three fields as depicted in Figure 5.12. The application control and function code fields are the same as in an application request header.

←	Application Response Header		→
Application Control (1 octet)	Function Code (1 octet)	Internal Indications (2 octets)	

Figure 5.12: Application response header

The application control octet provides information needed to construct and reassemble multiple fragment messages and to indicate whether the receiver's Application Layer must return an Application Layer confirmation message. It also provides information to assist in duplicate message detection. Application control fields is shown in Figure 5.13.

Bit # →	7	6	5	4	3	2	1	0
Fields →	FIR	FIN	CON	UNS	SEQ			

Figure 5.13 Application control fields

The FIR field is a single bit, which when set, indicates that this is the first fragment of a message. The FIN field is a single bit, which when set, indicates that this is the final fragment of a message. The CON field is a single bit, which when set, indicates that the receiver's Application Layer must return an application confirmation message. An Application Layer confirmation message is a very brief message that is used to verify

that a complete fragment arrived at its destination. The UNS field is a single bit, which when set, indicates the message contains an unsolicited response or a confirmation of an unsolicited response. The SEQ field is 4 bits wide. It is used to verify that fragments are received in the correct order and to detect duplicated fragments.

The function code octet identifies the purpose of the message. Request messages from masters use function codes in the range of 1 to 128, and response messages from outstations use function codes with values ranging from 129 to 255 as shown in Table 5.1. Application Layer confirmations use the CONFIRM function code.

The function code octet as mention in Figure 5.12 identifies the purpose of the message. Request messages from masters use function codes in the range of 1 to 128, and response messages from outstations use function codes with values ranging from 129 to 255 as shown in Table 5.1. Application Layer confirmations use the CONFIRM function code. Table 5.1 gives a brief description of each function code.

Table 5.1: Function Code Table

Message Type	**Code**	**NAME**	**Brief Description**
Confir-mation	0 0x00	CONFIRM	Confirm Function Code: Master sends this to an outstation to confirm the receipt of an Application Layer fragment.
Request	1 0x01	READ	Read Function Code: Outstation shall return the data specified by the objects in the request.

Message Type	Code	NAME	Brief Description
Request	2 0x02	WRITE	Write Function Code: Outstation shall store the data specified by the objects in the request.
Request	3 0x03	SELECT	Select Function Code: Outstation shall select (or arm) the output points specified by the objects in the request in preparation for a subsequent operate command. The outstation shall not activate the outputs until a request with a matching Operate function code is received.
Request	4 0x04	OPERATE	Operate Function Code: Outstation shall activate the output points selected (or armed) by a previous select function code command.
Request	5 0x05	DIRECT_OPERATE	Direct Operate Function Code: Outstation shall immediately actuate the output points specified by the objects in the request. A prior matching select command is not required.
Request	6 0x06	DIRECT_OPERATE_NR	Direct Operate – No Response Function Code: Same as function code 5 but outstation shall not send a response.
Request	7 0x07	IMMED_FREEZE	Immediate Freeze Function Code: Outstation shall copy the point data values specified by the objects in the request to a separate freeze (or holding) buffer (or register).
Request	8 0x08	IMMED_FREEZE_NR	Immediate Freeze – No Response Function Code: Same as function code 7 but outstation shall not send a response.
Request	9 0x09	FREEZE_CLEAR	Freeze and Clear Function Code: Outstation shall copy the point data values specified by the objects in the request into a separate freeze (or holding) buffer (or register). After the copy operation, clear the point data values to zero.

Message Type	Code	NAME	Brief Description
Request	10 0x0A	FREEZE_CLEAR_NR	Freeze and Clear – No Response Function Code: Same as function code 9 but outstation shall not send a response.
Request	11 0x0B	FREEZE_AT_TIME	Freeze at Time Function Code: Outstation shall copy the point data values specified by the objects in the request to a separate freeze (or holding) buffer (or register) at the time and/or time intervals specified in a special time data information object.
Request	12 0x0C	FREEZE_AT_TIME_NR	Freeze at Time – No Response Function Code: Same as function code 11 but outstation shall not send a response.
Request	13 0x0D	COLD_RESTART	Cold Restart Function Code: Outstation shall perform a complete reset of all hardware and software in the device.
Request	14 0x0E	WARM_RESTART	Warm Restart Function Code: Outstation shall reset only portions of the device.
Request	15 0x0F	INITIALIZE_DATA	Initialize Data Function Code: Obsolete – do not use for new designs.
Request	16 0x10	INITIALIZE_APPL	Initialize Application Function Code: Outstation shall place the applications specified by the objects in the request into the ready to run state.
Request	17 0x11	START_APPL	Start Application Function Code: Outstation shall start running the applications specified by the objects in the request.
Request	18 0x12	STOP_APPL	Stop Application Function Code: Outstation shall stop running the applications specified by the objects in the request.

Message Type	Code	NAME	Brief Description
Request	19 0x13	SAVE_CONFIG	Save Configuration Function Code: Outstation shall store into non-volatile memory the contents of a configuration file located in volatile memory.
Request	20 0x14	ENABLE_UNSOLICITED	Enable Unsolicited Responses Function Code: Enables outstation to initiate unsolicited responses from points specified by the objects in the request.
Request	21 0x15	DISABLE_UNSOLICITED	Disable Unsolicited Responses Function Code: Prevents outstation from initiating unsolicited responses from points specified by the objects in the request.
Request	22 0x16	ASSIGN_CLASS	Assign Class Function Code: Outstation shall assign the events generated by the points specified by the objects in the request to one of the classes.
Request	23 0x17	DELAY_MEASURE	Delay Measurement Function Code: Outstation shall report the time it takes to process and initiate the transmission of its response. This allows the master to compute the propagation delay in the communications channel. Used for non-LAN time synchronization.
Request	24 0x18	RECORD_CURRENT_TIME	Record Current Time Function Code: Outstation shall save the time when the last octet of this message is received. Used for LAN time synchronization.
Request	25 0x19	OPEN_FILE	Open File Function Code: Outstation shall open a file.
Request	26 0x1A	CLOSE_FILE	Close File Function Code: Outstation shall close a file.
Request	27 0x1B	DELETE_FILE	Delete File Function Code: Outstation shall delete a file.

Message Type	Code	NAME	Brief Description
Request	28 0x1C	GET_FILE_INFO	Get File Information Function Code: Outstation shall retrieve information about a file.
Request	29 0x1D	AUTHENTICATE_FILE	Authenticate File Function Code: Outstation shall return a file authentication key.
Request	30 0x1E	ABORT_FILE	Abort File Function Code: Outstation shall abort a file transfer operation.
Request	31 0x1F	ACTIVATE_CONFIG	Activate Configuration Function Code: Outstation shall use the configuration specified by the objects in the request.
	32 0x20 to 128 0x80		Reserved.
Response	129 0x81	RESPONSE	Solicited Response Function Code: Master shall interpret this fragment as an Application Layer response to an Application Layer request sent by the master.
Response	130 0x82	UNSOLICITED_RESPONSE	Unsolicited Response Function Code: Master shall interpret this fragment as an unsolicited response that was not prompted by an explicit request.
Response	131 0x83 to 255 0xFF		Reserved.

The detailed function code description is presented in Appendix B. The internal indication field appears in application response headers immediately following the function code octet. This field has two octets. The bits in these two octets indicate certain states and error conditions within the outstation.

5.3.2 Fragment rules

The following rules have been adopted while developing DNP3 application layer:

Rule 1 DNP3 devices that are able to set their maximum transmit fragment size larger than 2048 octets provide configuration down to 2048 octets.

Rule 2 All devices must accept fragments as small as 2 octets.

Rule 3 Outstations prepare to receive fragment sizes of at least 249 octets, and masters must be prepared to receive fragment sizes of at least 2048 octets.

Rule 4 Master devices only send requests that fit within a single fragment.

Rule 5 Master devices accept multiple fragment responses.

Rule 6 An outstation device returns all of its event and static data together, within a single response. If necessary, it shall use multiple fragments to convey the entire response.

Rule 7 Each fragment must be individually and completely passable. The FIR bit is set in the fragment that begins a message.

Rule 8 The FIN bit is set in the fragment that ends a message.

Rule 9 A message may consist of a single fragment having both the FIR and FIN bits set.

Rule 10 Masters shall never request Application Layer confirmation; i.e. they must not set the CON bit in request messages. This practice is now obsolete.

Rule 11 Outstations that receive a properly formatted fragment with the CON bit set, must immediately respond with an Application Layer confirm message (For backward compatibility).

Rule 12 Masters that receive a properly formatted fragment with the CON bit set, respond with an Application Layer confirm message before sending any other request message to that outstation.

Rule 13 For each new, non-retry request fragment it sends, a master increments the SEQ number by one count from its previous request fragment.

Rule 14 The first fragment of a **solicited** (polled) **response** message have the same SEQ number as the SEQ number in the request fragment. If the response requires multiple fragments, each subsequent fragment shall use a SEQ number incremented by one count from the previous.

Rule 15 A master send a retry request message if it uses the same SEQ number and all the other octets in the retry message match the original request message.

Rule 16 An outstation shall not retry sending solicited response messages.

Rule 17 A fragment containing a CONFIRM function code use the same SEQ number and UNS bit state as are in the fragment being confirmed.

Rule 18 Outstations ignore the SEQ number in broadcast request messages.

Rule 19 The SEQ numbers sent by an outstation in unsolicited responses are distinct from, and have no relationship to the SEQ numbers it sends in solicited responses.

Rule 20 An outstation that sends unsolicited responses choose any SEQ number for its first message after a restart. The master must accept these messages.

Rule 21 An outstation that restarts ignore the SEQ number in the first request it receives from a master after the restart, but otherwise shall execute the request. Thereafter, the outstation should examine the SEQ numbers in the received requests.

Rule 22 An outstation requests an Application Layer confirmation when it sends a fragment containing event objects. Receipt of the confirmation message from the master lets the outstation know that the event information arrived at the master and, therefore, the outstation may discard corresponding event data from its event buffers.

Rule 23 An Application Layer confirmation is required for each fragment of a multi-fragment message except the last fragment. Application Layer confirmation is optional for the last fragment of a multi-fragment message unless there is another reason why confirmation is mandatory, such as the last fragment contains events. Receipt of the confirmation signifies to the outstation that it may send the next fragment. It also informs the outstation that it can safely discard any event data in the confirmed fragment. Outstations must not send the next fragment of a multi-fragment response until the master confirms its previously transmitted fragment.

Rule 24 Application Layer confirmation is required to acknowledge receipt of unsolicited response messages. An outstation must not discard any

information or make any assumptions about what the master received if it does not receive a confirm message from the master.

Rule 25 Outstations are required to request Application Layer confirmation after a master sends an all-stations (broadcast) request. The particular all-stations address that the master uses in the message determines the need for confirmation.

5.3.3 Classes

There are four Classes of data in DNP3. Objects may be assigned to a class. Class 0 is reserved or static data objects (static data reflects the current value of data in the Outstation). Classes 1, 2 and 3 are reserved for event data objects (objects created as the result of data changes in the Outstation or some other stimulant). Each event object is assigned to Classes 1, 2 or 3. Objects may be grouped in Classes by priority (the priority is determined by the user) and the data classes polled at varying rates.

It is not required that an outstation have data assigned to Classes 1, 2 or 3. Class data is used by a master station to request pre-assigned data objects on a demand or availability basis from an outstation. Therefore, a class data object header is used only in a request (with no associate data object) to indicate to the outstation which data objects to return. The outstation will return (in the response) object headers for the ACTUAL data objects and NOT the class object header.

5.3.4 Time synchronisation

Time synchronisation is handled by the application layer but special services of the data link layer is also used. The application initiates the time synchronisation sequence by sending the appropriate request or response.

To synchronize Master station and Outstation time, the following procedure is used.

1. The Master station sends a Delay Measurement request to the Outstation. The master records the time of transmission of the first bit of the first byte of the request *(MasterSendTime)*.
2. The Outstation receives the first bit of the first byte of the Delay Measurement request at time *RtuReceiveTime* (this is a local time in the Outstation).

3. The Outstation transmits the first bit of the first byte of the response to the Delay Measurement request at time *RtuSendTime*. The response contains the Time Delay object (Time Delay Fine or Time Delay Course), with the time in this object equal to RtuTurnAround, where

$$RtuTurnAround = RtuSendTime - RtuReceiveTime$$

4. The Master station receives the first bit of the first byte of the Outstation's response at time *MasterReceiveTime*.

5. The master station can now calculate the one way propagation delay as

$$Delay = \frac{MasterSendTime - MasterReceiveTime - RtuTurnAround}{2}$$

6. The master now transmits the first bit of the first byte of a WRITE request at time *MasterSend*. The WRITE request contains the Time and Date object, with the time in the object representing a time equal to (*MasterSend* + *Delay*). This is the time that the Master station wants the Outstation to be set to.

7. The Outstation receives the first bit of the first byte of the WRITE request at time *RtuReceive*.

8. The Outstation will process the WRITE request, setting the Outstation clock to time *NewRtuTime*. The following algorithm is used:

Adjustment = CurrentRtuTime - RtuReceive

NewRtuTime = (time in the Time and Date object) + Adjustment

9. The Master and Outstation time are now synchronised.

5.3.5 DNP3 Level 1 implementation

When a Master or Slave satisfies all the requirements of a particular DNP3 subset, it is said to implement a particular level of the protocol. The term "Level" is chosen so as not

to conflict with DNP3 data classes or the OSI concept of layers. The abbreviation for a DNP subset implementation consists of "DNP", a dash, and "L" followed by the level number.

There are three levels of DNP3 which are called as Level 1 (L1), Level 2 (L2) and Level 3 (L3) of DNP3 of implementation. This level of implementation provides the simplest implementation of DNP3 for communicating between a Master and a typical IED. It would typically be used between a master station or data concentrator and a small end device (eg. meter, relay, auto-recloser or capacitor bank controller).

Level 2 contains a few more features than the Level 1 implementation. It is intended for communications between a master station or data concentrator and a device that could be called either a large IED or a small RTU. A Level 3 implementation uses a larger range of objects, variations, function and qualifier codes than the Level 2 implementation.

Level 1 implementation of DNP3 is used in IEPS-W. The Level 1 subset is based around Class Data polling. A Level 1 Slave must accept requests for:

- READs of Class Data Objects
- READs of Binary Output and Analog Output objects, if such outputs exist on the Slave.

- Control operations to Binary Output or Analog Outputs, if they exist on the Slave. If such objects do not exist, the Slave is allowed to respond OBJECT UNKNOWN.
- WRITEs to the RESTART Internal Indication
- COLD RESTARTs
- DELAY MEASUREMENTs and WRITEs to Time and Date, if the Slave sets the TIME SYNCHRONIZATION REQUIRED Internal Indication (See 4.13 Time Synchronization)

A Level 1 Master accepts a subset of object variations that includes most basic data types:

- Binary Inputs and Events
- Counters and Counter Events
- Analog Inputs and Events
- Binary and Analog Output Status

Table 5.2 describes the objects, function codes and qualifiers used in a Level 1 DNP3 implementation.

Table 5.2: Level 1 implementation (DNP-L1)

OBJECT			REQUEST (Slave must parse)		RESPONSE (Master must parse)	
Obj	**Var**	**Description**	**Func Codes (dec)**	**Qual Codes (hex)**	**Func Codes (dec)**	**Qual Codes (hex)**
1	0	Binary Input - All Variations				
1	1	Binary Input			129	00, 01
1	2	Binary Input with Status			129	00, 01
2	0	Binary Input Change - All Variations				
2	1	Binary Input Change without Time			129, 130	17, 28
2	2	Binary Input Change with Time			129, 130	17, 28
2	3	Binary Input Change with Relative Time			129, 130	17, 28
10	0	Binary Output - All Variations	1	06		
10	1	Binary Output				
10	2	Binary Output Status			129	00, 01
12	0	Control Block - All Variations				
12	1	Control Relay Output Block	3, 4, 5, 6	17, 28	129	echo of request
12	2	Pattern Control Block				
12	3	Pattern Mask				
20	0	Binary Counter - All Variations				
20	1	32-Bit Binary Counter			129	00, 01
20	2	16-Bit Binary Counter			129	00, 01
20	3	32-Bit Delta Counter			129	00, 01
20	4	16-Bit Delta Counter			129	00, 01
20	5	32-Bit Binary Counter without Flag			129	00, 01
20	6	16-Bit Binary Counter without Flag			129	00, 01
20	7	32-Bit Delta Counter without Flag			129	00 ,01
20	8	16-Bit Delta Counter without Flag			129	00,01
21	0	Frozen Counter - All Variations				
21	1	32-Bit Frozen Counter				
21	2	16-Bit Frozen Counter				
21	3	32-Bit Frozen Delta Counter				

OBJECT			REQUEST (Slave must parse)		RESPONSE (Master must parse)	
Obj	**Var**	**Description**	**Func Codes (dec)**	**Qual Codes (hex)**	**Func Codes (dec)**	**Qual Codes (hex)**
21	4	16-Bit Frozen Delta Counter				
21	5	32-Bit Frozen Counter with Time of Freeze				
21	6	16-Bit Frozen Counter with Time of Freeze				
21	7	32-Bit Frozen Delta Counter with Time of Freeze				
21	8	16-Bit Frozen Delta Counter with Time of Freeze				
21	9	32-Bit Frozen Counter without Flag				
21	10	16-Bit Frozen Counter without Flag				
21	11	32-Bit Frozen Delta Counter without Flag				
21	12	16-Bit Frozen Delta Counter without Flag				
22	0	Counter Change Event - All Variations				
22	1	32-Bit Counter Change Event without Time			129, 130	17, 28
22	2	16-Bit Counter Change Event without Time			129, 130	17, 28
22	3	32-Bit Delta Counter Change Event without Time			129, 130	17, 28
22	4	16-Bit Delta Counter Change Event without Time			129, 130	17, 28
22	5	32-Bit Counter Change Event with Time				
22	6	16-Bit Counter Change Event with Time				
22	7	32-Bit Delta Counter Change Event with Time				
22	8	16-Bit Delta Counter Change Event with Time				
23	0	Frozen Counter Event - All Variations				
23	1	32-Bit Frozen Counter Event without Time				
23	2	16-Bit Frozen Counter Event without Time				
23	3	32-Bit Frozen Delta Counter Event without Time				
23	4	16-Bit Frozen Delta Counter Event without Time				
23	5	32-Bit Frozen Counter Event with Time				
23	6	16-Bit Frozen Counter Event with Time				
23	7	32-Bit Frozen Delta Counter Event with Time				
23	8	16-Bit Frozen Delta Counter Event with Time				
30	0	Analog Input - All Variations				
30	1	32-Bit Analog Input			129	00,01
30	2	16-Bit Analog Input			129	00,01
30	3	32-Bit Analog Input without Flag			129	00,01
30	4	16-Bit Analog Input without Flag			129	00,01

OBJECT			REQUEST (Slave must parse)		RESPONSE (Master must parse)	
Obj	**Var**	**Description**	**Func Codes (dec)**	**Qual Codes (hex)**	**Func Codes (dec)**	**Qual Codes (hex)**
31	0	Frozen Analog Input - All Variations				
31	1	32-Bit Frozen Analog Input				
31	2	16-Bit Frozen Analog Input				
31	3	32-Bit Frozen Analog Input with Time of Freeze				
31	4	16-Bit Frozen Analog Input with Time of Freeze				
31	5	32-Bit Frozen Analog Input without Flag				
31	6	16-Bit Frozen Analog Input without Flag				
32	0	Analog Change Event - All Variations				
32	1	32-Bit Analog Change Event without Time			129,130	17,28
32	2	16-Bit Analog Change Event without Time			129,130	17,28
32	3	32-Bit Analog Change Event with Time				
32	4	16-Bit Analog Change Event with Time				
33	0	Frozen Analog Event - All Variations				
33	1	32-Bit Frozen Analog Event without Time				
33	2	16-Bit Frozen Analog Event without Time				
33	3	32-Bit Frozen Analog Event with Time				
33	4	16-Bit Frozen Analog Event with Time				
40	0	Analog Output Status - All Variations	1	06		
40	1	32-Bit Analog Output Status				
40	2	16-Bit Analog Output Status			129	00, 01
41	0	Analog Output Block - All Variations				
41	1	32-Bit Analog Output Block				
41	2	16-Bit Analog Output Block	3, 4, 5, 6	17, 28	129	echo of request
50	0	Time and Date - All Variations				
50	1	Time and Date	2 (see 4.14)	07 where quantity = 1		
50	2	Time and Date with Interval				
51	0	Time and Date CTO – All Variations				
51	1	Time and Date CTO			129, 130	07, quantity=1
51	2	Unsynchronized Time and Date CTO			129, 130	07, quantity=1
52	0	Time Delay - All Variations				

OBJECT			REQUEST (Slave must parse)		RESPONSE (Master must parse)	
Obj	**Var**	**Description**	**Func Codes (dec)**	**Qual Codes (hex)**	**Func Codes (dec)**	**Qual Codes (hex)**
52	1	Time Delay Coarse			129	07, quantity=1
52	2	Time Delay Fine			129	07, quantity=1
60	0					
60	1	Class 0 Data	1	06		
60	2	Class 1 Data	1	06,07,08		
60	3	Class 2 Data	1	06,07,08		
60	4	Class 3 Data	1	06,07,08		
70	1	File Identifier				
80	1	Internal Indications	2	00 index=7		
81	1	Storage Object				
82	1	Device Profile				
83	1	Private Registration Object				
83	2	Private Registration Object Descriptor				
90	1	Application Identifier				
100	1	Short Floating Point				
100	2	Long Floating Point				
100	3	Extended Floating Point				
101	1	Small Packed Binary-Coded Decimal				
101	2	Medium Packed Binary-Coded Decimal				
101	3	Large Packed Binary-Coded Decimal				
		No object	13			
		No object	23 (see 4.14)			

5.3.6 Implementation of DNP3 application layer

5.3.6.1 Outstation Fragment State Table

Table 5.3 specifies an outstation IED behavior with regard to fragment reception and transmission.

Table 5. 3: Outstation fragment state table

Current State	*Event that Triggers an Action and Possible Transition*				*Action*		*Transition To State*	
A	**B**	**C**			**D**		**E**	
If the software state is	and this occurs	and received fragment contains			then perform this action		and go to this state	
		UNS	SEQ	Function Code				
Idle	[RESTART] Outstation is configured to send unsolicited responses and a restart occurred.	—	—	—	Send unsolicited NULL response with UNS, CON and IIN1.7 bits set and seq = any legal value.		WaitUnsolCfm	**1**
	[UNSOL_TRIGGER] Outstation is configured to send unsolicited responses and something occurs to initiate a new unsolicited response sequence.	—	—	—	Send unsolicited response with UNS and CON bits set and increment M, modulo 16.		WaitUnsolCfm	**3**
	[BROADCAST_FRAG_RCVD] Fragment received with broacast address.	0	X	Valid Request	Accept fragment and process request. Never send a response.		Idle	**3**
	[FIRST_FRAG_RCVD] First request fragment received following a restart.	0	X	Valid Request	Accept fragment and process request. Set local variable FirstValidRequestAccepted. Send response if required.		If no response or txCON = 0, Idle; else WaitSolCfm	**4**
	[NEW_FRAG_RCVD] Request fragment received.	0	!=N	Valid Request	Accept fragment and process request. Send response if required.		If no response or txCON = 0, Idle; else WaitSolCfm	**5**
	[REPEAT_FRAG_RCVD] Request fragment received.	0	N	Valid Request	Compare octet-by-octet with previous request fragment. Do they match?		—	**6**
					Yes	Accept fragment then send same response. Do not process the request.	If no response or txCON = 0, Idle; else WaitSolCfm	**7**
					No	Accept fragment and process request. Send response if required.	If no response or txCON = 0, Idle; else WaitSolCfm	**8**

- **Keys for understanding Table 5.3:** X means don't care.The dash symbol '—' means "Not Applicable". != means "Not Equal To"

  (For example, !=N means not equal to N.)

Current State	*Event that Triggers an Action and Possible Transition*				*Action*		*Transition To State*	
A	**B**	**C**			**D**		**E**	
If the software state is	and this occurs	and received fragment contains			then perform this action		and go to this state	
		UNS	SEQ	Function Code				
Wait Solicited Confirm	[MATCHING_CFM_RCVD] Confirm fragment received. (N is SEQ value sent in response awaiting confirm.)	0	N	Confirm	Accept fragment and process confirm. If one fragment of multi-fragment message is being confirmed, and a subsequent fragment is necessary, then increment N, modulo 16, and send the next fragment.		If fragment is transmitted and txCON = 1, WaitSolCfm; else Idle	**9**
	[NON-MATCHING_CFM_RCVD] Confirm fragment received. (N is SEQ value sent in response awaiting confirm.)	0	!=N	Confirm	Discard confirm fragment; do not remove any events.		WaitSolCfm	**10**
	[UNSOL_CFM_RCVD] Confirm fragment received.	1	X	Confirm	Discard confirm fragment; do not remove any events.		WaitSolCfm	**11**
	[BROADCAST_FRAG_RCVD] Fragment received with broadcast address.	0	X	Valid Request	Assume confirmation is not forthcoming and confirmation failed. Accept fragment and process request. Never send a response.		Idle	**12**
	[NEW_FRAG_RCVD] Request fragment received. (N is SEQ value in last valid request received.)	0	!=N	Valid Request	Assume confirmation is not forthcoming and confirmation failed. Accept fragment and process request. Send response if required.		If no response or txCON = 0, Idle; else WaitSolCfm	**13**
	[REPEAT_FRAG_RCVD] Request fragment received. (N is SEQ value in last valid request received.)	0	N	Valid Request	Assume confirmation is not forthcoming and confirmation failed. Compare octet-by-octet with previous request fragment. Do they match?		—	**14**
					Yes	Accept fragment then send same response. Do not process the request.	WaitSolCfm	**15**
					No	Accept fragment and process request. Send response if required.	If no response or txCON = 0, Idle; else WaitSolCfm	**16**
	[CONFIRM_TIMOUT] Timeout waiting for Confirm	—	—	—	Note failure to confirm. Do not remove any events, do not send retries.		Idle	**17**

Current State	*Event that Triggers an Action and Possible Transition*				*Action*		*Transition To State*	
A	**B**	**C**			**D**		**E**	
If the software state is	and this occurs	and received fragment contains			then perform this action		and go to this state	
		UNS	SEQ	Function Code				
Wait Unsolicited Confirm (Region A)	[SOL_CFM_RCVD] Confirm fragment received.	0	X	Confirm	Discard confirm fragment.		WaitUnsolCfm	**18**
	[MATCHING_CFM_RCVD] Confirm fragment received.	1	M	Confirm	Accept fragment and process confirm.		Idle	**19**
	[NON-MATCHING_CFM_RCVD] Confirm fragment received.	1	!=M	Confirm	Discard confirm fragment.		WaitUnsolCfm	**20**
	[DISABLE_UNSOL_RCVD] Request to disable some or all unsolicited reporting is received	0	!=N	Disable Unsolicited	Terminate unsolicited response sequence and defer request until software enters the Idle state.		Idle	**21**
	[BROADCAST_FRAG_RCVD] Fragment received with broadcast address.	0	X	Valid Request	If a deferred read request exists, discard it. Accept fragment and process request. Never send a response.		WaitUnsolCfm	**22**
	[READ_REQ_RCVD] Read request received.	0	X	Read Request	If a deferred request already exists, replace it with this request. Defer parsing the new read request by holding it until the software enters the Idle state.		WaitUnsolCfm	**23**
	[NON-RD_REQ_RCVD] A non-read request is received.	0	!= N	Non-read Valid Request	If a deferred read request exists, discard it. Accept fragment and send response.		WaitUnsolCfm	**24**
	[REPEAT_NON-RD_ RCVD] A non-read request is received.	0	N	Non-read Valid Request	If a deferred read request exists, discard it. Compare octet-by-octet with previous request. Do they match?		—	**25**
					Yes	Accept fragment then send same response.	WaitUnsolCfm	**26**
					No	Accept fragment and process request. Send response if required.	WaitUnsolCfm	**27**
	[UNSOL_CONFIRM_TIMOUT_NO_DEFER] Timeout waiting for confirm. End of timing region A. A read request is not deferred.	—	—	—	Note failure to confirm. If last transmission retry has been sent, extend retry timer duration to infinity.		WaitUnsolRetry	**28**
	[UNSOL_CONFIRM_TIMOUT_DEFER] Timeout waiting for confirm. End of timing region A. A read request is deferred.	—	—	—	Note failure to confirm. Has read request been deferred for at least one full time period A?		—	**29**
					Yes	Discard read request. If last transmission retry has been sent, extend retry timer duration to infinity.	WaitUnsolRetry	**30**
					No	Continue to defer the read request and immediately resend the unsolicited response. Restart period A timing.	WaitUnsolCfm	**31**

Current State	*Event that Triggers an Action and Possible Transition*				*Action*	*Transition To State*	
A	**B**	**C**			**D**	**E**	
If the software state is	and this occurs	and received fragment contains			then perform this action	and go to this state	
		UNS	SEQ	Function Code			
Wait Usolicited Retry (Region B)	[CONFIRM_RCVD] A confirm is received	X	X	Confirm	Discard confirm fragment.	WaitUnsolRetry	**32**
	[DISABLE_UNSOL_RCVD] Request to disable some or all unsolicited reporting is received	0	!=N	Disable Unsolicited	Terminate unsolicited response sequence and defer request until software enters the Idle state.	Idle	**33**
	[BROADCAST_FRAG_RCVD] Fragment received with broadcast address.	0	X	Valid Request	If a deferred read request exists, discard it. Accept fragment and process request. Never send a response.	WaitUnsolRetry	**34**
	[READ_REQ_RCVD] Read request received.	0	X	Read Request	Defer parsing the new read request by holding it until the software enters the Idle state. Immediately transmit a retry of the unsolicited response. Restart period A timing.	WaitUnsolCfm	**35**
	[NON-RD_REQ_RCVD] A non-read request is received.	0	!= N	Non-read Valid Request	Accept fragment and send response.	WaitUnsolRetry	**36**
	[REPEAT_NON-RD_ RCVD] A non-read request is received.	0	N	Non-read Valid Request	Compare octet-by-octet with previous request. Do they match?	—	**37**
					Yes — Accept fragment then send same response.	WaitUnsolRetry	**38**
					No — Accept fragment and process request. Send response if required.	WaitUnsolRetry	**39**
	[RETRY_TIMER_TIMEOUT] End of timing region B, time for another retry.	—	—	—	Send repeat of unsolicited response. Restart period A timing.	WaitUnsolCfm	**40**
	[TRIGGER_EXPIRED_XMT_COUNT] Re-transmission counts have expired and a something occurs to trigger a new unsolicited sequence.	—	—	—	Send repeat of unsolicited response. Restart transmission retry counter. Restart period A timing.	WaitUnsolCfm	**41**

Keys for understanding Table 5.3

- The events referred in italics in the table heading are triggers that initiate an action and possible transition to a different state. They do not refer to the buffered events or event objects transported in messages.
- Labels inside square brackets [ ] in column B of Table 5.3 are triggering event names associated with the specific state in which it occurs.
- In column B, fragments that are received are assumed to be addressed to the outstation unless “with broadcast address” is stated. Fragments having other destination addresses are ignored.
- N and M represent sequence numbers.

  N is used with regard to the SEQ number received from a non-broadcast, valid master request or its response.

  M is used in regard to the SEQ number in the previous (most recently sent) unsolicited response transmited from the outstation.
- The terms appearing in the Function Code column are

  “Valid Request” means any valid request as describe above.

  “Confirm” refers to the confirm function code, CONFIRM.

  “Read Request” refers to a valid request having function code READ.

- When “txCON = 0” or “txCON = 1” appers in column E, it refers to the confirm bit in the application control octet of the outstation’s response being equal to zero or one.
- When “no response” appears in column E, it refers to the case where a request is received that does not require a response from the outstation.
- Two timers are referenced for unsolicited responses. One is used to limit the time waiting for a confirmation from the master (also referred to as region A). The second is used to measure the time until sending an unsolicited response retry (also referred to as region B).
- Upon entering the Idle state, if a deferred request exists, it is handled as though it were received immediately after entering the Idle state.
- For each row of Table the process behave as follows:

  The software is in the state shown in column A and waits until something occurs that initiates further action. The cause for action is described in column B. The UNS bit, SEQ number and Function Code in the received fragment are shown in column C when an action is triggered by receipt of a fragment from the master or is associated with a deferred request. The action performed is described in column D. After performing the action in column D, the software process transitions to the state specified in column E. Column E specifies one of the states listed under column A.

The outstation examine the FIR, FIN and UNS bits and the SEQ value in the application control octet of received fragments. It also inspects the Application Layer function code. In addition, it remembers the SEQ value and all of the octets in request fragments that it accepts and in response fragments that it transmits.

The outstation accepts request fragments if they contain a *valid request* and meet the criteria as described in Table 5.3, otherwise it discards the fragments and remains in the same reception state. The outstation does not remember application control octet bits or values or any of the octets from fragments that it discards.

In this section, the term “valid request” refers to a fragment received with a function code that has a value in the range of 1 to 127. FIR, FIN and UNS bits in the application control octet have the following conditions as described in Table 5.3:

- FIR = 1
- FIN = 1
- UNS = 0

The outstation maintain a local boolean variable, *FirstValidRequestAccepted*, in order to synchronise the processing of SEQ values in valid requests. The value of this variable is cleared to false at startup, immediately following a restart. It is set to true when the first valid request is received as shown in Table 5.3.

Outstation process undergoes four states for proper reception:

1. **Idle** state: The software is idle waiting for a fragment to arrive or for an event to occur that would trigger an unsolicited response. In some cases, a deferred request may be available upon entry to this state as a consequence of actions in another state. When there is such a deferred request available, it processes immediately as though it had just been received. The software starts up in this state.
2. **Wait Solicited Confirm** state (abbreviated WaitSolCfm in Table 5.3): The device received from the master a request that caused the outstation to send a response requiring a confirmation (e.g., includes events or has multiple fragments), and the outstation is waiting for the confirmation.
3. **Wait Unsolicited Confirm** state (abbreviated WaitUnsolCfm in Table 5.3): The device transmitted an unsolicited response and is waiting for a confirmation from the master.
4. **Wait Unsolicited Retry** state (abbreviated WaitUnsolRetry in Table 5.3): The timer used for unsolicited response confirmation timed out and the device is waiting until it is time to transmit a retry of the unsolicited response.

Figure 5.14 depicts Outstation Fragment State Diagram which has been implemented using OPNET as shown in Figure 5.15 incorporating all the functions, rules and requirements.

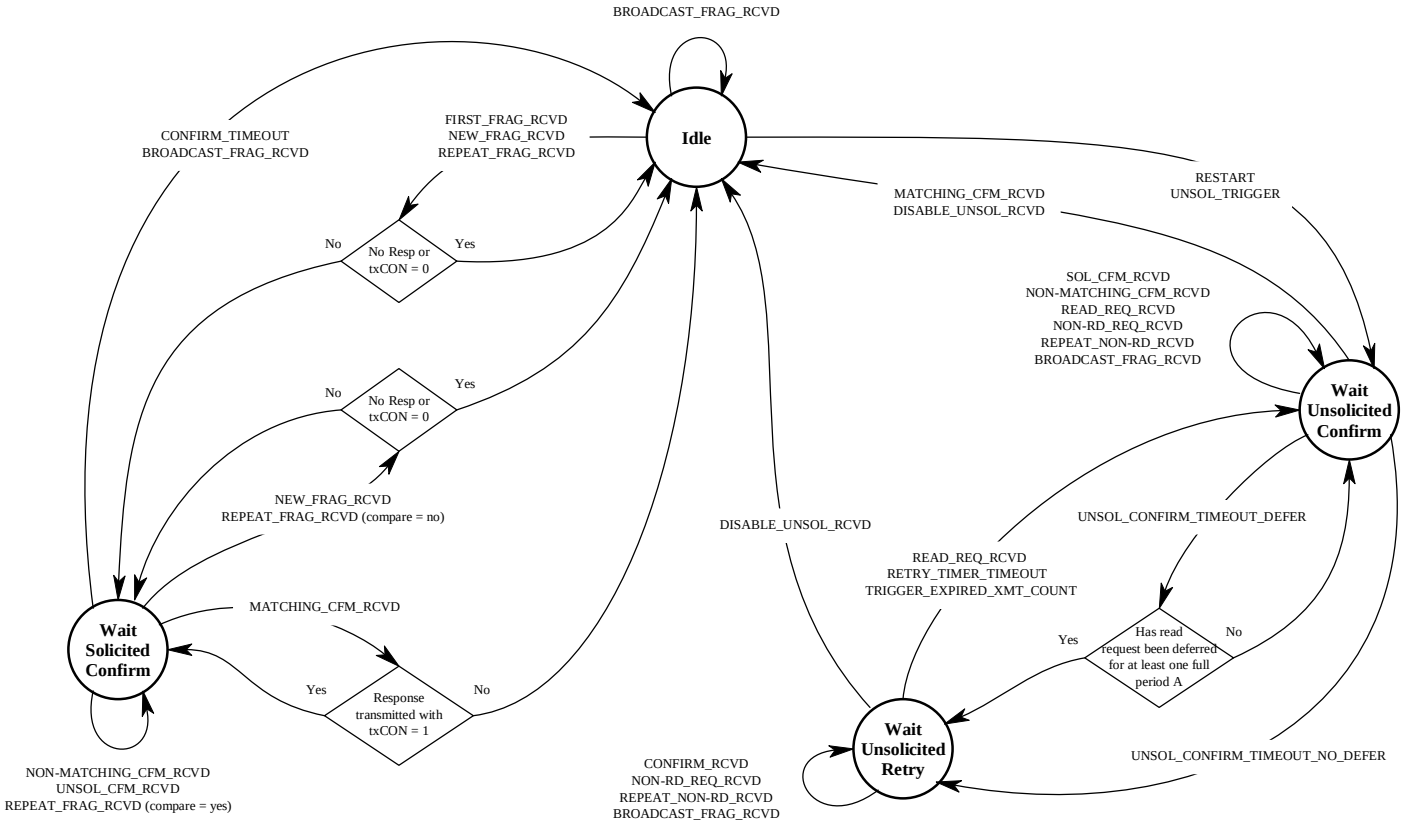


Figure 5.14: Outstation fragment state diagram

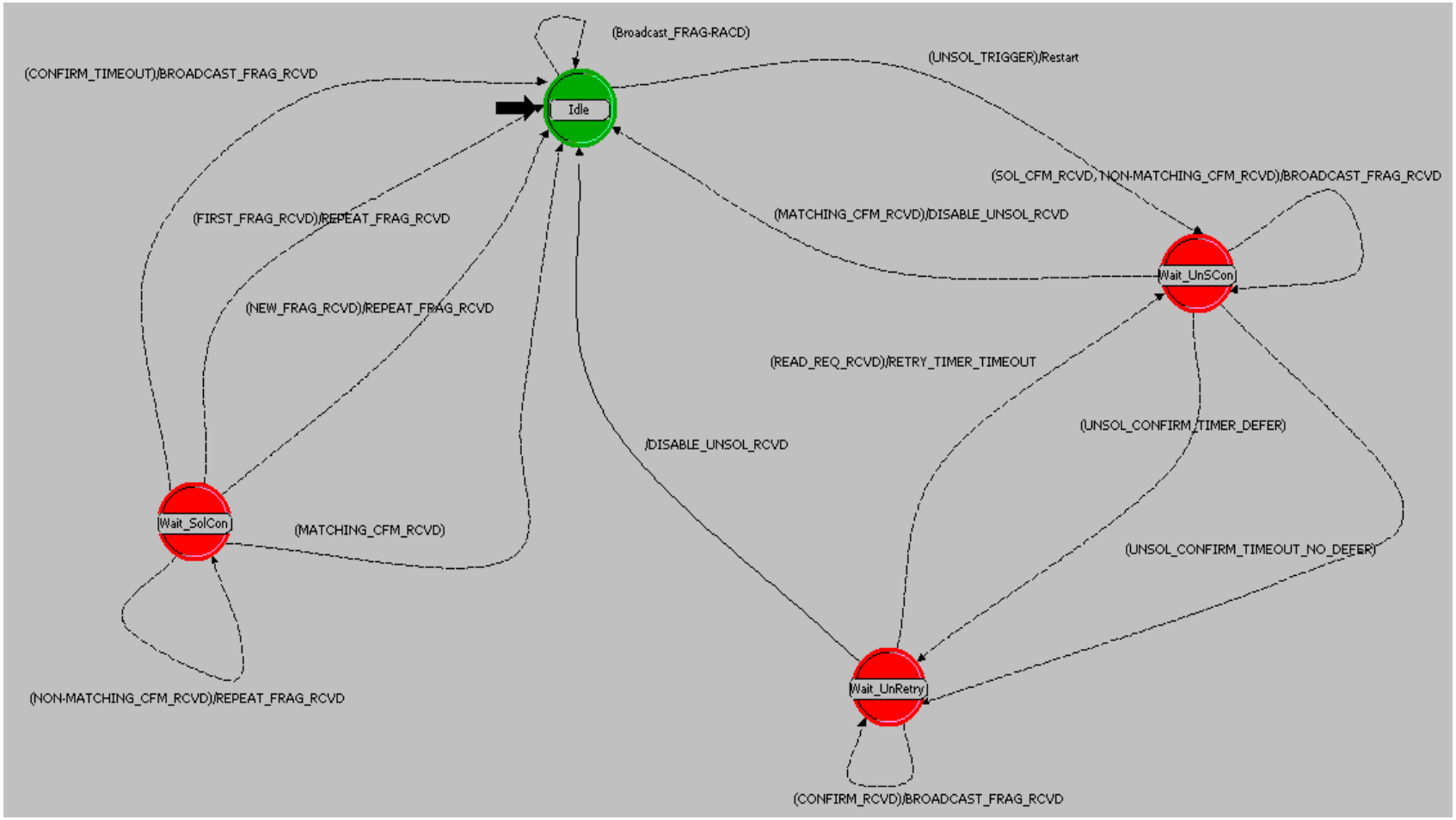


Figure 5.15: Outstation fragment state diagram in OPNET environment

5.3.7. Master solicited response reception state

The purpose of this reception state is to specify a master's behavior when fragments are received with the UNS bit equal to 0 in the application control octet. The master software examines the FIR and FIN bits and the SEQ value in the application control octet. It also remembers the FIR and FIN bits, the SEQ value and all of the octets from the previously accepted solicited response fragment. The master accepts the fragment if it meets the criteria in the Table 5.4, otherwise it discards the fragment. The master does not remember application control octet bits or values or any of the octets from fragments that it discards. The master must also remember the SEQ value from the last request fragment that it sent in a request to the outstation.

Master software for handling solicited responses requires **three states for proper operation**.

1. **Idle** state: The master is waiting for the DNP3 user software at a higher layer to initiate a request. The master starts in this state immediately following a reset.
2. **AwaitFirst** state: The software is waiting for the first fragment of the expected response to arrive from the outstation.
3. **Assembly** state: While in this state, the master is awaiting more fragments from a multi-fragment response.

Keys for understanding Table 5.4:

- For each row of the Table , the software behave as follows:

  If the software is currently in the state listed in column A, and the user initiates transmission of a request, the response timer times out or a fragment is received with the fields of the application control octet as shown in column B. The fields of the application control octet in the most recently accepted solicited fragment were as shown in column C. The sequence number in the request's application control octet was as shown in column D, then the action is performed as described in column E.

Table 5.4: Master reception state table (Solicited Responses)

Current State	*Event that Triggers an Action and Possible Transition*							*Action*	*Transition To State*	
A	**B**			**C**			**D**	**E**	**F**	
If the software state is	and the user initiates a new request, the response timer times out or a fragment is received with these fields			and the fields in the most recently **accepted solicited** fragment were			and field in request was	then perform this action	and go to this state	
	FIR	FIN	SEQ	FIR	FIN	SEQ	SEQ			
Idle	X	X	X	X	X	X	X	Discard fragment and do not confirm.	Idle	**1**
	User initiates a request			—	—	—	—	Transmit the user request and if response expected, start fragment receive timer.	If response expected AwaitFirst; else Idle.	**2**
AwaitFirst	0	X	X	X	X	X	X	Discard fragment and do not confirm.	AwaitFirst	**3**
	1	0	N	X	X	X	N	Send confirm if requested, accept fragment, process fragment and start fragment receive timer.	Assembly	**4**
	1	X	!=N	X	X	X	N	Discard fragment and do not confirm.	Idle	**5**
	1	1	N	X	X	X	N	Send confirm if requested, accept fragment, and process fragment.	Idle	**6**
	Response timer times out			X	X	X	X	Note lack of response.	Idle	**7**
Assembly	0	0	N	0	0	N	X	Compare octet-by-octet with previous accepted fragment. If octets match, send confirm if requested, take no further action and start fragment receive timer. If octets do not match, discard fragment and do not confirm.	If octets match, Assembly; else Idle	**8**
	0	0	N	1	0	N	X	Discard fragment and do not confirm.	Idle	**9**
	0	0	N + 1	X	0	N	X	Send confirm if requested, accept fragment, process fragment and start fragment receive timer.	Assembly	**10**
	0	0	!=N and != N + 1	X	0	N	X	Discard fragment and do not confirm.	Idle	**11**
	0	1	N + 1	X	0	N	X	Send confirm if requested, accept fragment, and process fragment.	Idle	**12**
	0	1	!= N + 1	X	0	N	X	Discard fragment and do not confirm.	Idle	**13**

Current State	*Event that Triggers an Action and Possible Transition*							*Action*	*Transition To State*	
A	**B**			**C**			**D**	**E**	**F**	
If the software state is	and the user initiates a new request, the response timer times out or a fragment is received with these fields			and the fields in the most recently **accepted solicited** fragment were			and field in request was	then perform this action	and go to this state	
	FIR	FIN	SEQ	FIR	FIN	SEQ	SEQ			
	1	0	N	1	0	N	N	Compare octet-by-octet with previous accepted fragment. If octets match, send confirm if requested, take no further action and start fragment receive timer. If octets do not match, discard fragment and do not confirm.	If octets match, Assembly; else Idle	**14**
	1	0	N	0	0	N	X	Discard fragment and do not confirm.	Idle	**15**
	1	0	!=N	X	0	N	X	Discard fragment and do not confirm.	Idle	**16**
	1	1	X	X	X	X	X	Discard fragment and do not confirm.	Idle	**17**
	Response timer times out			X	X	X	X	Note lack of response.	Idle	**18**

Keys for understanding table 5.4

- The events referred to in italics in the table heading are triggers that initiate an action and possible transition to a different state. They do not refer to the buffered events or event objects transported in messages.
- X means don't care.
- The dash symbol '—' means "Not Applicable".
- N is any valid sequence number.
- N + 1 is N plus 1 modulo 16.

Figure 5.16 illustrates Master Solicited Response Reception Diagram. The logic and rules described in Table 5.4 was implemented in Figure 5.16 for solicited master responses. This represents the real life control centre commands to the field devices to take control actions such as opening and closing devices with special command from control room.

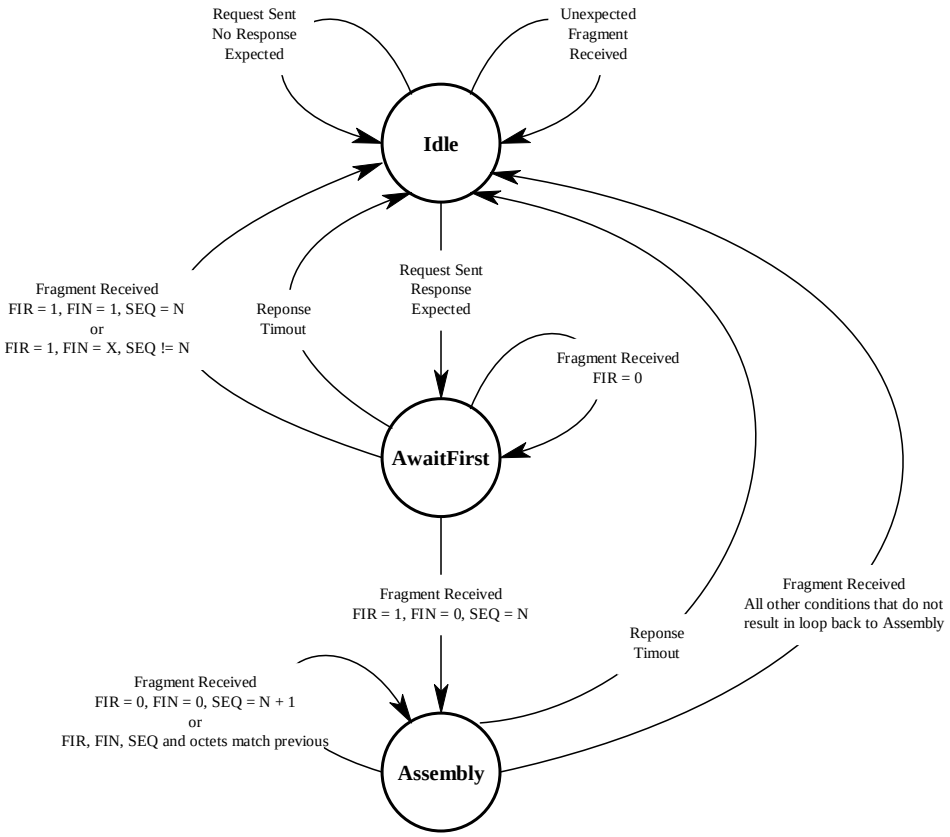


Figure 5.16: Master solicited response reception diagram

Figure 5.16 is translated into Figure 5.17 using OPNET platform incorporating all the rules, functions and requirements of DNP3 application layer solicited response.

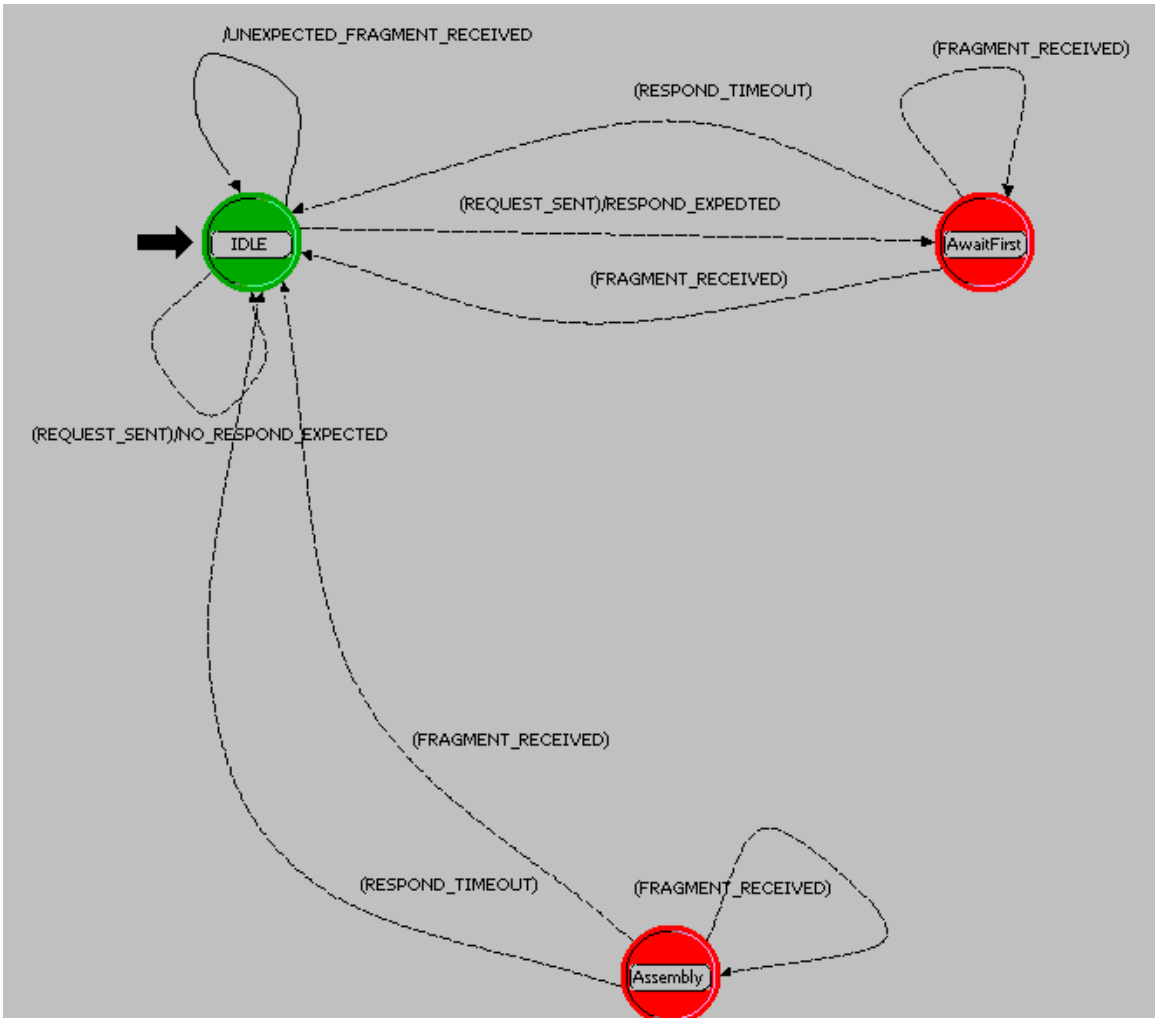


Figure 5.17: Master solicited response reception diagram in OPNET

5.4 Conclusion

This chapter presents the development of DNP3 data link, transport and application layer using OPNET environment. The Chapter also briefly discussed about OPNET technology. OPNET is a powerful Object Oriented (OO) base network simulator which

allows for the modelling, implementation, simulation and performance analysis of communication networks and distributed applications. The development of all layers of DNP3 protocol in OPNET environment provides a good engineering platform to further develop DNP3 protocol to be used more effectively in the power industry. Various rules, functions, classes and logic were implemented in all layers of DNP3 protocol.

In DNP3 application layer, only solicited response case is presented in this Chapter. Further development and design along with unsolicited scenario of DNP3 application layer will be discussed in Chapter 6.

CHAPTER 6

MODELLING OF AN EFFICIENT INFORMATION EMBEDDED POWER SYSTEM

6.0 Introduction

The development of DNP3 in OPNET environment has been presented in the previous chapter. From the experimental analysis which was discussed in Chapter 4, propagation delay associated in DNP3 is high when data are sent from control room to RTU over WAN. Power utility cannot accommodate such propagation delay as real time data and information is very vital for immediate response from control room. This chapter presents the development of more efficient IEPS-W model for more reliable and effective power system communication infrastructure. Section 6.1 elaborates the importance of efficient time critical infrastructure for power system. Section 6.2 discusses the implementation and development of more efficient and reliable protocol based on DNP3 which improves the performance of IEPS-W model significantly having low propagation delay. Section 6.3 provides conclusion remark of the Chapter.

6.1 Importance of time critical communication infrastructure for power system

The structure of the electric power industry is changing. The traditional attributes of the power industry, such as monopoly status, government ownership and government regulations are yielding to free-market forces. The future of power industry around the globe will be driven by competition, privatisation and deregulation. Global competition, increasing customer demands, capital liquidity and environmental concerns are all driving forces that, when coupled with deregulation of the industry, will create great change. These trends are affecting the use of networks and information systems in the power industry.

Without a good communications network, modern power systems would be inefficient. Operators communicate with each other to coordinate actions and exchange all kinds of operational information. The communications network conveys signals for the remote control of unmanned stations, to transfer data and load values from sites across the power system to central control, and transmits central control commands to the sites. Most crucially, the communications network carries many of the vital signals that have to be instantly exchanged in real time between different locations to ensure optimum control of the power system. In short, communications networks help power utilities keep electricity flowing all the way from generator to consumer [119].

Only an efficient network management system can achieve maximum availability at minimum maintenance cost to deliver the greatest benefits to users. It enables the remote supervision, diagnostics and configuration of equipment at any location.

6.2 Development and modelling of efficient IEPS-W

Random traffic present on WAN can cause delays in delivering vital control commands to devices present in the network. Thus, the state of the network can have a large impact on the operation of the power system. The converse of this statement is also true, because the state of the power system can also affect the operation of the computer network. For example, if a power system is operating close to its operating limits, the frequency of control commands from the control center may increase in order to keep the power system within safe operating limits. The increased frequency of control commands can lead to large traffic levels on the computer network and thus lead to greater packet delays. The scenario will be even more critical when power utility share cooperate network with SCADA network. Thus, an intelligent way is required to tackle this obstacle.

Generally, unsolicited responses from outstation IED increases network traffic and eventually make propagation delay significantly higher. Nonetheless, it is not possible to avoid unsolicited response as it transmits crucial data to the master when some uncommon behaviour is experienced by the system. Section 6.3.1 discusses the

implementation of unsolicited responses for IEPS-W such that propagation delay is significantly reduced.

6.2.1 Implementation of unsolicited responses for IEPS-W

Unsolicited responses [118] in DNP3 are messages spontaneously sent from an outstation IED without a specific request from a master when “something of significance” occurs. On the other hand, equipment that implements unsolicited messages is more complex because the issues of media access and collision avoidance must be considered. Master software requires accepting messages from any of its outstations at any time which will degrade system performance due to unpredictable nature of traffic during heavy communication. Continuous transmission of power system data also contributes to higher propagation delay. Hence, a smart and careful modelling is required to overcome this issue.

6.2.1.1 Unsolicited Response Timing

Figure 6.1 illustrates timing parameters associated with an unsolicited message.

The process in Figure 6.1 takes as below:

1. First, is the time that it takes to transmit the response from the outstation to the master.

2. The next timing value is the duration that the outstation waits to receive a confirmation back from the master.

3. Another parameter is the interval of time between retries. Ideally, this interval contains a random component, so that the time between retries varies from retry-to-retry and amongst outstations whose transmissions are triggered by a common event.

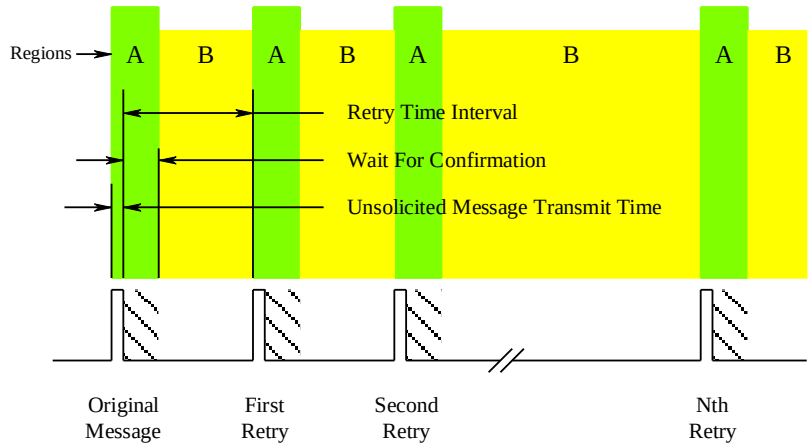


Figure 6.1: Unsolicited timing diagram

4. There are two regions labeled A and B in the figure. The purpose for identifying these regions is to aid discussion of outstation actions upon receiving requests from the master during these time regions.

Region A starts when the unsolicited response is initiated and ends when an Application Layer confirmation is received or the confirmation timer times out, whichever occurs first.

Region B is the time between when the confirmation timer times out and the initiation of an unsolicited response retry.

6.2.1.2 Outstation Compulsory Configuration

Devices that support unsolicited responses must support end-user configuration of the following parameters:

1. The destination address of the master device where the unsolicited responses will be sent.
2. The unsolicited response mode is configured off, the device must never send an unsolicited response, but otherwise responds to master requests.
3. The timeout period for unsolicited response confirmation is the amount of time that the outstation will wait for an Application Layer confirmation back from the master indicating that the master received the unsolicited response message. As a minimum, the range of configurable values must include times from one second to one minute, however, devices may offer longer and shorter timeouts for systems with slower or faster media.
4. The maximum number of unsolicited retry transmissions is the number of times that an outstation will retry transmitting an unsolicited message if it does not receive

confirmation back from the master. One of the choices must provide for an indefinite (and potentially infinite) number of retries. An outstation must not give up on or discard the unsolicited response when all retransmissions have been exhausted and confirmation not received. Continued unsolicited response transmissions are postponed until another opportunity occurs to restart the transmissions, such as the receipt of a read request from the master.

The following configuration parameters have been implemented to enhance IEPS-W performance:

1. Minimum back-off time is used when an outstation detects that if it were to initiate a transmission, a collision would occur. The outstation then delays by a certain amount of time before attempting the transmission. The delay also includes a random component.
2. Retry timing interval parameters is used to minimize potential collisions and optimise the chance of getting the response to the master. A common event (or events) within a system can sometimes cause multiple outstations to simultaneously attempt sending an unsolicited response. Collisions are likely to occur repeatedly if all the outstations use identical retry time intervals. It is often beneficial to add a random amount of time to the basic retry interval in order to increase the probability of only one outstation attempting a transmission. Setting the maximum random adder is recommended for tuning a system. Another technique is to progressively increase

the time interval between retries up to a maximum value. Thus the retry time for an outstation is calculated as:

Retry Time = Base Retry Interval * M * (1 + R)

where M is a number that starts at 1 and increases with each retry to a maximum value. The increment and maximum are configurable.

and R is a random number that varies between 0 and a configurable maximum value. For example, if the configured maximum is 0.2, R would be a number that varies from 0 to 0.2.

3. Whether a burst option is functional, number of tries per burst and the extended time period between bursts is a variation of sending an indefinite number of unsolicited response retries where the outstation retries several times, waits for an extended time period, and then begins another burst of retries. This behavior is repeated indefinitely until an Application Layer confirmation is received.

   The benefit of using this scheme is that an outstation never gives up trying to notify the master of a change, but the outstation pauses for extended periods to allow time for “data storms” to clear.

4. Maximum hold time before initiating an unsolicited response is delaying for a configurable amount of time after detecting each new event is often beneficial for allowing multiple changes to complete prior to transmitting an unsolicited response message. The advantages are the increased possibly of capturing all the changes in a single response, and, depending upon the timing, potentially eliminating the need

for additional unsolicited responses after the first change is reported. The timer is retriggered each time a new event is detected.

5. Number of queued events before initiating an unsolicited response is when events occur too often, and the maximum hold time is relatively long, the event buffer or queue may continue to accumulate events before an unsolicited message is transmitted. Without this counter, the buffer or queue can overflow causing a loss of events. With the counter, a message is initiated when its count reaches the configured amount. This gives time to transmit a quantity of events and then remove the acknowledged events from the queue, thus making room for more.
6. Prioritising the critical data which represents the status of current, voltage and power has been given priority over all other data in the network. This has given the upper hand for the SCADA data in the network.

6.2.1.3 Normal Runtime Behaviour

The following rules have been implemented for unsolicited responses :

Rule 1 An outstation only initiates unsolicited responses for those points that have been enabled.

Rule 2 An outstation only includes event data in an unsolicited response.

Rule 3 Unsolicited responses must fit within a single fragment. If the outstation has more data than fits within a single fragment, it includes only as much data as

fits into a single fragment. The outstation waits until that response is confirmed, and then it creates a new unsolicited response to transmit the remaining data.

Rule 4 A master must return confirmations to unsolicited responses immediately upon receipt, regardless of where it is in its polling sequence, even if it is waiting for a response to a solicited response.

Rule 5 Masters examines the SEQ number in a received fragment and compares it with the previously received unsolicited fragment. If the SEQ numbers are different, it assumes a new fragment has been received, but if the SEQ numbers are the same, it compares all of the octets to determine if the response is new or a repeat.

Rule 6 An outstation never discard event information because of an expected confirmation was not received.

Rule 7 An outstation does not initiate a new unsolicited response while it is waiting for confirmation to a solicited response until either confirmation is received or the confirmation timer times out.

Rule 8 Once an outstation has transmitted a new unsolicited message, it cannot add objects to, subtract objects from or modify the objects in retried fragments. Retried fragments must exactly match those of the fragment for the original message of an unsolicited response sequence.

Rule 9 An outstation immediately clear corresponding event data from its event buffer(s) upon receipt of a confirmation during time region A as shown in Figure 6.1. It performs the clearing action prior to responding to any pending requests or generating a new unsolicited response sequence. Confirmations received during time region B as shown in Figure 6.1 are ignored.

Rule 10 If the configured number of unsolicited response retries have been sent and confirmation is not received by the end of the last retry's confirmation timeout period, the outstation postpones transmitting the next unsolicited retry for an indefinite period by increasing the duration of region B to infinity.

Rule 11 If the unsolicited transmission retries expire without receiving a confirmation from the master and unsolicited reporting was postponed, The following are alternatives that was be used alone or in combination with each other:

- A new event has occurred and at least one retry interval (region B time of Figure 6.1) has transpired since the end of region A for the last retry. The new event is not added to the unsolicited response; it is reported after the unsolicited response is confirmed.
- The master has issued to the outstation a ***READ*** request for any data; in this situation the outstation shall respond with the unsolicited response in lieu of whatever was in the ***READ*** request.
- For connection-oriented systems, the master has connected to the outstation and issued a request of any kind.

- At least T_n seconds have transpired since confirmation timeout for the last retry. T_n is a configurable time, usually of long duration. The benefit of this option is that it does not depend upon a stimulus from the field or from the master to begin again.

Rule 12 If a request is received from master having function code DISABLE_UNSOLICITED during time regions A or B as shown Figure 6.1, regardless of which object headers appear in the disable request, the outstation shall:

- Immediately cancel any expectation of confirmation for the entire unsolicited response.
- Make the events that were in the unsolicited response available for reporting in a response to a solicited ***READ*** request.
- If there are still any events available and enabled for reporting in unsolicited responses (because the request only disabled some but not all events), initiate a new unsolicited response sequence at an appropriate time.

Rule 13 If a ***READ*** request of any kind is received during an unsolicited response sequence, perform the following:

If the request arrives in time region A of Figure 6.1, defer building the response until either:

- The confirmation is received in time region A. In this case the read request is treated like a normal solicited ***READ*** request and a response transmitted.
- Time region A expires and time region B is entered. In this case the ***READ*** request is treated as though it were received in time region B.

If the request arrives in time region B of Figure 6.1, including an extended region B period that postpones unsolicited transmissions, immediately respond with the unsolicited response in lieu of whatever is requested in the ***read*** request. This starts a new time region A. The ***READ*** request is deferred during this new region A interval until either confirmation of the unsolicited response is received or the unsolicited response confirmation timer times out.

- If confirmation of the unsolicited response is received, respond to the deferred ***READ*** request as though it had just been received.
- If the confirmation timer times out, discard the ***READ*** request.

Rule 14 If a non-read request of any kind is received during an unsolicited response sequence, including postponed unsolicited transmissions, the outstation shall respond immediately.

Rule 15 If a ***READ*** response is deferred and another request of any kind is received from the master, then perform the following:

- If new request is a ***READ*** request, it replaces the already deferred request. It is deferred and handled according to Rule 14, as appropriate.
- If the new request is a non-read request, the deferred read request is discarded and the new request is handled according to Rule 15.

Rule 16 The transmission by the outstation of an unsolicited response causes it to disregard the sequence number in the most recently responded to read request and treat a subsequently received repeat of that original read request as a new read request. (This situation can occur if the original ***READ*** response did not arrive intact at the master.)

6.2.1.4 Unsolicited message timing examples

This section illustrates the behaviour associated with unsolicited response messages which have been implemented to make an efficient IEPS-W model. Figure 6.2 shows the ideal situation where unsolicited responses are confirmed and there is no overlap between master requests and the outstation waiting for confirmations. The shaded region A's in Figure 6.2 represents A regions which was first introduced in Figure 6.1. Time advances from top to bottom in the diagram. Each request, response or confirmation is given a number inside close and open brackets [n] to aid in the description. At the top, the outstation transmits an unsolicited response [1], and receives a confirmation [2]. As soon as the confirm is received, A region ends; there is no B region. The outstation removes or clears from its buffer(s) the events that it reported in

the unsolicited response [1] because confirmation [2] was received from the master that the event(s) arrived there.

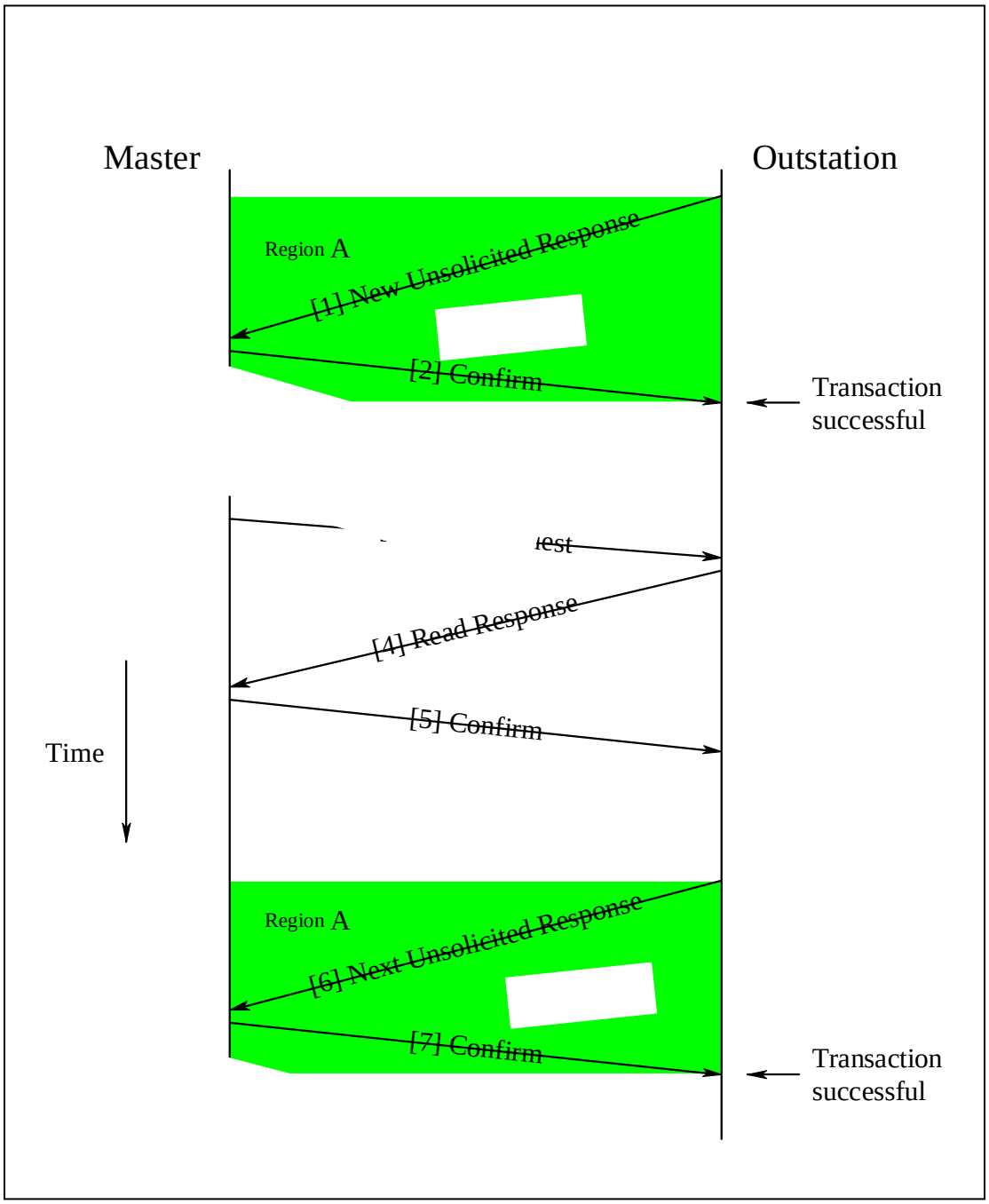


Figure 6.2: Ideal mixed unsolicited and solicited communications

Later, the outstation transmits another new unsolicited response [6] and receives confirmation [7] from the master. The outstation again removes or clears from its buffer(s) the events that it reported in the unsolicited response [6] because confirmation [7] was received that the event(s) arrived at the master. Everything worked as expected. Responses were transmitted and confirmations received. Figure 6.3 shows an example where confirmations to unsolicited responses are not received as expected.

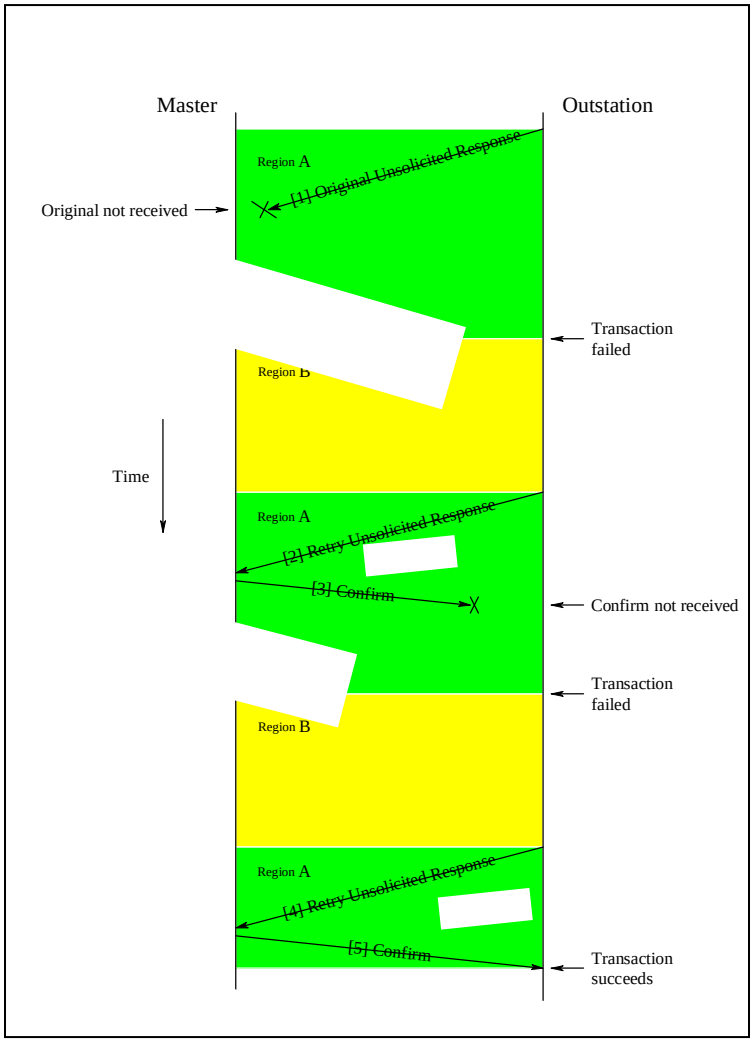


Figure 6.3: Unsolicited response or confirmation not received

Figure 6.3 illustrates two retries of an unsolicited response before the unsolicited transaction is successful. At the top, the outstation sends an unsolicited response [1] that is not received by the master. The outstation waits for the confirmation back; this time is indicated as region A. When timeout occurs, the transaction has failed. After the first transaction fails, the outstation waits during region B until it is time to transmit a retry [2] of the original unsolicited response. This response contains the same Application Layer sequence number that the original used.

The confirm [3] from the master does not reach the outstation, but the outstation keeps waiting until its confirmation timer times out. At that time the transaction is again failed. Once more, the outstation waits until it is time to send another retry. This is the second region B time. When region B ends, the outstation sends another retry [4]. This time confirmation [5] is received from the master, and the transaction is finally successful. The outstation must now remove or clear from its buffer(s) the events that it reported in the unsolicited response [4] because confirmation [5] was received from the master. Figure 6.4 illustrates a read request received during region A while waiting for a confirmation to an unsolicited response. At the top of the diagram, the original unsolicited response [1] is transmitted, but its confirmation [2] does not make it back to the outstation. The outstation waits until the confirmation timer times out at the end of region A, and then waits during region B until it is time to send a retry of the unsolicited response.

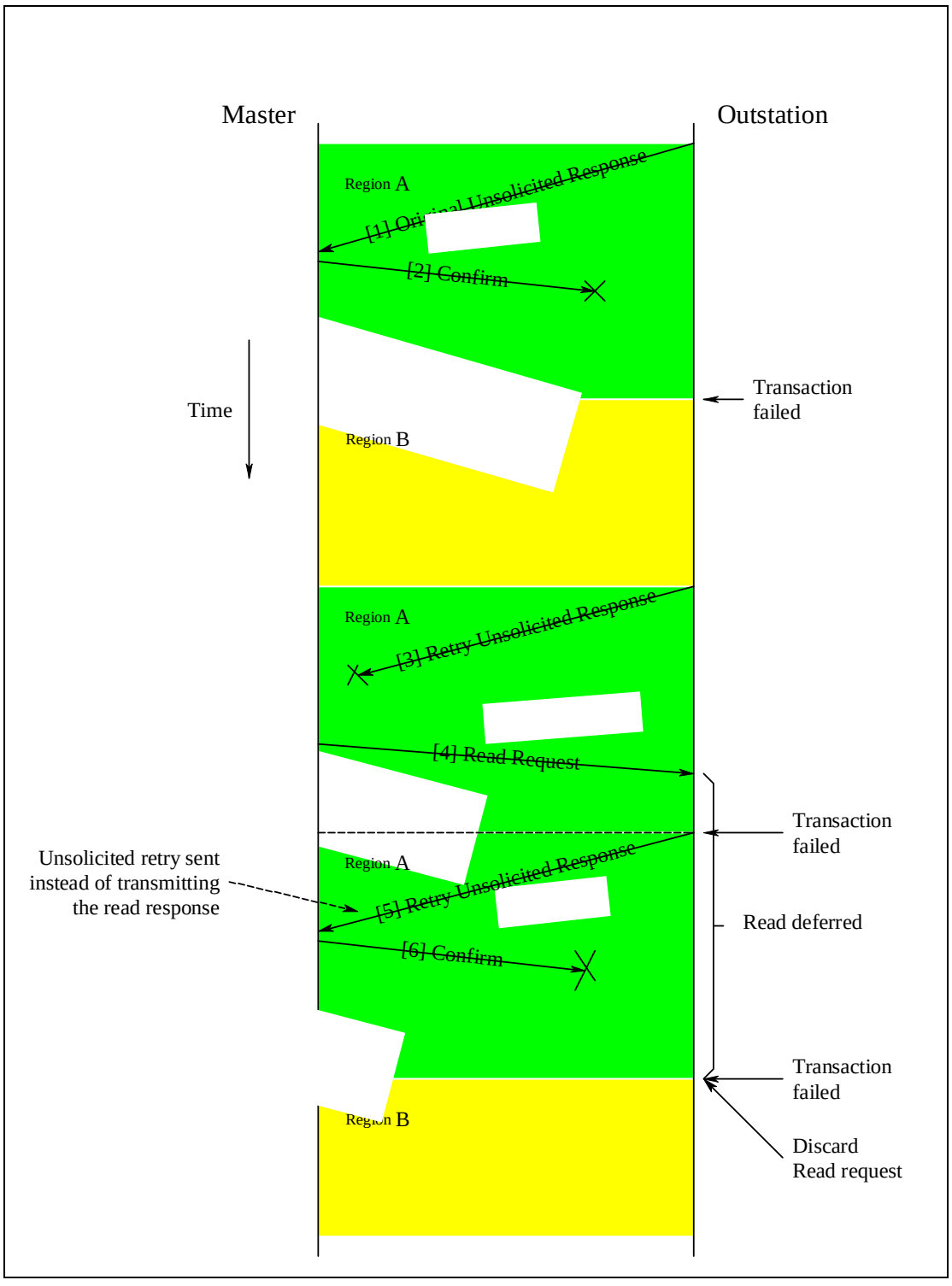


Figure 6.4: Read request received in region A(2)

In the middle of the diagram, the outstation initiates the sending of the unsolicited retry [3] in the second region A.

In this diagram, however, the retried unsolicited response [3] does not reach the master. By coincidence, the master sends a read request [4] that arrives at the outstation while the outstation is still waiting for the unsolicited response confirmation. The outstation defers the read request [4] in region A and does not process its contents while it continues to wait for a confirmation to its retried unsolicited response [3].

At the end of the second region A, the outstation sends a retry of the unsolicited response [5] instead of sending a response to the master's read request. The outstation waits in the third region A until it either receives a confirmation to its retried unsolicited response or the confirmation timer times out. In the diagram, the master received the retried unsolicited response [5], sent the confirmation [6], but that confirmation did not arrive intact at the outstation, so the outstation discards the deferred read request and continues to wait.

Figure 6.5 is similar to Figure 6.4 except in this diagram the unsolicited transaction eventually succeeds. At the top of Figure 6.5, the original unsolicited response [1] is transmitted, but its confirmation [2] does not make it back to the outstation. The outstation waits until the confirmation timer times out at the end of region A, and then waits during region B until it is time to send a retry of the unsolicited response. In the middle of the diagram, the outstation initiates the sending of the unsolicited retry [3] in

the second region A. However, the retried unsolicited response [3] does not reach the master.

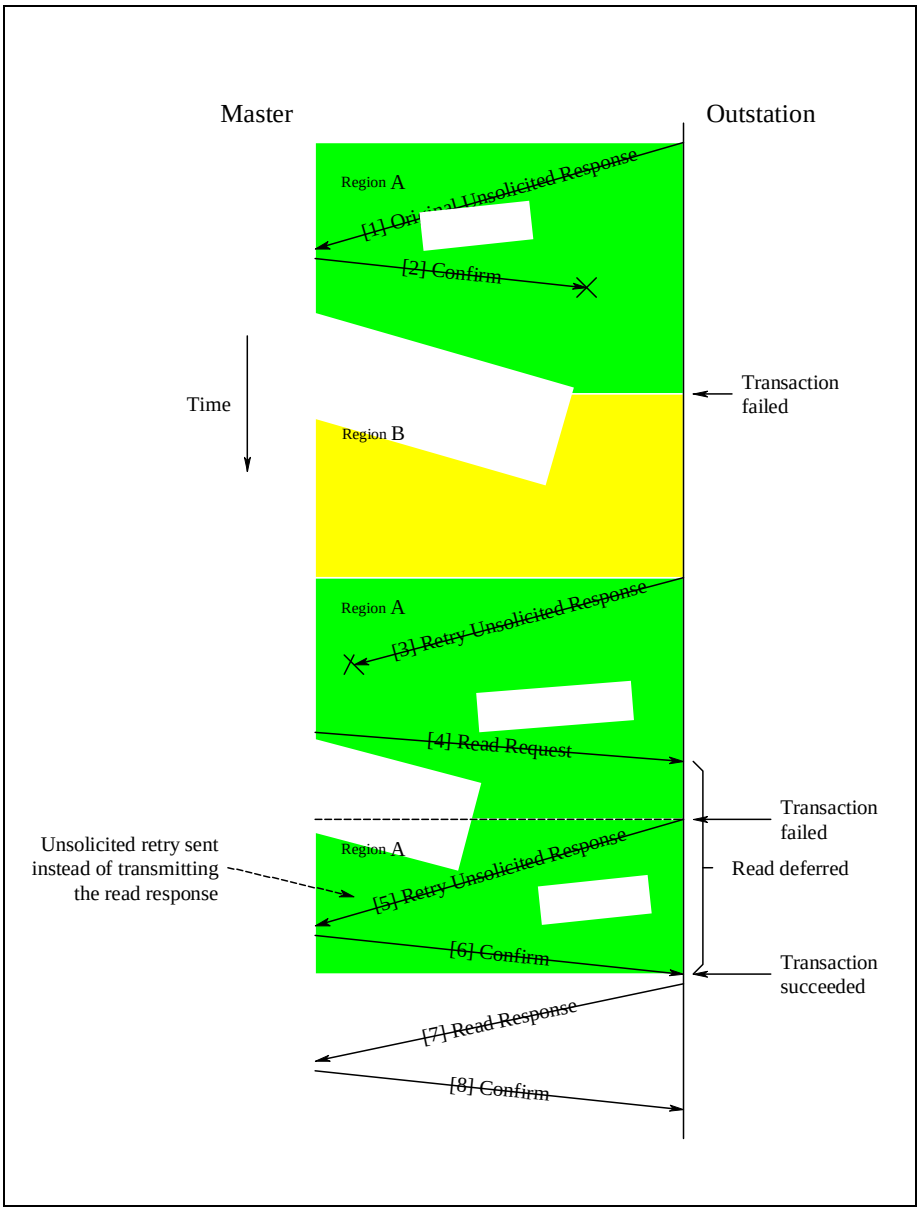


Figure 6.5: Read request received in region A (2)

By coincidence, the master issues a read request [4] that arrives at the outstation while the outstation is still waiting for the unsolicited response confirmation. The outstation defers the read request [4] in region A and while it continues to wait for a confirmation to its retried unsolicited response [3].

At the end of the second region A, the outstation continues to defer the ***read*** request and sends a retry of the unsolicited response [5]. This time, the confirmation [6] reaches the outstation. Upon receiving confirmation [6], the outstation marks the events reported in the retried unsolicited response [5] as sent (removed from the outstation's event buffers) and transmits a response [7] to the deferred ***read*** request [4]. This response must not report the same events that were reported in the retried unsolicited response [5] because confirmation was received for those events.

Figure 6.6 illustrates the behaviour when a read request arrives during period B. The actions are similar to those shown in Figure 6.5 while the difference being that the outstation immediately sends a message after the read request is received instead of waiting for a timeout. A read request [4] is received from the master during period B, which is while the outstation is waiting to send another retry of the unsolicited response. Instead of sending the response to the read request [4], the outstation defers the read request and instead immediately sends a retry of the unsolicited response [5]. The outstation discards the read request at the end of the third region A period because the confirmation to the unsolicited response [6] did not reach the outstation.

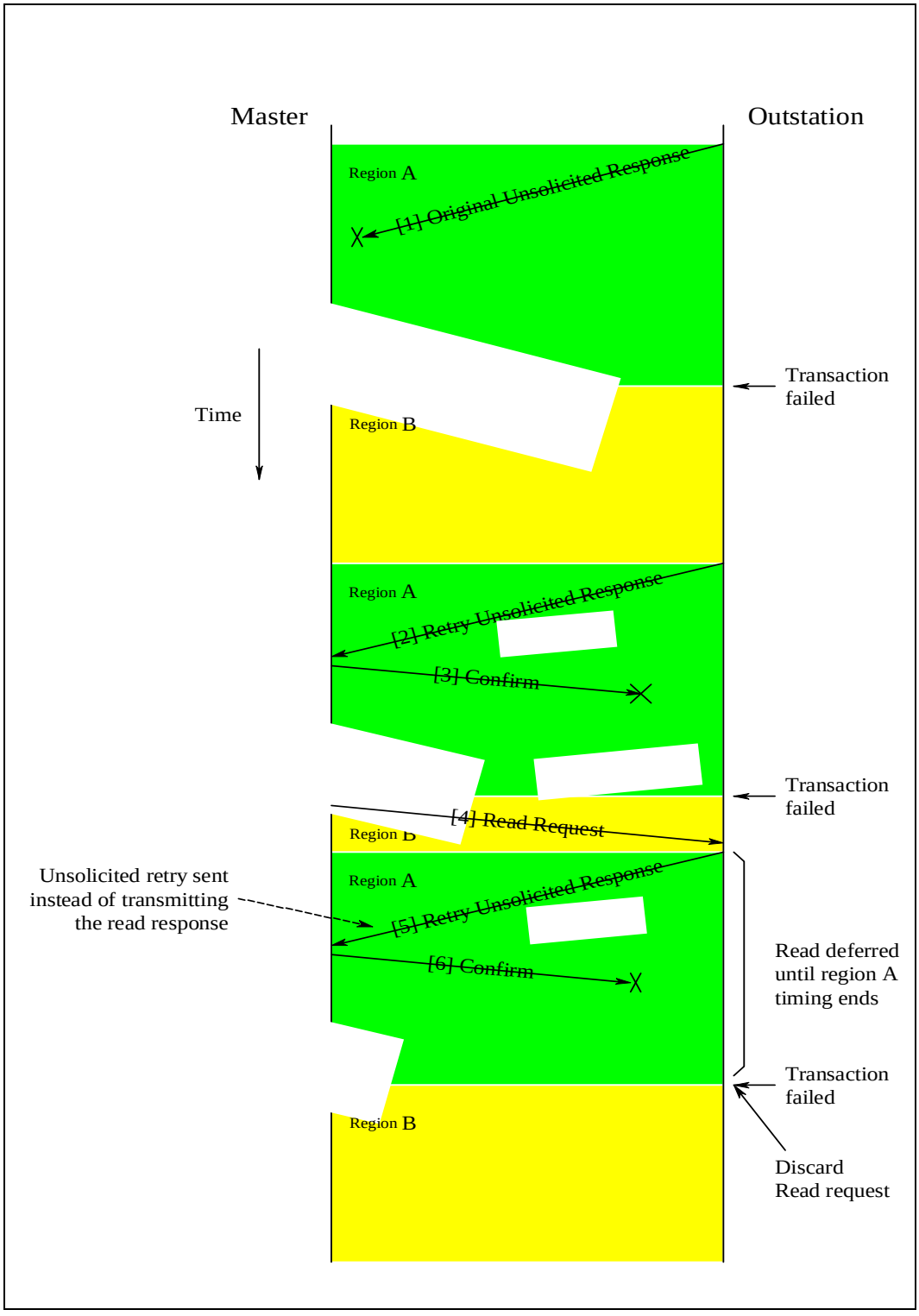


Figure 6.6: Read request received in period B (1)

Figure 6.7 is the last illustration in this series.

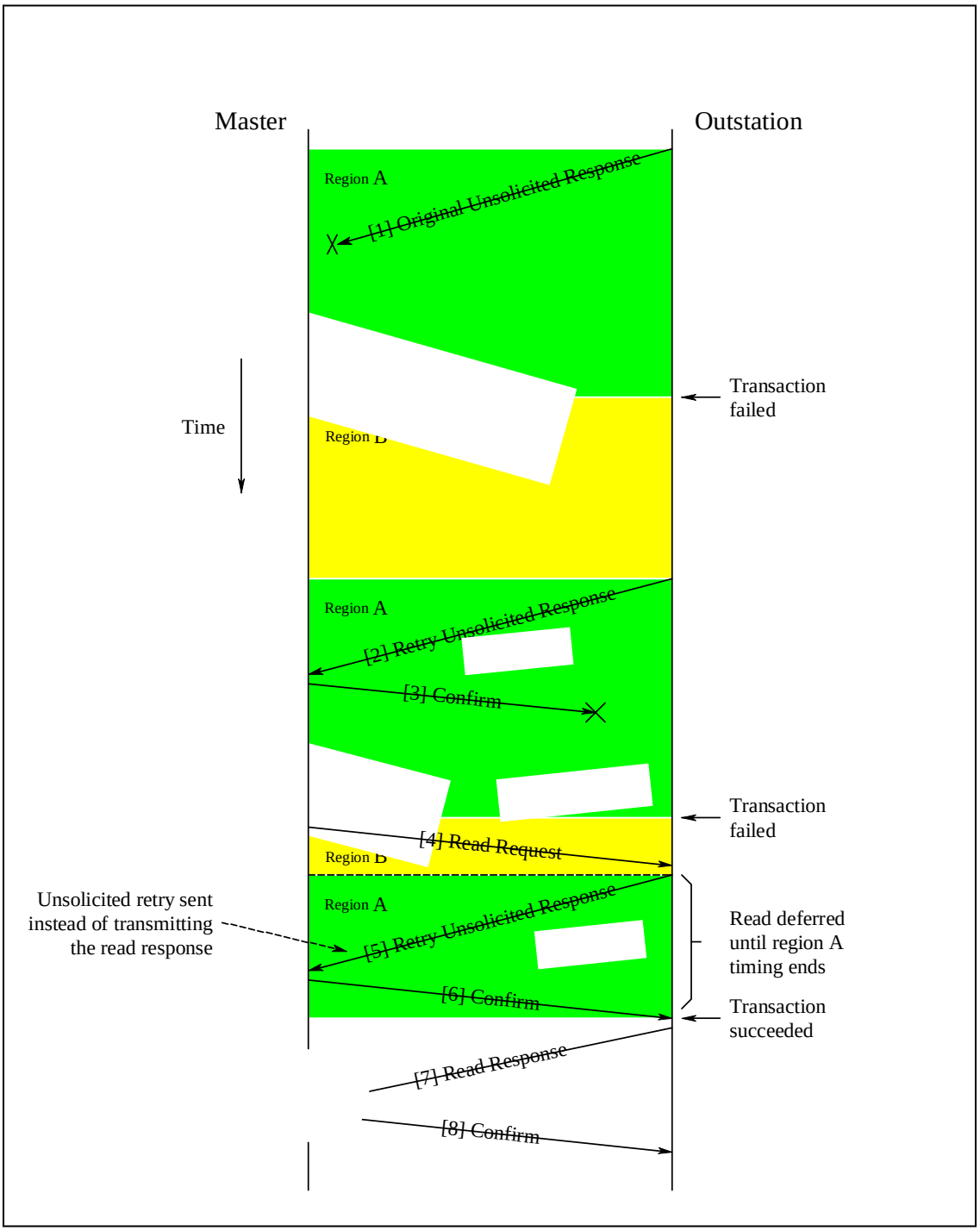


Figure 6.7: Read request received in period B (2)

Figure 6.7 is similar to Figure 6.6 except the unsolicited confirmation eventually succeeds. The diagram shows a ***read*** request [4] arriving in period B. The outstation defers the ***read*** request and immediately sends the unsolicited response [5]. Upon receiving confirmation [6], the outstation marks the events reported in the retried unsolicited response [5] as sent (removed from the outstation's event buffers) and transmits a response [7] to the deferred ***read*** request [4]. This response must not report the same events that were reported in the retried unsolicited response [5] because confirmation was received for those events.

6.2.2 Master unsolicited response reception state table

The purpose of the reception state table is to specify a master's behaviour when fragments are received from outstation with unsolicited response message. Master software for handling unsolicited responses requires three states for proper operation.

1. **Startup** state: The master just started after a reset for any reason and has **not** performed an initial integrity poll.
2. **FirstUR** state: The master started up, completed an initial integrity poll and is waiting for the first unsolicited response from the outstation.
3. **Idle** state: The software is idle waiting for a unsolicited response fragment to arrive.

Figure 6.8 shows master unsolicited response which implements all the states and events shown in Table 6.1. When the software in the state shown in column A of Table

6.1, and the SEQ number appears in column B, and SEQ number application control octet in most recently accepted fragment is as shown in column C, the actions is then perform in column D. The software state then exeute as specified in column E.

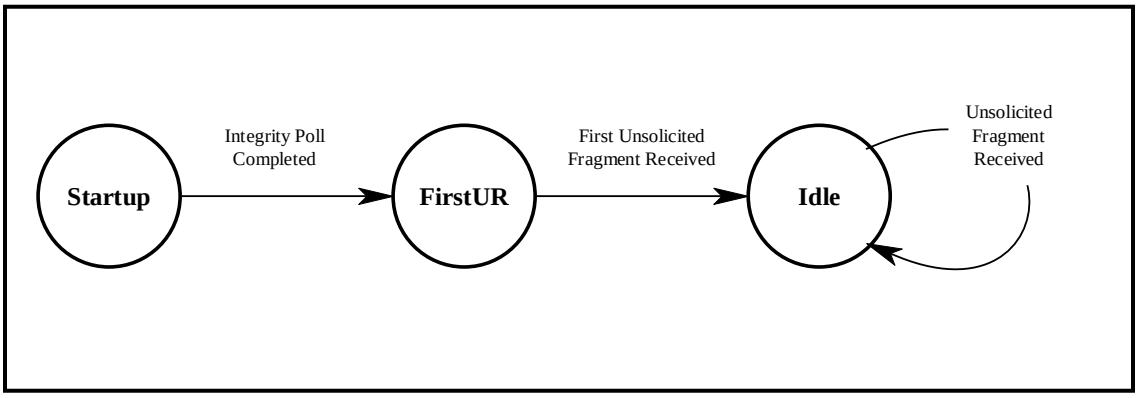


Figure 6.8: Master unsolicited response reception diagram

Table 6.1: Master reception state table, Unsolicited Responses

Current State	*Event that Triggers an Action and Possible Transition*		*Action*	*Transition To State*	
A	**B**	**C**	**D**	**E**	
If the software state is	and a fragment is received with SEQ number	and the SEQ number in the most recently **accepted unsolicited** fragment was	then perform this action	and go to this state	
Startup	X	—	Discard fragment and do not confirm.	Startup	**1**
	Initial integrity poll completed	—	Prepare to receive unsolicited responses.	FirstUR	**2**
FirstUR	X	—	Send confirm if requested, accept fragment and process fragment	Idle	**3**
	X and IIN1.7	—	Send confirm if requested, accept fragment, process fragment and send reset IIN1.7 request and perform integrity poll.	Idle	**4**
Idle	N	N	Send confirm if requested. Compare octet-by-octet with previous fragment. If octets match, take no further action. If octets do not match, accept fragment, process fragment and perform integrity poll.	Idle	**5**
	N + 1	N	Send confirm if requested, accept fragment and process fragment	Idle	**6**
	!= (N + 1)	N	Send confirm if requested, accept fragment, process fragment ‡ and optionally perform integrity poll.	Idle	**7**
	X and IIN1.7	N	Send confirm if requested, accept fragment, process fragment and send reset IIN1.7 request and perform integrity poll.	Idle	**8**

Keys for understanding Table 6.1: ‡ means possible data loss or duplicate data. X means don't care.The dash symbol '—' means "Not Applicable".N is any valid sequence number.N + 1 is N plus 1 modulo 16.!= means "Not Equal To". (For example, !=N means not equal to N.)

Figure 6.9 shows the implementation of master unsolicited response in OPNET platform.

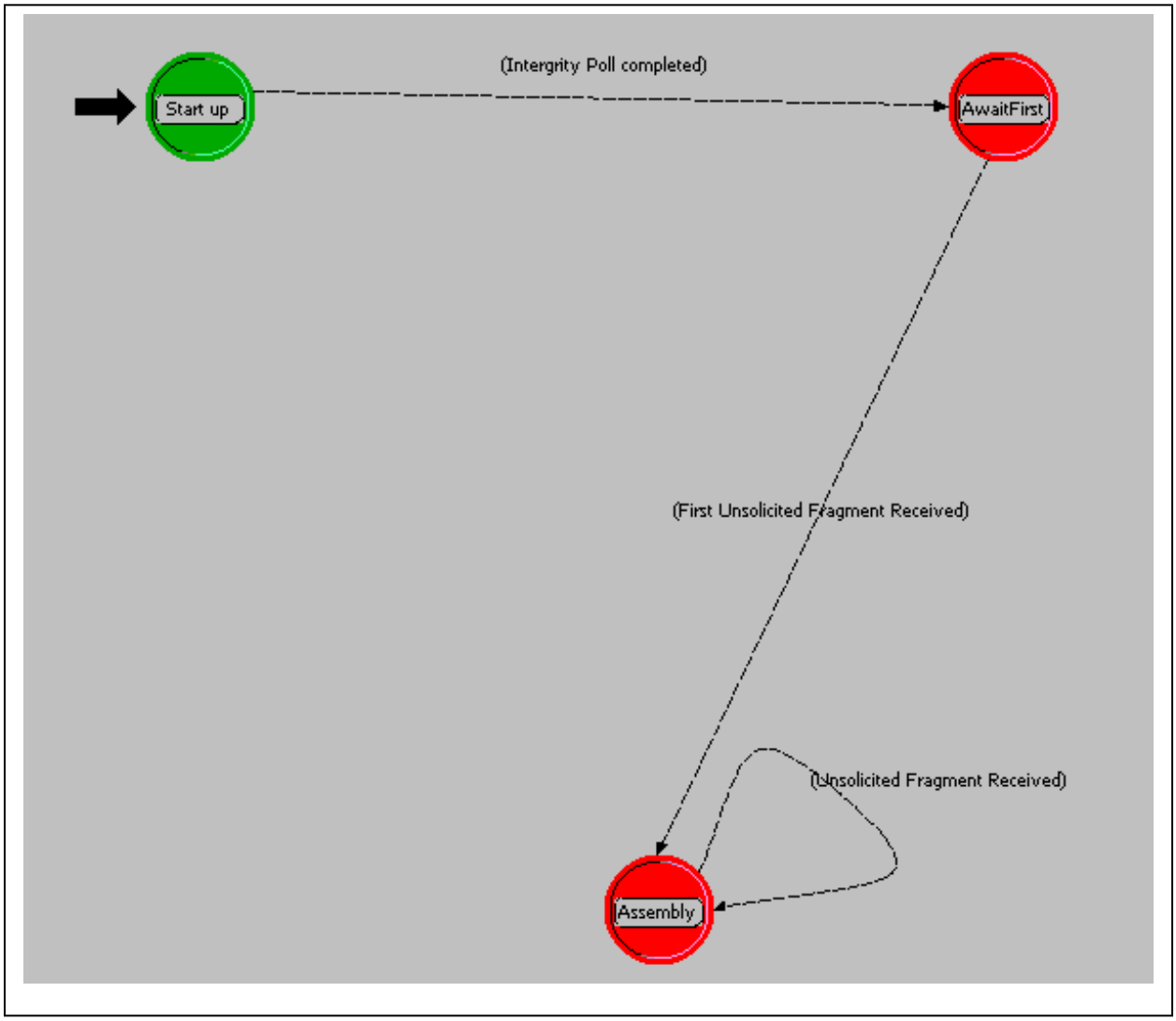


Figure 6.9: Master unsolicited response in OPNET platform

The implementation of unsolicited response completes the development of DNP3 in OPNET environment. Many unsolicited response in SCADA network could increase data traffic in the network and hence propagation delay could be higher than normal

condition. Hence, all the rules and states were implemented in DNP3 protocol so that the priority is given to critical unsolicited data. After the implementation of DNP3 protocol in OPNET modeller, IEPS-W was developed as shown in Figure 6. 10.

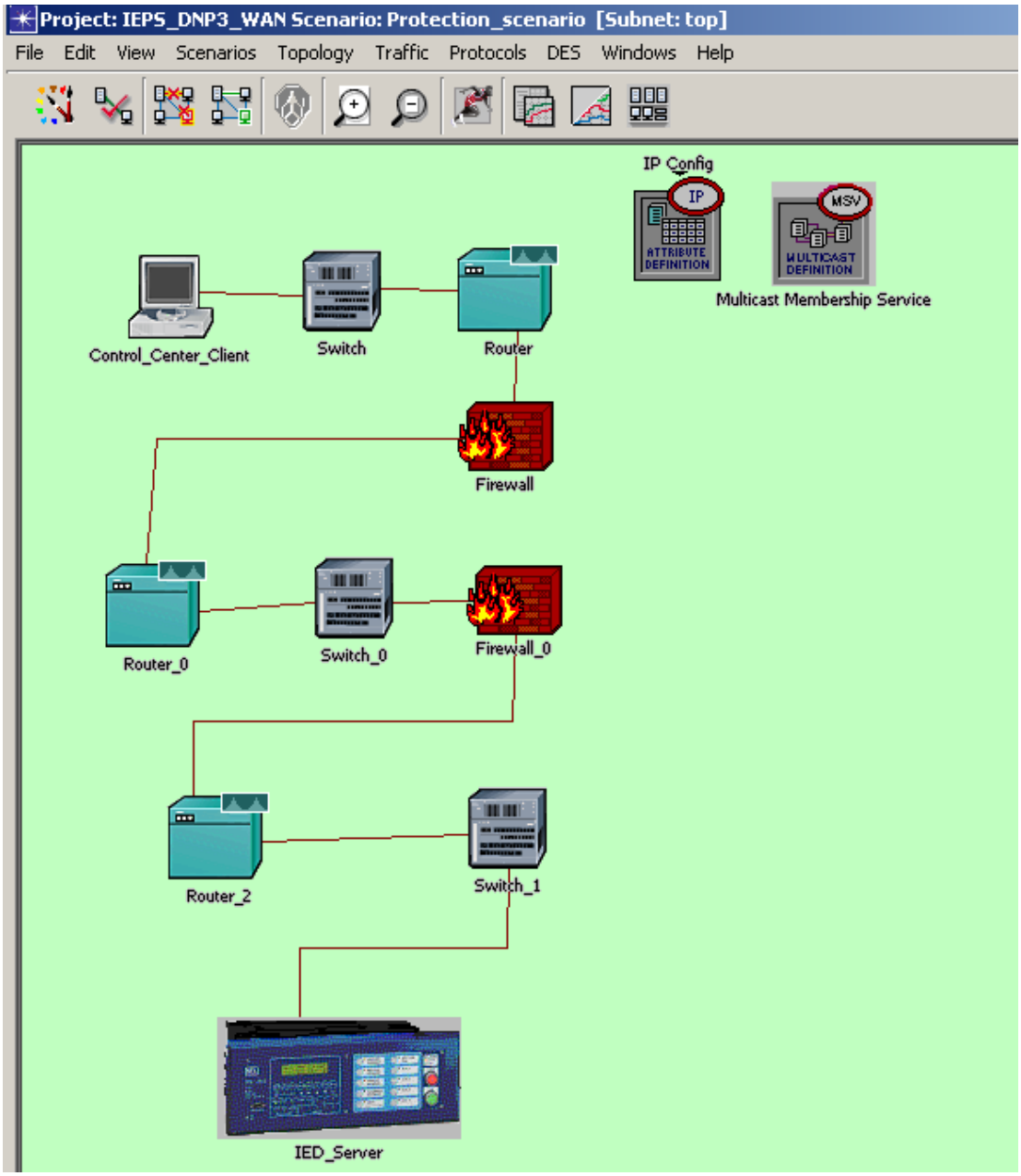


Figure 6.10: IEPS-W in OPNET environment

This model is in congruent with the experiment performed which was discussed in Chapter 4. This consists of one RTU sending data to control centre via WAN using the developed DNP3 protocol. The simulation was performed in 10%, 20%, 40%, 60% and 80% data traffic. Figure 6.11 depicts simulation result which shows improve performance of IEPS-W model with lower propagation delay.

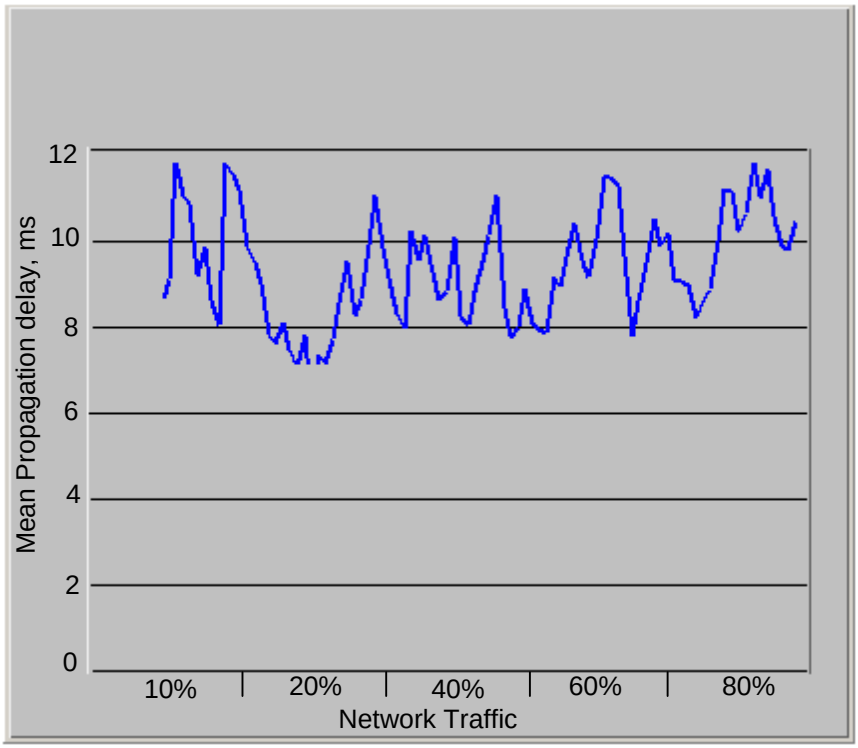


Figure 6.11: Mean propagation delay of efficient IEPS-W

As seen in Figure 6.11, propagation delay has reduced significantly. This makes IEPS-W more efficient and reliable. As it can be observed from the Figure, propagation delay was initially higher and then it drops to nearly 7 ms. It then increases to 11 ms. The peak mean propagation delay is about 11.5 ms.

6.3 Conclusion

Propagation delay associated in power system communication protocols are a major concern for power industry especially when power system protocols are used over WAN. Most of the modern day power system communication was not originally developed to be used in WAN. With the advancement in WAN technology, power industry employs WAN to transmit both critical and non-critical data over WAN. This brings a concern to enhance existing protocols so that they can perform efficiently under this deregulated environment where real time data has become so crucial. As discussed in this chapter earlier, unsolicited messages in DNP3 increases network traffic and hence increases propagation delay in the network. However, with intelligently designing the transmission process of unsolicited messages, the IEPS-W model is now more efficient and reliable.

CHAPTER 7

MODELLING OF SECURE INFORMATION EMBEDDED POWER SYSTEM

7.0 Introduction

The development of efficient and reliable information embedded power system has been discussed in the previous chapter. Since security is a major concern in IEPS-W in general and SCADA system in particular, a more secure information embedded power system is required to make power system more reliable, protective and secure. To address these issues, Section 7.1, briefly discusses the importance of secure information system for power system industry along with security issues associated with IEPS-W. The development and implementation of security features in IEPS-W model has been discussed in Section 7.2. Section 7.3 provides the conclusion remarks for this chapter.

7.1 Secure communication system for utilities

As discussed earlier, Supervisory Control and Data Acquisition (SCADA) is one of the vital part of modern information embedded power system. SCADA networks control the critical utility and process control infrastructures in many countries. The SCADA

architecture consists of one or more Master Terminal Units (MTUs) which the operators utilise to monitor and control a large number of Intelligent Electronic Devices (IEDs) installed in power network.

SCADA performs crucial functions for utility companies including electricity, natural gas, oil, water, sewage and railroads. However, little attention was given to security considerations in the initial design and deployment of these systems, which has caused an urgent need to upgrade existing systems to withstand unauthorised intrusions [120]. Nonetheless, considerable attention was lately poured by different organisations to power system security issues.

SCADA technology was initially designed to maximise functionality and performance with little attention to security. This weakness in security makes the SCADA systems vulnerable to manipulation of operational data that could result in serious disruption to public health and safety. A SCADA system involves significant capital investment, so replacement of legacy systems with a new architectural design or new technologies to obtain increased security can be costly. The SCADA systems are built using public or proprietary communication protocols which are a set of formal rules or specifications describing how to transmit data and commands, especially across a network. The security of a SCADA network can be improved in a number of ways such as installing firewalls, securing devices that make the network, implementing access control, network enhancements and so forth. It is necessary to identify SCADA communication protocol

such as DNP3 as the most essential and appropriate place to enhance the security and propose various methods to secure the protocols.

Few publications are available on SCADA security, such as the American Gas Association Report No. 12 (AGA 12) [120]. AGA 12 recommends practices designed to protect SCADA's Master-Slave serial communication links from a variety of active/passive cyber attacks. One of these standards is AGA 12-1, Cryptographic Protection of SCADA Communications. The solution protects against hijacking or modifying the communication channel. In another research, Patel and James [121] examined three security enhancements in SCADA communications to reduce the vulnerability of cyber attacks.

7.1.1 Threats Analysis of DNP3 protocol

Security was not part of the design of the DNP3. DNP3 does not include authentication or encryption technologies in its structure. Intruder uses several ways to compromise the security of SCADA systems and networks including at protocols level.

The Intruder could use protocol analyser tools such as "Ethereal" or other well known techniques to intercept the DNP3 frames. As a result, the Intruder grabs unencrypted (plaintext) frames from a DNP3 SCADA system network application. By doing so, the Intruder will capture the address of the source and destination systems. The Intruder could use the unencrypted data frames contain control and settings information in

subsequent attacks on either the SCADA system or the IEDs. Such attacks could take the form of shutting off MTU or making RTUs or IEDs stop functioning. In addition, the Intruder could change the settings on the IED, controller, or SCADA system such that the equipment either (a) fails to operate when it should, causing bus, line, or transformer damage, or (b) operates when it shouldn't, causing service interruption [122].

An Intruder, after managing to get between the Master and the Slave, intercepts the transmission of the frames and can possibly implement the attack in two phases:

Plan the attack: An important feature of DNP3 is the ability for the Slave to generate unsolicited report by exception (RBE) event and send it to the Master. Unsolicited message (alarming) generation for event reporting is configurable by the Master Station through the usage of the configuration functions in the application function code. The Intruder understands the structure of the DNP3 protocol and plans the attack as shown in Figure 7.1.

1. The Master initiates a connection with the Slave
2. Unknown to both the Master and the Slave, the Intruder is waiting to intercept the connection
3. The Intruder receives Master's request for a connection (authentication capability is not implemented in DNP3, so the Intruder does not have to authenticate himself to the Slave)

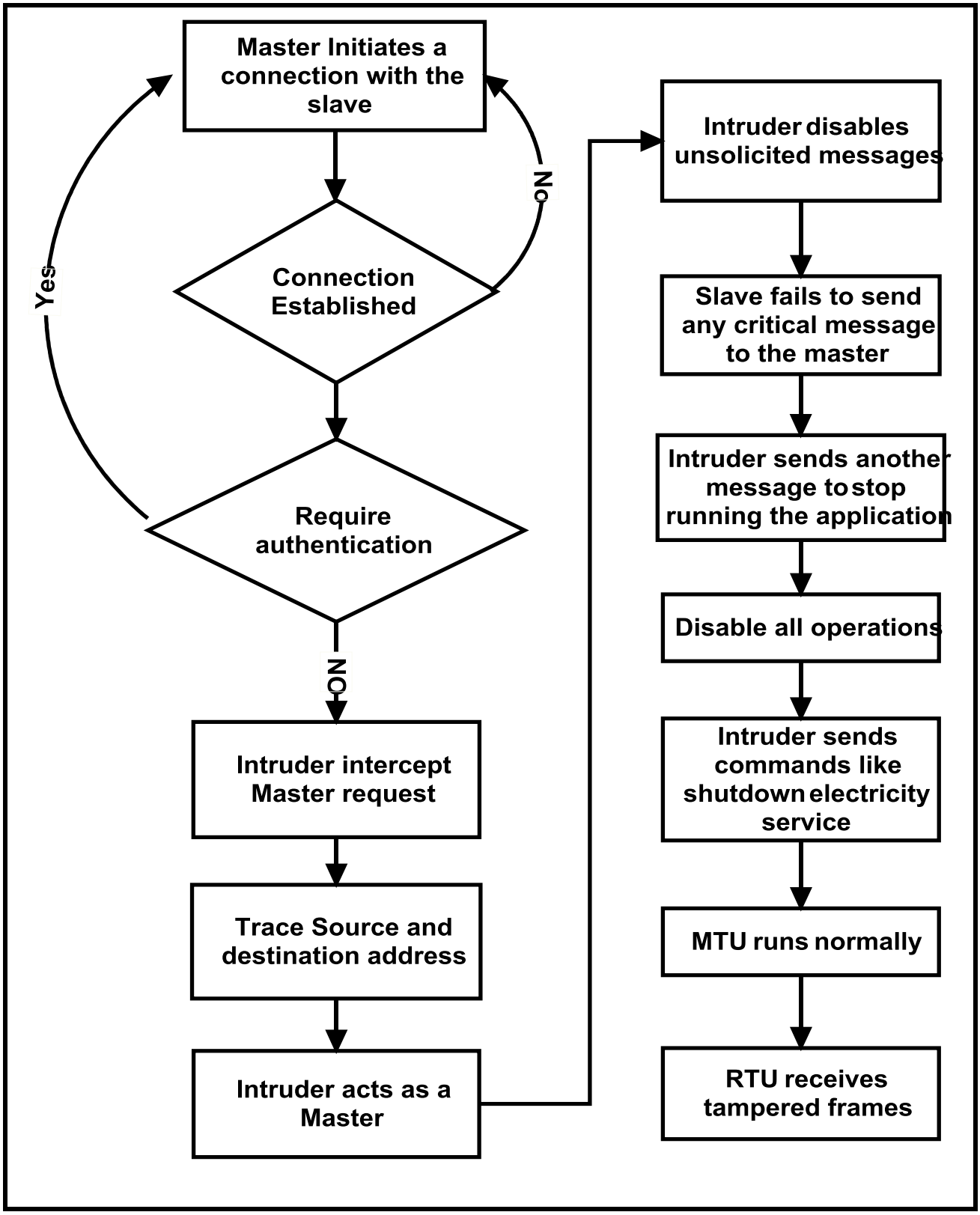


Figure 7.1: Planning the attack

4. The source address (#0), the destination address (#245), the function codes and the data objects are available in clear text

Disable DNP3 unsolicited messaging (alarming) by attacking one or more Slave units: The Intruder implements the attack by following these steps:

5. The Intruder then initiates a connection with the Slave posing as Master

6. The Intruder sends a message to Slave unit #245 with code function code 21 (disable unsolicited messages).

7. Slave unit #245 receives the message and disables unsolicited messages function. At this point, the Slave will not be able to send any alarming messages to the Master in case there is a failure or abnormal operation at the Slave unit.

8. The Intruder sends another message with code function code #18. Code #18 gives instructions to the Slave to stop running the application specified in the message.

9. A simultaneous attack on other Slave units will disable all operations on a communication channel (DNP3 has the capability to send a broadcast message to all Slave units by using address #65535). This could interrupt the utilities services at that region, like shutting down the electricity services.

10. At this stage, the MTU in the Master Station reports that the application is running normally, while the RTU in the Slave Stations receives tampered frames.

The best way to protect a communications network is the correct and conscious use of cryptographic and authentication suites at the DNP3 Data Link layer in both the master (client) and the slave (server) ends.

7.1.2 SCADA security issues

SCADA security measures consist of physically securing MTUs, RTUs and the media and employing cyber security features such as password protection. Although SCADA MTUs are typically located in a secured facility, RTUs and IEDs may be in unmanned stations secured by barbed wires. Very few communication links have physical security. Cyber security measures might include a dial-up line with a “secret” phone number, using leased lines, RTUs requiring passwords, or using “secret” proprietary protocols instead of using open protocols. However, such measures are weak since a war dialler program can be used to identify the phone numbers that can successfully make a connection with a computer modem, a leased line can be tapped without much effort, passwords are either sent in plaintext of seldom changed, the proprietary protocols provide very little “real” security, and they can be decoded by reverse engineering. Some organizations install firewalls and gateways but they have their own limitations especially that they fail to provide end-to-end (application-to-application) security. A few SCADA protocols have built-in security features in them since they were primarily designed to maximize features such as performance, reliability, robustness and functionality. Security features were either overlooked in favour of these features or

ignored completely since most protocols were designed and developed before the issue of security arises.

7.1.3 Approaches to enhance IEPS- W security

There are several ways and approaches to secure IEPS - W with the use of existing technology. Since this thesis investigates security issues in DNP3, security issues in DNP3 protocol has been identified into three categories:

(1) Solutions that wrap the DNP3 protocols without making changes to the protocols,

(2) Solutions that alter the DNP3 protocols fundamentally, and

(3) Enhancements to the DNP3 application.

The solutions that wrap the protocols include Secure Sockets Layer / Transport Layer Security (SSL/TLS) and Secure IP (IPsec), which would provide a quick and low-cost security enhancement. The solutions that would require altering the DNP3 protocols tend to be more time-consuming to implement and expensive but provide better end-to-end application specific security. Such solutions can either be deployed at either protocol level (“objects security”), or within an application.

7.1.3.1 SSL/TLS Solution

The implementation of SSL/ TLS protocol secures communication channels over TCP/IP. SSL/TLS secures communication between a client and a server by allowing mutual authentication and provides integrity (verifying that the original contents of information have not been altered or corrupted) by using digital signatures and privacy via encryption (transforming data into a form unreadable to everyone except the receiver). The SSL/TLS protocols were specifically designed to protect against both man-in-the-middle and replay attacks. Other SSL/TLS features include error-encryption, data compression and transparency. SSL is well established in areas of Web browser, Web servers and other Internet systems that require security. As more systems connect to Internet and more Internet transactions require security, SSL/TLS's influence will only grow. DNP3 would benefit by going with this prominent and open source SSL/TLS solution that provides critical security features.

In addition to these inherent SSL/TLS benefits, "wrapping" DNP3 with SSL/TLS has the following benefits [120]:

1. SSL/TLS covers the most of necessary components expected at a protocol level.
2. The implementation would be fast, cost-effective and straightforward.
3. The IEC Technical Committee has recently accepted SSL/TLS as a part of a security standard for their communication protocols [123]. This endorsement is noteworthy and relevant especially considering DNP3's similarity with IEC protocol.

However, SSL/TLS solutions are not without limitations. The SSL/TLS protocols have fundamental constrains such as it runs only on a reliable transport protocol such as TCP having higher performance costs associated with it. It is unable to provide non-repudiation service (i.e., assurance that the sender is provided with proof of delivery and that the recipient is provided with proof of the sender's identity so that neither can later deny having processed the data). It can provide only channel security (not object security).

Secondly, the protocols rely on other components such as encryption and signature algorithms. No SSL/TLS implementation can be any stronger than the cryptographic or signature tools on which it is based. In particular, it does not provide protection against an attack based on a traffic analysis. Thirdly, SSL/TLS cannot protect data before it is sent or after it reaches its destination. That is, SSL/TLS cannot be used to store encrypted data on a disk or in a cookie.

Several other open source choices are also available some of which are listed in reference [124]. Considering the advantages and disadvantages of SSL/TLS, it is still the best choice to implement SSL/TLS on DNP3.

7.1.3.2 IPsec (secure IP) Solution

Security can also be provided at the lower layer of the protocol stacks than TCP, such as at the IP level, by securing IP packets (pieces of data divided up for transit). IPsec

operates at a lower level than SSL/TLS does, but provides many of the same security services. Since the security at the lower levels of the stack can account for more traffic, IPsec can secure any TCP or IP traffic as opposed to SSL/TLS securing only the traffic running on TCP. This can be advantageous for capturing some attacks. Particularly, solutions that operate above the Transport Layer, such as SSL/TLS, only prevent arbitrary packets from being inserted into a session. They are unable to prevent a connection reset (denial of service attack) since the connection handling is done by a lower level protocol (i.e., TCP). On the other hand, the Network Layer cryptographic solutions such as IPsec prevents both arbitrary packets entering a Transport-Layer stream and connection resets because connection management is integrated into the secured Network Layer. Additionally, unlike SSL/TLS, IPsec provides security for any traffic between two hosts. This means that once IPsec is installed, all applications gain some security.

IPsec's place in the protocol stacks is also a reason for its limitations. Since IPsec is lower in the stack than SSL/TLS is, it is even more sensitive to interference by intermediaries in the communications channel. So, it is complicated to send encrypted or authenticated data to a machine behind a firewall. Additionally, the lower level protocols provide less flexibility in security. In other words, they fail to provide the exact security that the application needs. For example, they cannot provide advanced features such as non-repudiation. In that regard, the higher-level security measures are preferred to those applied to the lower levels.

SSL/TLS is a compromise between application security (which offers better protection) and IP security (which offers more generality) [125]. Rescorla [125] suggests that if TCP is used for connection, SSL would work better. If only IP is used, it is wise to use IPsec. If communication parties are not directly connected, then it is wise to use application-level security. Considering the criticality of the SCADA networks and low cost of implementations, it will be effective to combine both the solutions: SSL/TLS and IPsec.

7.1.3.3 Protocol enhancements: Object security

As discussed earlier, SSL/TLS provides “channel security” by associating security with the communication channel, independent of the characteristics of the data moving over the channel which is a similar approach used by modems that encrypt data. A different approach to security is to provide security services for data objects which associate security with distinct chunks of data. A server assumes some of the end-to-end duties of the client, including the work of adding and removing security wrappers to the data objects.

In object security, as the data move through each leg of the communication system, associated security information moves with the data. Instead of encrypting the channel, object security sends protected objects over a clear channel. Hence the security mechanism is entirely independent of the details of the communications channels. This approach is sometimes referred to as using a security wrapper [126] and can be implemented in addition to or in lieu of channel security. A disadvantage of this

approach is that since the individual protocol object need to be secured, object security protocols are usually application specific. For example, Secure HTTP (which provides security for HTTP transactions) and S/MIME which provides security for Internet mail messages) are quite different. That is, since security is implemented at higher protocol levels, object security approach is less general than SSL/TLS approach. So, if a SCADA organisation decides to adopt this approach, costly and fundamental modifications to their SCADA/DNP3 application would be required. In return, by applying digital signature and encryption services to DNP3 objects, DNP3 could ensure authentication and non-repudiation of data origin and message integrity by using digitally signed messages and confidentiality (privacy). Data security can be further achieved by using encryption which reduces the risks of eavesdropping, man-in-the-middle and replay attacks.

7.1.3.3.1 Application enhancements

Instead of thorough changes to the DNP3 fundamentals to make it secure, organisations can enhance security by applying standard technologies to DNP3 applications. Even though the work may include tasks such as revising the message formats, making changes in data and control structures, or including authentication and encryption in DNP3, the effort would not be as complex and costly as adding object security and still would provide the end-to-end security at the application level. This approach would provide much better security than that provided by securing the lower

levels (IP or the Transport Layer) by using SSL/TLS or IPsec. This approach does not have to be an all-or-none approach in terms of implementation.

7.1.3.3.2 Message encryption

The only good solution to the threats of eavesdropping and traffic analysis is complete encryption of a protocol stream. Unfortunately, encryption can be very processing-intensive and would not be a good solution for some of the smaller devices currently deploying DNP3 since this would decrease communication speed to a great extent [127]. The will consequently provide communication delay in the system and increases propagation delay significantly.

7.1.3.3.3 Authentication using message authentication object

To detect modification of a transmitted message, an authentication object can be designed which can be appended to each message or to any DNP3 message that required authentication. The DNP Technical Committee has discussed a possibility of such an object called Message Authentication Object (MAO) [127] which has fields for timestamp, nonce, hash-method, length and hash value. It would contain the results of a secure hash function performed on the concatenation of the message and a secret, or password with only the valid sender and receiver knowing the secret. The hash would verify that the message has not been changed in transmission. However, authentication methods exist that are faster and yet can protect against the active threats of spoof,

replay, repudiation and modification. Objects such as MAO will not protect against eavesdropping or traffic analysis. Nevertheless, it can prevent outputs from being incorrectly activated by unauthorised users even if these users have the power to eavesdrop on the network.

7.1.3.3.4 Authentication using Hash Algorithms

Standard hash algorithms provide data integrity assurance and data origin authentication avoiding man-in-the-middle attacks. Per an estimate by DNP3 Technical Committee, a total of 59 to 77 bytes may be needed to be added to every protected message [105]. It was also found that implementing encryption would be a similar amount of work to implement the hash algorithm. However, processing time of encryption versus just hashing may be different.

In that case, it can be chosen to encrypt only the control messages and authenticate all messages. Assuming this data works for all devices and situations, it means that using the MAO on every message does not provide significant processor savings over encrypting the entire stream.

However, using the MAO on selected messages, say only on controls, would still be better than encrypting the complete stream. Even if the DNP3 data should be encrypted, there is still need of an authentication function, for which MAO can be used.

7.1.3.3.5 Other security enhancement approaches

Several additional security enhancements are also being investigated. A “switchboard” architecture [128] for continuous monitoring of the credentials and the trust relationships that were validated at the time the connection was established should be evaluated. Client-server communications that do not monitor connections once they are established are vulnerable to several threats common to prolonged communications. Considering the fact that SCADA connections stay on for extensive periods of time, such enhancements could be valuable augmentation to security. It is advisable to evaluate a secure group layer (SGL) that builds on InterGroup protocols [129] to provide SSL-like security for groups. SGL provides distributed applications with a platform they could use to achieve reliable and secure communication among distributed components.

Finally, more work needs to be done in fundamental security analysis of the SCADA and DNP3 security issues using tools various available tool. Yasinsac and Childs [130] have done some initial work in this direction for general Internet security. However, adding too much security in a power system could increase the propagation delay (which is also critical) for power system. Longer keys provide an increased level of security but at a performance cost.

7.2 Development and implementation of DNPSec for IEPS-W

As discuss in Section 7.2, there are several ways to make IEPS-W secure. However, none of techniques available is strong enough to avoid possible security threat. Hence, it is essential to develop and implement security features in DNP3 itself. DNP3 security (DNPSec) framework is implemented for IEPS-W in order to make DNP3 more secure and reliable so as to enable confidentiality, integrity and authenticity of DNP3 protocol itself. Such framework requires some modifications in the data structure of the DNP3 Data Link layer. This implementation provides enhance security features with a minimum performance impact on the communication link; and without requiring modification to the much more expensive Master Station and Substation devices and the applications supporting them. The framework is built along the lines of the IPSec standards [131-134], but has some unique features to maintain the specifications and the requirements of the DNP3 and SCADA architecture.

7.2.1 DNP3 security (DNPSec) framework

DNPSec authentication and integrity framework capabilities verifies the frame origin which assure that the frame sent is the frame received with additional assurance that the network headers have not changed since the frame was sent, and give anti-replay protection. DNPSec confidentiality framework capability encrypts frames to protect against eavesdropping and hide frame source by applying encryption methods. Some

modifications to the DNP3 LPDU or frame structure are made to provide these capabilities.

Cyclic Redundancy Code (CRC) is a common technique used in DNP3 for detecting data transmission errors. CRCs occupy 34 bytes out of 292 bytes of the DNP3 LPDU for integrity. These bytes are utilised in a different way in the DNPSec framework. There are two main components of the DNPSec. The first is the DNPSec structure to construct the frame and transfer data in secure mode between the Master Station and the Slave RTUs or IEDs.

The second is the key exchange established during the installation and connection setup between the Master and the Salve. DNPSec structure consists of five fields as shown in Figure 7.2 which are the new header, the key sequence number, the original LH header, the payload data, and the authentication data.

The new header is an unsigned 4 bytes field containing the destination address (DA) which occupies 2 bytes; the MH flag bit to recognize if the message is coming from the Primary Master host (0) or from the Secondary Master Host (1); the SK flag bit to indicate to the Slave if the message contains the new session key (1) or to decrypt the message using the session key in the S-keydb (0); and 14 bits reserved.

The key sequence number is an unsigned 4 bytes field containing a counter value that increases by one for each message sent by the Master.

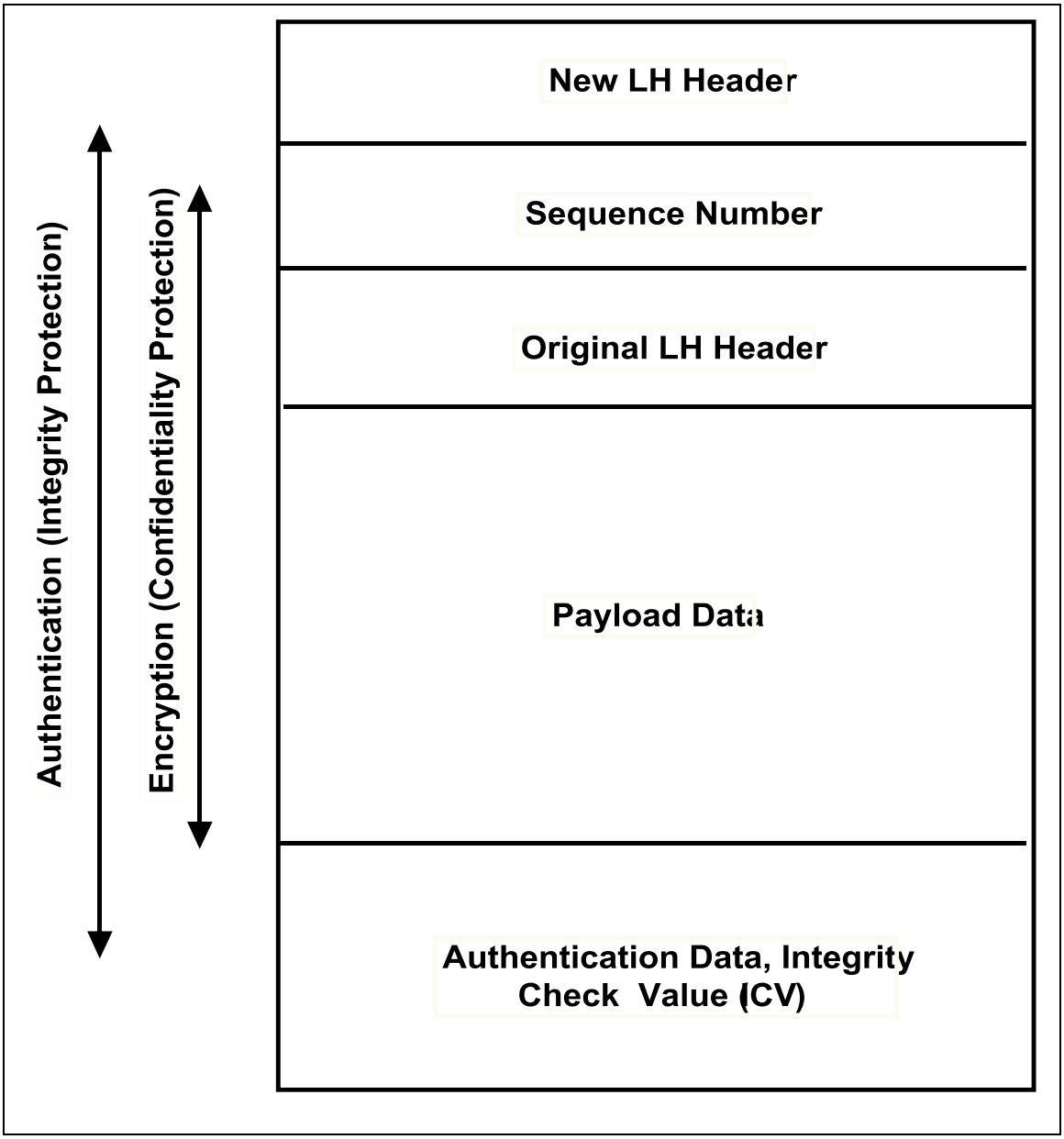


Figure 7.2 DNPSec protocol structure

Each time a Master sends a message it increments the counter by one and places the value in the key sequence number field. Thus, the first value to be used is 1. The Master must not allow the key sequence number to cycle past 232 – 1 back to zero. If

the limit of 232 – 1 is reached, the Master terminates the session key and sends a new key to the Slave using the value zero in the frame sequence number.

This functionality guarantees that the Master and the Slave continues establishing a new session key even if the connection is always open. Moreover, the security policy indicates a new session key is established between the Master and the Slave in case the Slave used the same session key for a certain time period. DNPSec uses the variable key-session-life-time to keep track of the life span of the session key.

The original LH header (DNP3 data link header without the 2 CRCs) and the payload data is protected by encryption and composed of 264 bytes field containing, 8 link protocol data unit header bytes, 250 Transport Protocol Data Unit bytes and 6 padding dummy bytes. 264 bytes is a multiple of 4 bytes, which provides alignment of 4 bytes boundary and provides boundaries of 64 bits to support the encryption algorithms. For example, Data Encryption Standard (DES) specifies that the plaintext is 64 bits in length and the key is 56 bits in length. Longer plaintexts are processed in 64-bit blocks.

The authentication data field containing an Integrity Check Value (ICV) computed over the key sequence number, the original LH header and the payload data fields. ICV provides integrity services and is provided by a specific message authentication algorithm (MAC) such as, HMAC-MD5-96 or HMAC-SHA-1-96.

The integrity algorithm specification specifies the length of the ICV and the comparison rules and processing steps for validation. DNPSec requires 20 bytes for the authentication data field. To simplify the key management process, the Master/Slave encryption/decryption session key is used to calculate the authentication data.

The DNPSec fields are as follows:

0 – 3	**New Header (4 bytes)**	
	DA: 0-1	Destination Address (2 bytes)
	MH: 2(bit 0)	0: Primary Master Host, 1: Secondary Master Host
	SK: 2(bit 1)	0: Fitch the database for the session key, 1: The frame contains a Key Sequence Number (KSN) value from the Master.
	2(bits 2-7)-3	Reserved (2 bytes)
4 – 7	**Key Sequence Number (4 bytes)**	
8 – 15	**Original LH Header (8 bytes)**	
	8 – 9	Sync (2 bytes)
	10 - 10	Length (1 byte)
	11 – 11	Link Control (1 byte)
	12 – 13	Destination Address (2 bytes)
	14 – 15	Source Address
16 – 271	**Payload data (256 bytes)**	
	16 – 265	TPDU data

266 – 271 Padding dummy data

272 – 291 **Authentication Data (20 bytes)**

7.2.2 Key management

The key management operations in DNPSec are very simple to accommodate the static nature of the SCADA environment. They occur during the configuration of the Primary Master host, the Secondary Master host and the Slaves to establish the initial connection between them; after the re-initialization of the KSN to generate and distribute a new key to the hosts; and after the timeout of the usage of the session key.

The Master host generates and manages a secure database “M_Keydb” for the shared session keys with the Slaves. The database consists of four fields: the Slave address used as an index key to the database, the shared session key, the time stamp used to limit the usage of the shared key for a certain pre-defined time period, and the Key Sequence Number. The Master calls “M_GenKey” to generate a unique session key when the old session key expired. “M_PutKey” is the function used to insert the new session key into the database. The M_PutKSN is the function used to insert the new KSN into the database.

The Slave needs to maintain two session keys, one for communicating with the Primary Master host and the other for the Secondary Master host as depicted in Figure 7.3.

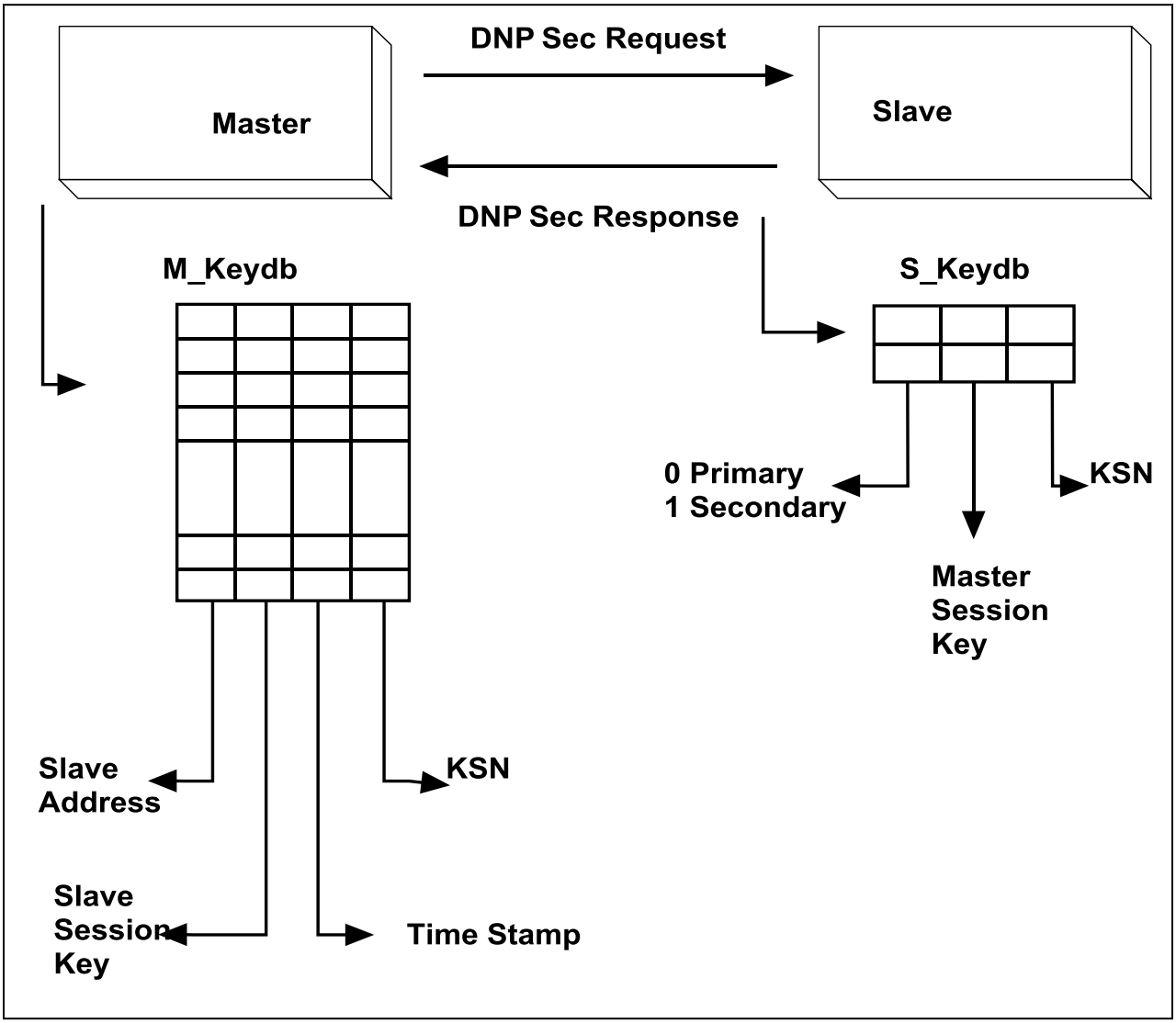


Figure 7.3: DNPSec request / respond link communication

It manages a secure database “S_Keydb” for the shared session keys with the Master hosts. The database consists of three fields and two records: (0, Primary Master Session Key, Key Sequence Number and 1, Secondary Master Session Key, Key Sequence Number).

The simple ”S_PutKey” is the function used to update the database with a new session key and the “S_PutKSN is the function used to update the database with a new KSN.

7.2.3 Analysis of the approach

Reliability and time to delivery of DNP3 frames are very important requirements for SCADA/DNP3 Systems. These requirements are vital to market acceptance of a particular DNP3 security implementation. Reliability, as per DNP Group, is provided by CRC function in the Data Link Layer. CRC is noncryptographic mechanism for detecting transmission errors.

DNPSec added more efficient reliability and security capabilities by introducing cryptographic and authentication capabilities in the DNPSec framework. Such capabilities introduced new challenges related to time to delivery of the frames. DNP3 provides several different means of retrieving data. These methods for retrieving data require different means of efficiency, quiescent and unsolicited report-by-exception operation requires real-time efficiency.

Several performance studies on the effect of cryptography on the set-up time and the delivery of the messages from one end to the other indicate that the delay is not significant based on the advanced technologies in the communication networks, processing power at the end systems and the cryptographic algorithms [135-137].

Kim and Montgomery [138] examined the dynamic behaviour and relative performance characteristics of large scale **virtual private network** (VPN) environments based upon IPSec and Internet key exchange (IKE). The results of their study are summarised in Table 7.1.

Table 7.1: Dynamic behaviour and performance of large scale VPN environments

Operation, Based on 128 bit key	DES	3-DES
Encryption Speed (Kbits/s)	10508 kbits/sec	4178 kbit/sec
Decryption Speed (Kbits/s)	10519 kbits/sec	4173 kbit/sec

Based on the performance information above, the worst case scenario was calculated to measure the time of delivery for the unsolicited message from the Slave to the Master, which required real-time delivery. Although, the numbers are far from exact, they should be usable as a first approximation. The total time to deliver such message is the sum of the encryption speed (ES), the decryption speed (DS), encryption key set up (EK), decryption key set up (DK) and the transmission time (TT).

Unsolicited delivery time = ES + DS + EK + DK + TT

Accordingly, adding the operations above to include cryptographic and authentication operations will not affect the efficiency and the speed of delivery of DNP3 messages.

7.2.4 SCADA / DNP3 over IP

As discussed earlier, several SCADA vendors have successfully implemented SSL/TLS in their applications. The implementation is provided by wrapping DNP3 with SSL/TLS protocols in the transport layer level. For example, Bow Networks eLAN SSL/TLS module is currently available with DNP3 to provide secure communications in SCADA architecture [139]. Also, California Independent System Operator (ISO) in their "Remote Intelligent Gateway (RIG) Technical Specification" recommends the usage of SSL/TLS to their members [140].

SCADA/DNP3 security can also be provided by wrapping DNP3 with Internet Protocol Security (IPSec) in the Network layer. For example, Bow Networks eLAN VPN is currently available to support DNP3 in secure communications. The eLAN VPN is a stand alone application which provides a secure tunnel between two sites at the IP layer. The eLAN VPN solution is based on IPSec [139]. A summary of the advantages and disadvantages of various security enhancement techniques are given in Table 7-2.

Table 7.2: Advantages and Disadvantages of DNPSec (proposed solution), DNP3/IPSec, and DNP3/SSL/TLS architectures

SCADA/DNP 3 Security Solutions	Advantages	Disadvantages
Wrapping DNP3 frame	• The IEC Technical Committee has	• Run only on a reliable

with SSL/TLS	accepted SSL/TLS as part of a security standard for their communication protocol [15] • Freely available for all common OS • Relatively mature	transport protocol (TCP and not for UDP) • High performance cost • No non-repudiation services • Can't protect data before it is sent or after it arrives its destination • Implementation of the protocol required understanding of the application, OS, and its specific system calls • CA are rather expensive and not really compatible with each other
Wrapping DNP3 frame with IPSec	• Protection against DOS • Implemented by Operating Systems, Routers, …etc. • Transparent to applications (below transport layer) • No need to upgrade applications	• Very complex and hard to implement [9] • Higher performance cost • All devices shall support TCP and UDP communications on port number 20000
DNPSec	• End-to-End security at the application level to support any communication link • Protocol is simple	• Required some modification to the DNP3 Data Link Layer • Theoretical approach, needs

	eliminating the complexity of the key exchange and management issues • Implement it once for all communication networks	to proof the concept (in going work)

7.2.5 Implementation of DNPSec in IEPS-W

During the installation of SCADA Systems, a system administrator configures all SCADA units using authentication and cryptographic algorithms as per the Company's policy. Also, a system administrator manually configures each Master/Slave with common session keys. This could be a good solution for the SCADA systems since these systems are relatively static. The Slave is only going to be exchanging data with its predefined Master (Primary or Secondary) and the same is applied to the Master. The database administrator creates M-keydb table with four fields (Slave address, Master-Slave session key, time-stamp, Key-Sequence-Number) in the Primary Master host and the Secondary Master host. The number of records will be equal to the number of Slaves associated with the Master. The database administrator creates S-keydb table in each Slave unit with three fields (Master address, Master-Slave session key, Key-Sequence- Number). Initially, the Key-Sequence-Number will have the value one. Each time the Master sends a message to a Slave, it will increase the Key-Sequence-Number by one. The Slave will not have the privilege to change the Key-Sequence- Number

value. This helps in maintaining the value of the Key-Sequence- Number at the Master level and will give control to the Master to effectively decide when to generate and send a new session key to the Slave.

7.2.5.1 Polling process (Send Request)

The following steps of DNP3Sec have been implemented for the Master to follow in IEPS-W model:

a. Fetch the Slave record from the M_keydb. The Slave address will be the key for the record.

b. If (current-system-time) – (time-stamp) < key-session-life-time

100: {If (232 – 1) > KSN > 0

{

Do (* all frames belong to the same message *)

{DNP3 using DNPSec build the frames from the message;

Encrypt the frame's original LH Header and the Payload

Data using the Master-Slave session key;

Compute the authentication data over the frame's KSN,

Original LH Header, and the Payload Data;

Send frame;

} (* End Do *)

Increment Key-Sequence-Number by 1;

M_PutKSN (Slave-Address, new KSN value);

}

Else (* key session expired – exceeds number of transmissions *)

{Call M_GenKey(new-key);

Send a message to the Slave with the new key,

KSN = 0, and requesting confirmation message;

Wait for confirmation message;

M_PutKey (Slave-Address, new key);

M_PutKSN (Slave-Address, KSN=1);

Go-To 100;

}

Else (* key session expired – time out *)

{Call M_GenKey(new-key);

Send a message to the Slave with the new key,

KSN = 0, and requesting confirmation message;

Wait for confirmation message;

M_PutKey (Slave-Address, new key);

M_PutTime (Slave-Address, current-system-time);

M_PutKSN (Slave-Address, KSN=1);

Go-To 100;

}

7.2.5.2 Polling process (Receive response)

Accordingly, the Master will follow these rules:

a. Fetch the Slave record from the M-keydb. The Slave address will be the key for the record.

b. While receiving all frames of same message

{Decrypt the frame using the Master-Slave session key;

Calculate and validate the authentication data;

Process the data;

}

If (current-system-time) – (time-stamp) < key-session-life-time

{If (232 – 1) > KSN > 0

{Increment KSN by 1;

M_PutKSN (Slave-Address, new KSN value);

Send a message to the Slave with the

KSN new value and SK = 1;

}

Else (* key session expired – exceeds number of transmissions *)

{Call M_GenKey(new-key);

Send a message to the Slave with the new key,

KSN = 0, and requesting confirmation message;

Wait for confirmation message;

M_PutKey (Slave-Address, new key);

M_PutKSN (Slave-Address, KSN=1);

}

Else (* key session expired – time out *)

{Call M_GenKey(new-key);

Send a message to the Slave with the new key,

KSN = 0, and requesting confirmation message;

Wait for confirmation message;

M_PutKey (Slave-Address, new key);

M_PutTime (Slave-Address, current-system-time);

M_PutKSN (Slave-Address, KSN=1);

}

7.2.5.3 Polling process (Accepting/processing request)

The Slave will follow these steps:

a. If (Key-Sequence-Number < > 0)

{S_GetKey(MH, current-key); (* get the key from S_Keydb *)

Decrypt all frames with the same sequence number;

Calculate and validate the authentication data;

Process the request;

S_PutKSN(MH, KSN);

}

Else (* Master sending new key or KSN to the Slave *)

{If (KSN =0) and (SK = 0) (* new key *)

S_GetKey(MH, current-key);

Decrypt the frame using the current key;

Calculate and validate the authentication value;

S_PutKey(MH, first 64 bits of the payload); (* assuming the key

size is 64 bits *)

S_PutKSN(MH, KSN=1);

Send confirmation message to Master;

}

Else (* new KSN from the Master *)

S_PutKSN(MH, KSN);

7.2.5.4 Polling process (Responding Process)

The Slave will follow these steps:

a. S_GetKey(MH, current-key)

S_GetKSN(MH, KSN)

Build the frame using the application data and the information above;

Encrypt the original header and the payload data;

Calculate the authentication value;

Build the frame;

Send the frame;

The time of retrieving data from the Slave or the time the Slave needs to send unsolicited messages to the Master does not significantly delay by the implementation of DNPSec.

The implementation of DNP3Sec at the data link layer of DNP3 has made IEPS-W more secure and reliable compared to other security technology which has been discussed earlier.

A proper analysis was carried out after implementing DNPSec in IEPS-W. For the DNPSec implementation in IEPS-W model, the size of the DNPSec message is 292 bytes while the network bandwidth is 1.5 Mbps.

As the main concern of this thesis is achieving less propagation delay, further analysis was carried to investigate the effect of data added with the addition of DNPsec. Table 7.3 shows the performance of each operation:

Table 7.3: The performance of DNPSec implementation in IEPS-W model

Operation	Performance	Time
Encryption Speed	4178 kbits/sec	0.00007 sec
Decryption Speed	4173 kbits/sec	0.00007 sec
Transmission Time	1.5 Mbit/sec	0.0002 sec

As seen in Table 7.2, the addition of DNPSec in IEPS-W does not adversely affect overall performance. However, it improves the security of the protocol.

Moreover, DNPSec protects the frames between the Master and the Slaves as follows: only the Master and the Slave can read the content of the frames exchanged. A message sent from Master to Slave cannot be changed in transit (assuring integrity of the data exchanged). Master and Slave authenticate each other to make sure Master is truly Master (rather than the Intruder).

In this process, a copy of the session keys is stored in the Master and all Slaves to ensure protection against man-in-the-middle-attacks. When the session key expires (frame sequence number reaches 232 – 1 or the time period using the same key reached), the Master sends a new session key to the Slave encrypted with the previous session key and the attacker cannot recover the session key without the previous session key.

7.3 Conclusion

DNP3 was not designed with security capabilities in mind. The SCADA vendors can build such capabilities by utilising the DNPSec framework with a minimum time and cost without a major impact on the systems components and the application supporting them.

This Chapter has discussed the implementation of DNPSec framework in IEPS-W. It has also discussed how DNPSec works, and provided elaborate analysis to the approach. The framework enables confidentiality, integrity and authenticity in the DNP3. Such a framework requires some enhancements in the data structure of the DNP3 Data Link layer, without requiring modification to the Master Station and Substation devices and the applications supporting them. Confidentiality and integrity are achieved by encrypting frames between the Master and the Slaves using a common session key. This was proven with simulation work carried out in this work after implementation of DNPSec in IEPS-W.

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

8.0 Introduction

This Chapter details with the major findings and accomplishments of this work and how the work has addressed the aims proposed in Chapter 1. It also presents the conclusions that are drawn from the findings as well as its limitations. Future research directions are also outlined in this Chapter.

Power utilities operate more and more globally and require flexible, future-proof communication systems to cope with changing operational requirements, philosophies and technologies. Furthermore, power system deregulation brings broader reliance on information systems and telecommunication network to share the critical and non-critical data. Large amount of critical data are shared between various utilities and among utilities. Due to this significant changes in the power system industry, information embedded power system via wide area network (IEPS-W) is essential to accurately and effectively monitor, control and use telecommunication facilities for the efficient power system operation.

This thesis examined how communication delays in delivering power system measurements across WAN can affect the accuracy of these measurements when power system employs DNP3 protocol as its communication backbone for SCADA network. Large amounts of data traffic may result in large measurement errors in the data network and temporarily render part of the power system unobservable due to significant traffic delays.

In this thesis, research on the experimental analysis and development of IEPS-W has been presented. The thesis has addressed major challenges and several key issues related to DNP3 protocol including security issues when power system employs DNP3 protocol over WAN. Performance characteristic of DNP3 over WAN was carried out through experimental analysis and followed by the development of an efficient and secure IEPS-W model.

Major findings of this thesis, results and novel ideas have been reported in related publications in the 'List of Publications' section of this thesis. Section 8.2 of this Chapter presents a general overview of the specific tasks carried out to achieve the successful completion of this research and describes how the accomplished work has addressed the aims outlined in Chapter 1. Last of all, Section 8.3 details the future research directions and possible future works that can be applied to the study described in this thesis.

8.1 Summary and achievements of the research

Communication requirement for modern power system along with the impact of IT on power system monitoring, protection and control was discussed in Chapter 2. Various power system communications protocol was also investigated in Chapter 2, which helped to comprehend mechanism involve in power system communication controls. Detail study on SCADA system, which is one of the significant components of power system communication infrastructure, provided insight into SCADA system.

One of the primary objectives of this work is to develop efficient and secure IEPS-W for modern power system. The details elaboration of IEPS-W was made in Chapter 3. As the main focus of this work is to investigate power system communication protocol particularly DNP3 protocol for IEPS-W, details study on various power system communication protocols helped to understand critical role play by power system communication protocol in the SCADA environment.

The research in this work was carried out in two major streams. The first part which is discussed in Chapter 4 is to experimentally analyse the performance characteristic and propagation delays associated in DNP3 protocol when data were sent from RTUs to control centre via WAN. Detailed experimental analysis on DNP3 over WAN has given significant result and performance characteristic of DNP3 protocol. The real life experiment was carried out in different communication traffic and major discovery was made which guides to develop DNP3 further. The experimental result showed that

DNP3 over WAN has significant propagation delay which could lead to major failure in power system due to its possible data traffic increase in the power system network.

Major work in this thesis is presented in Chapter 5 on the development of DNP3 protocol based on the experimental analysis performed. OPNET modeller was used to develop DNP3 protocol. Each layer of DNP3 protocol was developed in OPNET environment to further enhance the DNP3 protocol to efficiently use over WAN for modern power system. Vital platform was created using OPNET modeller to further develop DNP3 protocol.

Significant achievement on DNP3 protocol was presented in Chapter 6. After successful development of DNP3 protocol in OPNET modeller, further work was carried out to enhance DNP3 protocol in order to provide less propagation delay. Desirable and reliable result was obtained from the development process. The newly developed DNP3 protocol now has significantly low propagation delay which makes IEPS-W more attractive and effective.

Security is a major concern in modern power system as it employs WAN to transmit critical and non critical data. Various security issues and solutions have been discussed in Chapter 7. After investigating all the security measures, DNPSec has been implemented in IEPS-W which makes it more secure and reliable.

Finally, the research carried out in this work has specifically achieved the followings:

1. The performance characteristic and propagation delay of DNP3 over WAN was practically investigated through purposely built real life experiment by using industry base transmission facilities, equipments and precise SCADA networking technologies. This has provided comprehensive result and understanding on the performance characteristic of DNP3 protocol. The propagation delay obtained from the experiment provides concrete platform to develop more efficient and reliable IEPS-W model based on DNP3.

2. The development and implementation of each layer of DNP3 protocol in OPNET modeller is a pioneering engineering achievement accomplished in this work as this provides a permanent solution to carry further research and development in improving DNP3 protocol using OPNET modeller.

3. After discovering significant propagation delays associated in DNP3 over WAN from the purpose built experiment, a more reliable and efficient IEPS-W was developed which has considerably less propagation delay that is acceptable by power industry. The newly developed model is capable of handling high volume of traffic and transmits high priority critical data efficiently from the large volume of data in the SCADA network.

4. Power system security issues were thoroughly examined in this work as security is a major concern for utility. A powerful and robust security technique was

developed at the DNP3 data link year. This accomplishes the gap remains in the power system security issues.

8.3 Future work

The experimental work carried out in this research was base on one RTU directly transmitting data to the control room via WAN as discussed in Chapter 4. In this research, RTU was located at Richmond Terminal Station while control room was positioned at Victoria Network Switching Centre. It is not physically possible for a power utility to use single RTU to transmit critical data. In reality, there are hundreds of RTUs and IEDs directly connected to control centre SACDA network via either WAN or dedicated link. The experimental platform was specifically designed to perform this research work as DNP3 protocol was not in use in SP AusNet network when the experiment was carried out.

The following further research works are required in extension to this work:

1. A more real time broader experimental analysis must be carried out on power system communication protocols before adopting to the network to study performance characteristic of power system communication protocols. The experimental platform must consist of considerable numbers of IEDs and RTUs so as to provide a realistic outcome of the experiment. Random traffic present on WAN can cause delays in delivering vital control commands to devices

present in SCADA network. Thus, the state of the computer network can have a large impact on the operation of the power system.

2. Furthermore, the experimental work should also be carried out when the power system network is merged with the co-operate network in order to study the effect of such infrastructure. In practical, most utilities combine SACDA and co-operate network to reduce the cost. However, this could bring unexpected consequences when there is significant delay in the power network. Further research is required in this scenario and made a dedicated pathway for SCADA critical data.

3. As DNP3 protocol was not originally developed to be used in WAN, significant attention is required to enhance the message structure of DNP3 protocol especially on application layer. Further research is required in this direction.

4. Security is major concern particularly when utility employs WAN to transmit its critical data as WAN is susceptible to the hackers. Currently available security technology is not sufficient and strong enough to counter the risk associated with it. The existing security measures are dedicated to lower level such as TCP/IP and data link layer. Significant research direction is required to look at application layer based security features which will make IEPS-W more secure and reliable.

5. Large amount of data propagate across SCADA network and co-operate network in power system. Further research work is required to develop more competent and economic power system communication model so that utility avoids any catastrophic failure due to ineffective power system model.

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APPENDIX A

EXPERIMENTAL DATA

As presented in Chapter 4, this work carried out real time experimental analysis using SP AusNet transmission and SCADA network facilities to investigate the performance and propagation delays associated in DNP3 protocol over WAN. The details experimental result is presented in the following sections.

A.1 Experimental data for 10% data traffic

The details experimental result is presented in Table A -1 for 10% data traffic in the network when data was sent from a RTU to the Control centre using DNP3 protocol over WAN. The total time delay is shown in the Table. There are many more data collected, however few only are presented as samples.

Table A - 1: Experiment data for 10% data normal traffic (DNP3_WAN_TCP/IP)

Send	Receive	Total Time Delay
15:20:56.829	15:20:56.851	0:00:00.022
15:20:58.939	15:20:58.961	0:00:00.022
15:21:01.049	15:21:01.068	0:00:00.019
15:21:03.156	15:21:03.177	0:00:00.021
15:21:05.266	15:21:05.287	0:00:00.021
15:21:07.373	15:21:07.394	0:00:00.021

15:21:09.483	15:21:09.501	0:00:00.018
15:21:11.593	15:21:11.615	0:00:00.022
15:21:13.702	15:21:13.723	0:00:00.021
15:21:15.811	15:21:15.825	0:00:00.014
15:21:17.920	15:21:17.946	0:00:00.026
15:21:20.029	15:21:20.042	0:00:00.013
15:21:22.139	15:21:22.156	0:00:00.017
15:21:24.249	15:21:24.267	0:00:00.018
15:21:26.359	15:21:26.394	0:00:00.035
15:21:28.465	15:21:28.486	0:00:00.021
15:21:30.575	15:21:30.580	0:00:00.005
15:21:32.686	15:21:32.709	0:00:00.023
15:21:34.796	15:21:34.821	0:00:00.025
15:21:36.905	15:21:36.921	0:00:00.016
15:21:39.015	15:21:39.039	0:00:00.024
15:21:41.125	15:21:41.137	0:00:00.012
15:21:43.235	15:21:43.256	0:00:00.021
15:21:45.344	15:21:45.385	0:00:00.041
15:21:47.454	15:21:47.478	0:00:00.024
15:21:49.564	15:21:49.585	0:00:00.021
15:21:51.673	15:21:51.696	0:00:00.023
15:21:53.783	15:21:53.804	0:00:00.021
15:21:55.893	15:21:55.913	0:00:00.020
15:21:58.001	15:21:58.019	0:00:00.018
15:22:00.110	15:22:00.134	0:00:00.024
15:22:02.220	15:22:02.236	0:00:00.016
15:22:04.330	15:22:04.339	0:00:00.009
15:22:06.440	15:22:06.461	0:00:00.021
15:22:08.549	15:22:08.716	0:00:00.167
15:22:10.659	15:22:10.678	0:00:00.019
15:22:12.769	15:22:12.789	0:00:00.020
15:22:14.878	15:22:15.035	0:00:00.157
15:22:16.988	15:22:17.008	0:00:00.020
15:22:19.098	15:22:19.105	0:00:00.007
15:22:21.206	15:22:21.214	0:00:00.008
15:22:23.317	15:22:23.337	0:00:00.020
15:22:25.424	15:22:25.444	0:00:00.020
15:22:27.534	15:22:27.555	0:00:00.021
15:22:29.641	15:22:29.654	0:00:00.013

15:22:31.751	15:22:31.771	0:00:00.020
15:22:33.861	15:22:33.874	0:00:00.013
15:22:35.972	15:22:35.989	0:00:00.017
15:22:38.081	15:22:38.095	0:00:00.014
15:22:40.191	15:22:40.210	0:00:00.019
15:22:42.301	15:22:42.323	0:00:00.022
15:22:44.411	15:22:44.428	0:00:00.017
15:22:46.521	15:22:46.539	0:00:00.018
15:22:48.631	15:22:48.644	0:00:00.013
15:22:50.741	15:22:50.759	0:00:00.018
15:22:52.851	15:22:52.873	0:00:00.022
15:22:54.960	15:22:54.971	0:00:00.011
15:22:57.067	15:22:57.078	0:00:00.011
15:22:59.178	15:22:59.186	0:00:00.008
15:23:01.284	15:23:01.295	0:00:00.011
15:23:03.394	15:23:03.413	0:00:00.019
15:23:05.504	15:23:05.517	0:00:00.013
15:23:07.614	15:23:07.624	0:00:00.010
15:23:09.723	15:23:09.742	0:00:00.019
15:23:11.232	15:23:11.849	0:00:00.617
15:23:13.943	15:23:13.948	0:00:00.005
15:23:16.053	15:23:17.068	0:00:01.015
15:23:18.162	15:23:18.176	0:00:00.014
15:23:20.272	15:23:20.288	0:00:00.016
15:23:22.382	15:23:22.414	0:00:00.032
15:23:24.491	15:23:24.507	0:00:00.016
15:23:26.598	15:23:26.605	0:00:00.007
15:23:28.708	15:23:28.732	0:00:00.024
15:23:30.818	15:23:30.839	0:00:00.021
15:23:32.927	15:23:32.948	0:00:00.021
15:23:35.037	15:23:35.057	0:00:00.020
15:23:37.147	15:23:37.170	0:00:00.023
15:23:39.254	15:23:39.270	0:00:00.016
15:23:41.363	15:23:41.382	0:00:00.019
15:23:43.474	15:23:43.492	0:00:00.018
15:23:45.584	15:23:45.596	0:00:00.012
15:23:47.692	15:23:47.695	0:00:00.003
15:23:49.801	15:23:49.818	0:00:00.017
15:23:51.911	15:23:51.927	0:00:00.016

15:23:54.021	15:23:54.039	0:00:00.018
15:23:56.130	15:23:56.152	0:00:00.022
15:23:58.240	15:23:58.262	0:00:00.022
15:24:00.350	15:24:00.376	0:00:00.026
15:24:02.460	15:24:02.478	0:00:00.018
15:24:04.569	15:24:04.592	0:00:00.023
15:24:06.676	15:24:06.695	0:00:00.019
15:24:08.786	15:24:08.803	0:00:00.017
15:24:10.893	15:24:10.914	0:00:00.021
15:24:13.002	15:24:13.026	0:00:00.024
15:24:15.112	15:24:15.133	0:00:00.021
15:24:17.222	15:24:17.244	0:00:00.022
15:24:19.331	15:24:19.355	0:00:00.024
15:24:21.441	15:24:21.463	0:00:00.022
15:24:23.551	15:24:23.564	0:00:00.013
15:24:25.659	15:24:25.674	0:00:00.015
15:24:27.768	15:24:27.789	0:00:00.021
15:24:29.875	15:24:29.893	0:00:00.018
15:24:31.985	15:24:32.001	0:00:00.016
15:24:34.095	15:24:34.116	0:00:00.021
15:24:36.204	15:24:36.225	0:00:00.021
15:24:38.311	15:24:38.333	0:00:00.022
15:24:40.421	15:24:40.439	0:00:00.018
15:24:42.527	15:24:42.552	0:00:00.025
15:24:44.637	15:24:44.664	0:00:00.027
15:24:46.747	15:24:46.760	0:00:00.013
15:24:48.857	15:24:48.879	0:00:00.022
15:24:50.966	15:24:50.975	0:00:00.009
15:24:53.076	15:24:53.087	0:00:00.011
15:24:55.186	15:24:55.202	0:00:00.016
15:24:57.296	15:24:57.314	0:00:00.018
15:24:59.405	15:24:59.418	0:00:00.013
15:25:01.512	15:25:01.533	0:00:00.021
15:25:03.622	15:25:03.641	0:00:00.019
15:25:05.728	15:25:05.750	0:00:00.022
15:25:07.838	15:25:07.857	0:00:00.019
15:25:09.945	15:25:09.965	0:00:00.020
15:25:12.055	15:25:12.074	0:00:00.019
15:25:14.161	15:25:14.180	0:00:00.019

15:25:16.271	15:25:16.278	0:00:00.007
15:25:18.381	15:25:18.399	0:00:00.018
15:25:20.491	15:25:20.505	0:00:00.014
15:25:22.011	15:25:22.600	0:00:00.589
15:25:24.711	15:25:24.732	0:00:00.021
15:25:26.821	15:25:26.843	0:00:00.022
15:25:28.930	15:25:28.953	0:00:00.023
15:25:31.037	15:25:31.046	0:00:00.009
15:25:33.147	15:25:33.167	0:00:00.020
15:25:35.255	15:25:35.276	0:00:00.021
15:25:37.364	15:25:37.388	0:00:00.024
15:25:39.471	15:25:39.494	0:00:00.023
15:25:41.581	15:25:41.604	0:00:00.023
15:25:43.688	15:25:43.734	0:00:00.046
15:25:45.798	15:25:45.806	0:00:00.008
15:25:47.908	15:25:47.917	0:00:00.009
15:25:50.018	15:25:50.037	0:00:00.019
15:25:52.127	15:25:52.149	0:00:00.022
15:25:54.237	15:25:54.257	0:00:00.020
15:25:56.344	15:25:56.368	0:00:00.024
15:25:58.454	15:25:58.476	0:00:00.022
15:26:00.560	15:26:00.575	0:00:00.015
15:26:02.670	15:26:02.689	0:00:00.019
15:26:04.780	15:26:04.802	0:00:00.022
15:26:06.890	15:26:06.910	0:00:00.020

A.2 Experimental data for 20% data traffic

The details experimental result is presented in Table A - 2 for 20% data traffic in the network when data was sent from RTU to Control centre using DNP3 protocol over WAN. The total time delay is shown in the Table. There are many more data collected, however few only are presented as samples.

Table A - 2: Experiment data for 20% traffic increased (DNP3_WAN_TCP/IP)

Send	Receive	Total Time Delay
11:35:10.014	11:35:10.033	0:00:00.019
11:35:10.014	11:35:10.526	0:00:00.512
11:35:12.281	11:35:12.296	0:00:00.015
11:35:14.547	11:35:14.565	0:00:00.018
11:35:16.922	11:35:16.941	0:00:00.019
11:35:19.188	11:35:19.208	0:00:00.020
11:35:21.454	11:35:21.476	0:00:00.022
11:35:23.721	11:35:23.738	0:00:00.017
11:35:25.987	11:35:26.006	0:00:00.019
11:35:28.253	11:35:28.272	0:00:00.019
11:35:30.520	11:35:30.534	0:00:00.014
11:35:32.858	11:35:32.883	0:00:00.025
11:35:35.135	11:35:35.158	0:00:00.023
11:35:37.427	11:35:37.443	0:00:00.016
11:35:39.693	11:35:39.714	0:00:00.021
11:35:41.960	11:35:41.981	0:00:00.021
11:35:44.226	11:35:44.248	0:00:00.022
11:35:46.493	11:35:46.514	0:00:00.021
11:35:48.759	11:35:48.783	0:00:00.024
11:35:51.025	11:35:51.046	0:00:00.021
11:35:53.292	11:35:53.303	0:00:00.011
11:35:55.558	11:35:55.577	0:00:00.019
11:35:57.824	11:35:57.842	0:00:00.018
11:36:00.091	11:36:00.110	0:00:00.019
11:36:02.357	11:36:02.379	0:00:00.022
11:36:04.624	11:36:04.647	0:00:00.023
11:36:06.890	11:36:06.914	0:00:00.024
11:36:09.156	11:36:09.182	0:00:00.026
11:36:11.423	11:36:11.444	0:00:00.021
11:36:13.689	11:36:13.707	0:00:00.018
11:36:15.955	11:36:15.976	0:00:00.021
11:36:18.222	11:36:18.238	0:00:00.016
11:36:20.488	11:36:20.507	0:00:00.019

11:36:22.755	11:36:22.774	0:00:00.019
11:36:25.021	11:36:25.037	0:00:00.016
11:36:27.287	11:36:27.303	0:00:00.016
11:36:29.554	11:36:29.576	0:00:00.022
11:36:31.821	11:36:31.837	0:00:00.016
11:36:34.087	11:36:34.105	0:00:00.018
11:36:36.353	11:36:36.388	0:00:00.035
11:36:38.619	11:36:38.633	0:00:00.014
11:36:40.886	11:36:40.909	0:00:00.023
11:36:43.152	11:36:43.171	0:00:00.019
11:36:45.418	11:36:45.442	0:00:00.024
11:36:47.685	11:36:47.708	0:00:00.023
11:36:49.951	11:36:49.975	0:00:00.024
11:36:52.218	11:36:52.237	0:00:00.019
11:36:54.484	11:36:54.566	0:00:00.082
11:36:56.804	11:36:56.827	0:00:00.023
11:36:59.053	11:36:59.070	0:00:00.017
11:37:01.319	11:37:01.339	0:00:00.020
11:37:03.586	11:37:03.605	0:00:00.019
11:37:05.852	11:37:05.875	0:00:00.023
11:37:08.118	11:37:08.135	0:00:00.017
11:37:10.385	11:37:10.396	0:00:00.011
11:37:12.651	11:37:12.674	0:00:00.023
11:37:14.917	11:37:14.941	0:00:00.024
11:37:17.184	11:37:17.207	0:00:00.023
11:37:19.450	11:37:19.505	0:00:00.055
11:37:21.717	11:37:21.735	0:00:00.018
11:37:23.983	11:37:24.002	0:00:00.019
11:37:26.249	11:37:26.271	0:00:00.022
11:37:28.516	11:37:28.551	0:00:00.035
11:37:30.782	11:37:30.801	0:00:00.019
11:37:33.049	11:37:33.065	0:00:00.016
11:37:35.315	11:37:35.338	0:00:00.023
11:37:37.582	11:37:37.602	0:00:00.020
11:37:39.848	11:37:39.869	0:00:00.021
11:37:42.114	11:37:42.137	0:00:00.023
11:37:44.381	11:37:44.399	0:00:00.018
11:37:46.647	11:37:46.664	0:00:00.017
11:37:48.913	11:37:48.939	0:00:00.026

11:37:51.180	11:37:51.202	0:00:00.022
11:37:53.446	11:37:53.469	0:00:00.023
11:37:55.712	11:37:55.725	0:00:00.013
11:37:57.979	11:37:57.994	0:00:00.015
11:38:00.245	11:38:00.268	0:00:00.023
11:38:02.512	11:38:02.534	0:00:00.022
11:38:04.778	11:38:04.801	0:00:00.023
11:38:07.044	11:38:07.057	0:00:00.013
11:38:09.320	11:38:09.341	0:00:00.021
11:38:11.586	11:38:11.609	0:00:00.023
11:38:13.853	11:38:13.878	0:00:00.025
11:38:16.119	11:38:16.142	0:00:00.023
11:38:18.385	11:38:18.402	0:00:00.017
11:38:20.652	11:38:20.671	0:00:00.019
11:38:22.918	11:38:22.938	0:00:00.020
11:38:25.185	11:38:25.212	0:00:00.027
11:38:27.451	11:38:27.472	0:00:00.021
11:38:29.717	11:38:29.740	0:00:00.023
11:38:31.984	11:38:32.007	0:00:00.023
11:38:34.250	11:38:34.270	0:00:00.020
11:38:38.783	11:38:38.804	0:00:00.021
11:38:41.049	11:38:41.067	0:00:00.018
11:38:43.316	11:38:43.330	0:00:00.014
11:38:45.582	11:38:45.601	0:00:00.019
11:38:47.848	11:38:47.903	0:00:00.055
11:38:50.115	11:38:50.139	0:00:00.024
11:38:52.381	11:38:52.425	0:00:00.044
11:38:54.648	11:38:54.667	0:00:00.019
11:38:56.914	11:38:56.938	0:00:00.024
11:38:59.180	11:38:59.200	0:00:00.020
11:39:01.447	11:39:01.470	0:00:00.023
11:39:03.713	11:39:03.738	0:00:00.025
11:39:05.979	11:39:06.001	0:00:00.022
11:39:08.246	11:39:08.266	0:00:00.020
11:39:10.512	11:39:10.527	0:00:00.015
11:39:12.779	11:39:12.800	0:00:00.021

11:39:15.045	11:39:15.067	0:00:00.022
11:39:17.311	11:39:17.334	0:00:00.023
11:39:19.578	11:39:19.595	0:00:00.017
11:39:21.844	11:39:21.862	0:00:00.018
11:39:24.111	11:39:24.130	0:00:00.019
11:39:26.377	11:39:26.400	0:00:00.023
11:39:28.643	11:39:28.670	0:00:00.027
11:39:30.910	11:39:30.939	0:00:00.029
11:39:33.176	11:39:33.189	0:00:00.013
11:39:35.443	11:39:35.468	0:00:00.025
11:39:37.709	11:39:37.723	0:00:00.014
11:39:39.975	11:39:39.995	0:00:00.020
11:39:42.242	11:39:42.293	0:00:00.051
11:39:44.508	11:39:44.528	0:00:00.020
11:39:46.775	11:39:46.795	0:00:00.020
11:39:49.041	11:39:49.063	0:00:00.022
11:39:51.307	11:39:51.327	0:00:00.020
11:39:53.574	11:39:53.590	0:00:00.016
11:39:55.840	11:39:55.859	0:00:00.019
11:39:58.106	11:39:58.123	0:00:00.017
11:40:00.373	11:40:00.392	0:00:00.019
11:40:02.639	11:40:02.660	0:00:00.021
11:40:04.906	11:40:04.920	0:00:00.014
11:40:07.172	11:40:07.193	0:00:00.021
11:40:09.438	11:40:09.448	0:00:00.010
11:40:11.705	11:40:11.715	0:00:00.010
11:40:13.971	11:40:13.992	0:00:00.021
11:40:16.237	11:40:16.257	0:00:00.020
11:40:18.504	11:40:18.520	0:00:00.016
11:40:20.770	11:40:20.797	0:00:00.027
11:40:23.037	11:40:23.058	0:00:00.021

11:40:25.303	11:40:25.324	0:00:00.021
11:40:27.569	11:40:27.584	0:00:00.015
11:40:29.836	11:40:29.858	0:00:00.022
11:40:32.102	11:40:32.130	0:00:00.028
11:40:34.369	11:40:34.397	0:00:00.028
11:40:36.635	11:40:36.659	0:00:00.024
11:40:38.901	11:40:38.919	0:00:00.018
11:40:41.168	11:40:41.188	0:00:00.020
11:40:43.434	11:40:43.456	0:00:00.022
11:40:45.701	11:40:45.718	0:00:00.017
11:40:47.967	11:40:47.986	0:00:00.019
11:40:50.233	11:40:50.253	0:00:00.020
11:40:52.500	11:40:52.521	0:00:00.021
11:40:54.766	11:40:54.794	0:00:00.028
11:40:57.032	11:40:57.042	0:00:00.010
11:40:59.299	11:40:59.318	0:00:00.019
11:41:01.565	11:41:01.590	0:00:00.025
11:41:03.832	11:41:03.854	0:00:00.022
11:41:06.098	11:41:06.121	0:00:00.023
11:41:08.364	11:41:08.384	0:00:00.020
11:41:10.631	11:41:10.644	0:00:00.013
11:41:12.897	11:41:12.920	0:00:00.023
11:41:15.164	11:41:15.184	0:00:00.020
11:41:17.430	11:41:17.456	0:00:00.026
11:41:19.696	11:41:19.717	0:00:00.021
11:41:21.963	11:41:21.980	0:00:00.017
11:41:24.229	11:41:24.249	0:00:00.020
11:41:26.495	11:41:26.508	0:00:00.013
11:41:28.762	11:41:28.781	0:00:00.019
11:41:31.028	11:41:31.050	0:00:00.022
11:41:33.295	11:41:33.310	0:00:00.015

11:41:35.561	11:41:35.586	0:00:00.025
11:41:37.827	11:41:37.842	0:00:00.015
11:41:40.094	11:41:40.105	0:00:00.011
11:41:42.360	11:41:42.381	0:00:00.021
11:41:44.627	11:41:44.656	0:00:00.029
11:41:46.893	11:41:46.918	0:00:00.025
11:41:49.159	11:41:49.175	0:00:00.016
11:41:51.426	11:41:51.449	0:00:00.023
11:41:53.692	11:41:53.715	0:00:00.023
11:41:55.959	11:41:55.975	0:00:00.016
11:41:58.225	11:41:58.245	0:00:00.020
11:42:00.491	11:42:00.513	0:00:00.022
11:42:02.758	11:42:02.779	0:00:00.021
11:42:05.033	11:42:05.052	0:00:00.019
11:42:07.310	11:42:07.333	0:00:00.023
11:42:11.843	11:42:11.867	0:00:00.024
11:42:14.108	11:42:14.130	0:00:00.022
11:42:16.376	11:42:16.395	0:00:00.019
11:42:18.640	11:42:18.661	0:00:00.021
11:42:20.908	11:42:20.929	0:00:00.021
11:42:23.173	11:42:23.195	0:00:00.022
11:42:25.442	11:42:25.464	0:00:00.022
11:42:27.706	11:42:27.725	0:00:00.019
11:42:29.974	11:42:29.998	0:00:00.024
11:42:32.239	11:42:32.259	0:00:00.020
11:42:34.507	11:42:34.526	0:00:00.019
11:42:36.772	11:42:36.790	0:00:00.018
11:42:39.040	11:42:39.081	0:00:00.041
11:42:41.304	11:42:41.330	0:00:00.026
11:42:43.572	11:42:43.585	0:00:00.013
11:42:45.837	11:42:45.856	0:00:00.019

11:42:48.105	11:42:48.122	0:00:00.017
11:42:50.370	11:42:50.388	0:00:00.018
11:42:52.638	11:42:52.657	0:00:00.019

A.3 Experimental data for 40% data traffic

The details experimental result is presented in Table A - 3 for 40% data traffic in the network when data was sent from RTU to Control centre using DNP3 protocol over WAN. The total time delay is shown in the table. There are many more data collected, however few only are presented as samples.

Table A - 3: Experiment data for 40% traffic increased (DNP3_WAN_TCP/IP)

Send	Receive	Total Time Delay
12:55:41.098	12:55:41.109	0:00:00.011
12:55:43.365	12:55:43.384	0:00:00.019
12:55:49.732	12:55:49.755	0:00:00.023
12:55:54.049	12:55:54.070	0:00:00.021
12:55:57.936	12:55:57.963	0:00:00.027
12:56:01.928	12:56:01.944	0:00:00.016
12:56:04.194	12:56:04.215	0:00:00.021
12:56:07.000	12:56:07.013	0:00:00.013
12:56:09.267	12:56:09.290	0:00:00.023
12:56:11.964	12:56:11.985	0:00:00.021
12:56:14.231	12:56:14.251	0:00:00.020

12:56:16.713	12:56:16.740	0:00:00.027
12:56:20.922	12:56:20.973	0:00:00.051
12:56:25.131	12:56:25.151	0:00:00.020
12:56:27.398	12:56:27.412	0:00:00.014
12:56:29.664	12:56:29.677	0:00:00.013
12:56:33.010	12:56:33.027	0:00:00.017
12:56:35.276	12:56:35.296	0:00:00.020
12:56:37.974	12:56:37.997	0:00:00.023
12:56:41.967	12:56:41.990	0:00:00.023
12:56:44.234	12:56:44.252	0:00:00.018
12:56:46.500	12:56:46.522	0:00:00.022
12:56:50.169	12:56:50.188	0:00:00.019
12:56:52.436	12:56:52.446	0:00:00.010
12:56:54.702	12:56:54.713	0:00:00.011
12:56:56.968	12:56:56.987	0:00:00.019
12:56:59.235	12:56:59.246	0:00:00.011
12:57:01.501	12:57:01.521	0:00:00.020
12:57:03.768	12:57:03.798	0:00:00.030
12:57:06.034	12:57:06.058	0:00:00.024
12:57:08.301	12:57:08.325	0:00:00.024
12:57:10.567	12:57:10.585	0:00:00.018
12:57:12.833	12:57:12.852	0:00:00.019
12:57:15.100	12:57:15.116	0:00:00.016
12:57:17.366	12:57:17.374	0:00:00.008
12:57:19.634	12:57:19.651	0:00:00.017
12:57:21.899	12:57:21.923	0:00:00.024
12:57:24.165	12:57:24.187	0:00:00.022
12:57:26.442	12:57:26.457	0:00:00.015
12:57:28.707	12:57:28.730	0:00:00.023
12:57:30.975	12:57:31.000	0:00:00.025
12:57:33.240	12:57:33.268	0:00:00.028

12:57:35.534	12:57:35.546	0:00:00.012
12:57:37.800	12:57:37.821	0:00:00.021
12:57:40.066	12:57:40.083	0:00:00.017
12:57:42.333	12:57:42.356	0:00:00.023
12:57:44.599	12:57:44.618	0:00:00.019
12:57:46.865	12:57:46.892	0:00:00.027
12:57:49.140	12:57:49.160	0:00:00.020
12:57:51.407	12:57:51.425	0:00:00.018
12:57:53.675	12:57:53.697	0:00:00.022
12:57:55.957	12:57:55.979	0:00:00.022
12:57:58.242	12:57:58.262	0:00:00.020
12:58:00.634	12:58:00.657	0:00:00.023
12:58:02.901	12:58:02.920	0:00:00.019
12:58:05.167	12:58:05.190	0:00:00.023
12:58:07.433	12:58:07.457	0:00:00.024
12:58:09.700	12:58:09.711	0:00:00.011
12:58:11.966	12:58:11.987	0:00:00.021
12:58:14.233	12:58:14.237	0:00:00.004
12:58:16.499	12:58:16.514	0:00:00.015
12:58:18.766	12:58:18.785	0:00:00.019
12:58:21.032	12:58:21.056	0:00:00.024
12:58:23.298	12:58:23.321	0:00:00.023
12:58:25.564	12:58:25.592	0:00:00.028
12:58:27.831	12:58:27.853	0:00:00.022
12:58:30.097	12:58:30.110	0:00:00.013
12:58:32.364	12:58:32.379	0:00:00.015
12:58:34.630	12:58:34.657	0:00:00.027
12:58:36.896	12:58:36.918	0:00:00.022
12:58:39.163	12:58:39.181	0:00:00.018
12:58:41.429	12:58:41.447	0:00:00.018
12:58:43.696	12:58:43.714	0:00:00.018

12:58:45.962	12:58:45.984	0:00:00.022
12:58:48.228	12:58:48.247	0:00:00.019
12:58:50.495	12:58:50.522	0:00:00.027
12:58:52.761	12:58:52.782	0:00:00.021
12:58:55.028	12:58:55.053	0:00:00.025
12:58:57.294	12:58:57.321	0:00:00.027
12:58:59.560	12:58:59.575	0:00:00.015
12:59:01.827	12:59:01.850	0:00:00.023
12:59:04.093	12:59:04.113	0:00:00.020
12:59:06.360	12:59:06.377	0:00:00.017
12:59:08.626	12:59:08.647	0:00:00.021
12:59:10.892	12:59:10.910	0:00:00.018
12:59:13.159	12:59:13.186	0:00:00.027
12:59:15.425	12:59:15.452	0:00:00.027
12:59:17.691	12:59:17.712	0:00:00.021
12:59:19.958	12:59:19.982	0:00:00.024
12:59:22.224	12:59:22.377	0:00:00.153
12:59:24.491	12:59:24.511	0:00:00.020
12:59:26.757	12:59:26.781	0:00:00.024
12:59:29.023	12:59:29.049	0:00:00.026
12:59:31.290	12:59:31.303	0:00:00.013
12:59:33.556	12:59:33.575	0:00:00.019
12:59:35.822	12:59:35.843	0:00:00.021
12:59:38.089	12:59:38.108	0:00:00.019
12:59:40.355	12:59:40.368	0:00:00.013
12:59:42.622	12:59:42.646	0:00:00.024

A.3 Experimental data for 60% data traffic

The details experimental result is presented in Table A - 4 for 60% data traffic in the network when data was sent from RTU to Control centre using DNP3 protocol over WAN. The total time delay is shown in the table. There are many more data collected, however few only are presented as samples.

Table A - 4: Experiment data for 60% traffic increased (DNP3_WAN_TCP/IP)

Send	Receive	Total Time Delay
12:59:44.888	12:59:44.904	0:00:00.016
12:59:47.155	12:59:47.186	0:00:00.031
12:59:49.421	12:59:49.441	0:00:00.020
12:59:51.687	12:59:51.711	0:00:00.024
12:59:53.954	12:59:53.975	0:00:00.021
12:59:56.220	12:59:56.239	0:00:00.019
12:59:58.486	12:59:58.509	0:00:00.023
12:00:00.753	12:00:00.770	0:00:00.017
13:00:03.019	13:00:03.044	0:00:00.025
13:00:05.286	13:00:05.303	0:00:00.017
13:00:07.552	13:00:07.576	0:00:00.024
13:00:09.818	13:00:09.833	0:00:00.015
13:00:12.085	13:00:12.109	0:00:00.024
13:00:14.351	13:00:14.373	0:00:00.022
13:00:16.617	13:00:16.641	0:00:00.024
13:00:18.884	13:00:18.906	0:00:00.022
13:00:21.150	13:00:21.178	0:00:00.028

13:00:23.417	13:00:23.442	0:00:00.025
13:00:25.683	13:00:25.692	0:00:00.009
13:00:27.949	13:00:27.973	0:00:00.024
13:00:30.216	13:00:30.237	0:00:00.021
13:00:32.482	13:00:32.501	0:00:00.019
13:00:34.749	13:00:34.773	0:00:00.024
13:00:37.015	13:00:37.033	0:00:00.018
13:00:39.281	13:00:39.294	0:00:00.013
13:00:41.548	13:00:41.579	0:00:00.031
13:00:43.814	13:00:43.830	0:00:00.016
13:00:46.080	13:00:46.106	0:00:00.026
13:00:48.347	13:00:48.366	0:00:00.019
13:00:50.613	13:00:50.641	0:00:00.028
13:00:52.880	13:00:52.901	0:00:00.021
13:00:55.146	13:00:55.170	0:00:00.024
13:00:57.412	13:00:57.435	0:00:00.023
13:00:59.679	13:00:59.706	0:00:00.027
13:01:01.945	13:01:01.972	0:00:00.027
13:01:04.212	13:01:04.219	0:00:00.007
13:01:06.478	13:01:06.498	0:00:00.020
13:01:08.744	13:01:08.755	0:00:00.011
13:01:11.011	13:01:11.029	0:00:00.018
13:01:13.277	13:01:13.299	0:00:00.022
13:01:15.544	13:01:15.568	0:00:00.024
13:01:17.810	13:01:17.830	0:00:00.020
13:01:20.076	13:01:20.094	0:00:00.018
13:01:22.343	13:01:22.365	0:00:00.022
13:01:24.609	13:01:24.635	0:00:00.026
13:01:26.875	13:01:26.894	0:00:00.019
13:01:29.142	13:01:29.159	0:00:00.017
13:01:31.408	13:01:31.426	0:00:00.018

13:01:33.675	13:01:33.698	0:00:00.023
13:01:35.941	13:01:35.964	0:00:00.023
13:01:38.207	13:01:38.230	0:00:00.023
13:01:40.474	13:01:40.487	0:00:00.013
13:01:42.740	13:01:42.750	0:00:00.010
13:01:45.007	13:01:45.022	0:00:00.015
13:01:47.273	13:01:47.305	0:00:00.032
13:01:49.541	13:01:49.565	0:00:00.024
13:01:51.806	13:01:51.828	0:00:00.022
13:01:54.072	13:01:54.091	0:00:00.019
13:01:56.339	13:01:56.353	0:00:00.014
13:01:58.605	13:01:58.623	0:00:00.018
13:02:00.871	13:02:00.891	0:00:00.020
13:02:03.138	13:02:03.159	0:00:00.021
13:02:05.404	13:02:05.425	0:00:00.021
13:02:07.670	13:02:07.697	0:00:00.027
13:02:09.937	13:02:09.961	0:00:00.024
13:02:12.203	13:02:12.219	0:00:00.016
13:02:14.470	13:02:14.490	0:00:00.020
13:02:16.736	13:02:16.754	0:00:00.018
13:02:19.002	13:02:19.019	0:00:00.017
13:02:21.269	13:02:21.294	0:00:00.025
13:02:23.535	13:02:23.552	0:00:00.017
13:02:25.802	13:02:25.827	0:00:00.025
13:02:28.068	13:02:28.090	0:00:00.022
13:02:30.334	13:02:30.365	0:00:00.031
13:02:32.601	13:02:32.621	0:00:00.020
13:02:34.867	13:02:34.884	0:00:00.017
13:02:37.133	13:02:37.150	0:00:00.017
13:02:39.400	13:02:39.419	0:00:00.019
13:02:41.666	13:02:41.691	0:00:00.025

13:02:43.933	13:02:43.953	0:00:00.020
13:02:46.199	13:02:46.211	0:00:00.012
13:02:48.465	13:02:48.489	0:00:00.024
13:02:50.732	13:02:50.751	0:00:00.019
13:02:52.998	13:02:53.018	0:00:00.020
13:02:55.265	13:02:55.286	0:00:00.021
13:02:57.531	13:02:57.552	0:00:00.021
13:02:59.797	13:02:59.818	0:00:00.021
13:03:02.064	13:03:02.084	0:00:00.020
13:03:04.333	13:03:04.346	0:00:00.013
13:03:06.606	13:03:06.628	0:00:00.022
13:03:08.872	13:03:08.896	0:00:00.024
13:03:11.138	13:03:11.157	0:00:00.019
13:03:13.405	13:03:13.426	0:00:00.021
13:03:15.671	13:03:15.690	0:00:00.019
13:03:17.938	13:03:17.959	0:00:00.021
13:03:20.204	13:03:20.227	0:00:00.023
13:03:22.470	13:03:22.492	0:00:00.022
13:03:24.737	13:03:24.763	0:00:00.026
13:03:27.004	13:03:27.025	0:00:00.021
13:03:29.278	13:03:29.300	0:00:00.022
13:03:31.545	13:03:31.563	0:00:00.018
13:03:33.811	13:03:33.837	0:00:00.026
13:03:36.078	13:03:36.093	0:00:00.015
13:03:38.344	13:03:38.368	0:00:00.024

A.5 Experimental data for 80% data traffic

The details experimental result is presented in Table A - 5 for 80% data traffic in the network when data was sent from RTU to Control centre using DNP3 protocol over WAN. The total time delay is shown in the table. There are many more data collected, however few only are presented as samples.

Table A - 5: Experiment data for 80% traffic increased (DNP3_WAN_TCP/IP)

Send	Receive	Total Time Delay
9:38:49.839	9:38:49.864	0:00:00.025
9:38:52.105	9:38:52.137	0:00:00.032
9:38:54.374	9:38:54.387	0:00:00.013
9:38:56.638	9:38:56.656	0:00:00.018
9:38:58.904	9:38:58.923	0:00:00.019
9:39:01.171	9:39:01.185	0:00:00.014
9:39:03.437	9:39:03.458	0:00:00.021
9:39:05.704	9:39:05.725	0:00:00.021
9:39:07.970	9:39:07.992	0:00:00.022
9:39:10.236	9:39:10.254	0:00:00.018
9:39:12.503	9:39:12.524	0:00:00.021
9:39:14.769	9:39:14.788	0:00:00.019
9:39:17.036	9:39:17.051	0:00:00.015
9:39:19.302	9:39:19.325	0:00:00.023
9:39:21.568	9:39:21.583	0:00:00.015
9:39:23.835	9:39:23.851	0:00:00.016
9:39:26.101	9:39:26.125	0:00:00.024
9:39:28.367	9:39:28.385	0:00:00.018
9:39:30.634	9:39:30.657	0:00:00.023

9:39:32.900	9:39:32.925	0:00:00.025
9:39:35.167	9:39:35.189	0:00:00.022
9:39:37.433	9:39:37.449	0:00:00.016
9:39:39.700	9:39:39.712	0:00:00.012
9:39:41.966	9:39:41.990	0:00:00.024
9:39:44.232	9:39:44.257	0:00:00.025
9:39:46.499	9:39:46.519	0:00:00.020
9:39:48.765	9:39:48.787	0:00:00.022
9:39:51.031	9:39:51.044	0:00:00.013
9:39:53.298	9:39:53.328	0:00:00.030
9:39:57.831	9:39:57.842	0:00:00.011
9:40:00.097	9:40:00.122	0:00:00.025
9:40:02.363	9:40:02.395	0:00:00.032
9:40:04.630	9:40:04.640	0:00:00.010
9:40:06.896	9:40:06.922	0:00:00.026
9:40:09.162	9:40:09.182	0:00:00.020
9:40:11.429	9:40:11.450	0:00:00.021
9:40:13.695	9:40:13.707	0:00:00.012
9:40:15.962	9:40:15.983	0:00:00.021
9:40:18.228	9:40:18.252	0:00:00.024
9:40:20.494	9:40:20.536	0:00:00.042
9:40:22.761	9:40:22.783	0:00:00.022
9:40:25.027	9:40:25.046	0:00:00.019
9:40:27.294	9:40:27.319	0:00:00.025
9:40:29.560	9:40:29.593	0:00:00.033
9:40:31.827	9:40:31.845	0:00:00.018
9:40:34.093	9:40:34.108	0:00:00.015
9:40:36.359	9:40:36.381	0:00:00.022
9:40:38.625	9:40:38.645	0:00:00.020
9:40:40.892	9:40:40.911	0:00:00.019
9:40:43.158	9:40:43.169	0:00:00.011

9:40:45.425	9:40:45.436	0:00:00.011
9:40:47.691	9:40:47.710	0:00:00.019
9:40:49.957	9:40:49.977	0:00:00.020
9:40:52.224	9:40:52.247	0:00:00.023
9:40:54.490	9:40:54.511	0:00:00.021
9:40:56.757	9:40:56.778	0:00:00.021
9:40:59.023	9:40:59.051	0:00:00.028
9:41:01.289	9:41:01.308	0:00:00.019
9:41:03.556	9:41:03.584	0:00:00.028
9:41:05.822	9:41:05.847	0:00:00.025
9:41:08.089	9:41:08.109	0:00:00.020
9:41:10.355	9:41:10.363	0:00:00.008
9:41:12.621	9:41:12.642	0:00:00.021
9:41:14.888	9:41:14.909	0:00:00.021
9:41:17.154	9:41:17.174	0:00:00.020
9:41:19.420	9:41:19.442	0:00:00.022
9:41:21.687	9:41:21.710	0:00:00.023
9:41:23.953	9:41:23.972	0:00:00.019
9:41:26.220	9:41:26.239	0:00:00.019
9:41:28.486	9:41:28.507	0:00:00.021
9:41:30.752	9:41:30.773	0:00:00.021
9:41:33.019	9:41:33.040	0:00:00.021
9:41:35.285	9:41:35.314	0:00:00.029
9:41:37.552	9:41:37.567	0:00:00.015
9:41:39.818	9:41:39.837	0:00:00.019
9:41:42.084	9:41:42.111	0:00:00.027
9:41:44.351	9:41:44.374	0:00:00.023
9:41:46.617	9:41:46.638	0:00:00.021
9:41:48.883	9:41:48.921	0:00:00.038
9:41:51.150	9:41:51.180	0:00:00.030
9:41:53.416	9:41:53.438	0:00:00.022

9:41:55.683	9:41:55.703	0:00:00.020
9:41:57.949	9:41:57.970	0:00:00.021
9:42:00.215	9:42:00.234	0:00:00.019
9:42:02.482	9:42:02.500	0:00:00.018
9:42:04.748	9:42:04.774	0:00:00.026
9:42:07.015	9:42:07.022	0:00:00.007
9:42:09.281	9:42:09.303	0:00:00.022
9:42:11.547	9:42:11.561	0:00:00.014
9:42:13.814	9:42:13.833	0:00:00.019
9:42:16.080	9:42:16.100	0:00:00.020
9:42:18.347	9:42:18.363	0:00:00.016
9:42:20.613	9:42:20.631	0:00:00.018
9:42:22.879	9:42:22.901	0:00:00.022
9:42:25.146	9:42:25.167	0:00:00.021
9:42:27.412	9:42:27.439	0:00:00.027
9:42:29.679	9:42:29.696	0:00:00.017
9:42:31.945	9:42:31.969	0:00:00.024
9:42:34.212	9:42:34.236	0:00:00.024
9:42:36.478	9:42:36.496	0:00:00.018
9:42:38.744	9:42:38.756	0:00:00.012
9:42:41.010	9:42:41.033	0:00:00.023
9:42:43.277	9:42:43.296	0:00:00.019
9:42:45.543	9:42:45.554	0:00:00.011
9:42:47.810	9:42:47.831	0:00:00.021
9:42:50.076	9:42:50.101	0:00:00.025
9:42:52.342	9:42:52.365	0:00:00.023
9:42:54.609	9:42:54.632	0:00:00.023
9:42:56.875	9:42:56.889	0:00:00.014
9:42:59.142	9:42:59.166	0:00:00.024
9:43:01.408	9:43:01.427	0:00:00.019
9:43:03.674	9:43:03.697	0:00:00.023

9:43:05.941	9:43:05.956	0:00:00.015
9:43:08.207	9:43:08.229	0:00:00.022
9:43:10.474	9:43:10.486	0:00:00.012
9:43:12.740	9:43:12.766	0:00:00.026
9:43:15.006	9:43:15.026	0:00:00.020
9:43:17.273	9:43:17.294	0:00:00.021
9:43:19.539	9:43:19.553	0:00:00.014
9:43:21.805	9:43:21.826	0:00:00.021
9:43:24.072	9:43:24.096	0:00:00.024
9:43:26.338	9:43:26.377	0:00:00.039
9:43:28.605	9:43:28.623	0:00:00.018
9:43:30.871	9:43:30.889	0:00:00.018
9:43:33.137	9:43:33.154	0:00:00.017
9:43:35.404	9:43:35.421	0:00:00.017
9:43:37.670	9:43:37.683	0:00:00.013
9:43:39.936	9:43:39.951	0:00:00.015
9:43:42.203	9:43:42.217	0:00:00.014
9:43:44.469	9:43:44.492	0:00:00.023
9:43:46.736	9:43:46.748	0:00:00.012
9:43:49.002	9:43:49.028	0:00:00.026
9:43:51.268	9:43:51.290	0:00:00.022
9:43:53.535	9:43:53.555	0:00:00.020
9:43:55.801	9:43:55.820	0:00:00.019
9:43:58.068	9:43:58.090	0:00:00.022
9:44:00.334	9:44:00.350	0:00:00.016
9:44:02.601	9:44:02.620	0:00:00.019
9:44:04.867	9:44:04.879	0:00:00.012
9:44:07.133	9:44:07.146	0:00:00.013
9:44:09.400	9:44:09.423	0:00:00.023
9:44:11.666	9:44:11.697	0:00:00.031
9:44:13.932	9:44:13.956	0:00:00.024

9:44:16.199	9:44:16.221	0:00:00.022
9:44:18.465	9:44:18.480	0:00:00.015
9:44:20.731	9:44:20.771	0:00:00.040
9:44:22.998	9:44:23.011	0:00:00.013
9:44:25.264	9:44:25.277	0:00:00.013
9:44:27.531	9:44:27.552	0:00:00.021

APPENDIX B
DETAILED FUNCTION CODE PROCEDURES

As discussed in Chapter 5, the detailed functions codes procedure contains implementation information, rules and recommendations [118]. The implementation information, rules and recommendations for each of the function codes are adopted and implemented in IEPS-W.

B.1.1 Function Code 0 – Confirm

A master sends a message with this function code to confirm receipt of a response fragment. An Application Layer confirmation message is a very brief message. It consists of the application control octet and the function code octet. There are no object headers or DNP3 object octets. Masters only send confirmation messages when outstation requests them. An outstation requests the master to confirm the receipt of a fragment by setting the CON bit in the application control header. A master is obligated to confirm messages that it receives with the CON bit set in the application control header.

B.1.2 Function Code 1 (0x01) - Read

The READ function code is the basic code used by a master to request data from an outstation. The object headers in the request specify which data the master desires and/or how many objects and sometimes what format to use in the response. A request message contains more than one object header, thereby effectively combining several requests into a single message.

Responses contain zero, one or more object headers; each object header is followed by its respective DNP3 objects. The general formats of read request and response messages are shown below. A single fragment response is assumed as shown in Figure B-1.

►►► Request Message											
	AC	FC	OH_0	OH_1	• • •	OH_n					

◄◄◄ Response Message (beginning)											
	AC	FC	$IIN_{1,2}$	OH_0	DIO_{00}	DIO_{01}	• • •	DIO_{0i}	OH_1	DIO_{10}	DIO_{11}

◄◄◄ Continuation of Response Message											
	• • •	DIO_{1j}	• • •	OH_n	DIO_{n0}	DIO_{n1}	• • •	DIO_{nk}			

Figure B-1: Single fragment response

where:

AC is the Application Control octet.

FC is the Function Code octet.

$IIN_{1,2}$ represents the Internal Indication octets.

OH_x is the xth Object Header (shown shaded).

DIO_{xy} is the yth Data Information Object associated with the xth object header.

The rules for the function READ are as follows:

Rule 1 If an outstation is waiting for an Application Layer confirmation to a previously transmitted **solicited response** message (because the master requested a ***READ***), and instead it receives a new request of any kind, the outstation:

- Assume the confirmation is not forthcoming.
- Retain the event data.
- Cancel the previous transaction.
- Process and respond to the new request as if there were no Application Layer confirmation outstanding.

This ensures that control operations and other vital functions receive priority over pending read operations. It also guarantees that the master retains control over polling sequences.

Rule 2 An outstation must delay formulation and transmission of a response when it receives a request having a READ function code while awaiting an Application Layer confirmation to a previously transmitted unsolicited response message. This requirement is necessary to prevent the outstation from prematurely removing events from its buffers.

Rule 3 Only the events requested return in a response. For example, if only class 1 and class 2 events are requested; the outstation may not include class 3 events in the response.

Rule 4 An event should be reported only once within a response. If an event happens to meet the criteria appearing in two or more request objects, only once the event is reported and it is not duplicated.

Rule 5 If event data is requested, the outstation must place it in the response ahead of any static data values that were also requested in the same request. Requests to read non-event data should be processed in the order of the object headers and object prefixes appearing in the request.

Rule 6 A master must process each DNP3 object returned in a response in the order that it appears in the received fragment. This causes the sequence of changes appearing in the master's database to correspond to the sequence order observed in the field, and the final state of each database point will contain the most recently occurring event state.

An example is given in Figure B-2 which shows a tiny fraction of all possible READ requests and responses; their purpose is to illustrate various features of the protocol. Only enough details of the actual DNP3 objects are given in the examples to help the reader understand the concepts.

This example shows a request for the static analog values from indexes 4 through 7 returned as a 16-bit value with a flag octet.

►►► Request Message											
	C3	01	1E	02	00	04	07				
	AC	FC	Grp	Var	Qual	Range					

◄◄◄ Response Message (beginning)											
	C3	81	00	00	1E	02	00	04	07	01	88
	AC	FC	IIN_1	IIN_2	Grp	Var	Qual	Range		Flg_4	LSB_4
										←	DIO_4

◄◄◄ Continuation of Response Message											
	13	01	20	4E	01	50	FB	01	60	00	
	MSB_4	Flg_5	LSB_5	MSB_5	Flg_6	LSB_6	MSB_6	Flg_7	LSB_7	MSB_7	
	→	←	DIO_5	→	←	DIO_6	→	←	DIO_7	→	

Figure B-2: Illustration of READ function code

B.3 Function Code 2 (0x02) – WRITE

The WRITE function code is complementary to the READ function code. Writing copies the contents of DNP3 objects from the master to the outstation. The object headers in the request specify which objects the master desires to write. The respective data information objects follow each object header. The general formats of WRITE request and response messages are shown in Figure B-3

►►► Request Message (beginning)											
	AC	FC	OH_0	DIO_0	DIO_1	• • •	DIO_i	OH_1	DIO_0	DIO_1	• • •

◄◄◄ Continuation of Request Message											
	DIO_j	• • •	OH_n	DIO_0	DIO_1	• • •	DIO_k				

◄◄◄ Response Message											
	AC	FC	$IIN_{1,2}$								

Figure B-3: Formats of WRITE request

where:

AC is the Application Control octet.

FC is the Function Code octet.

$IIN_{1,2}$ represents the Internal Indication octets.

OH_x is the xth Object Header (These are shown shaded).

DIO_x is the xth Data Information Object.

Masters does not retry WRITE request messages at either the Application or Data Link layers for time synchronization where the messages contain either an Absolute Time object, or a Last Recorded Time object. Figure B-4 provides an example for WRITE function shows a master clearing an outstation's IIN1.7 [DEVICE_RESTART] bit.

►►► Request Message											
	C3	02	50	01	00	07	07	00			
	AC	FC	Grp	Var	Qual	Start	Stop	Value			
						Range					

◄◄◄ Response Message											
	C3	81	00	00							
	AC	FC	IIN_1	IIN_2							

Figure B-4: Example of WRITE function code

B.4 Function Codes 3 (0x03) *and* 4 (0x04) - SELECT *and* OPERATE

The SELECT function code is used in conjunction with the OPERATE function code as part of the two-step, select-before-operate method for issuing control requests. This procedure is used for controlling binary and analog outputs. Requests with these function codes contain one or more objects that describe the desired output state or level. An outstation's SELECT and OPERATE responses contain the identical set of

object headers and objects, and in the same order as it appears in the master's request, unless the outstation determines an error condition exists.

B.4.1 SELECT- OPERATE philosophy

The general SELECT-OPERATE procedure is for the master to first send a SELECT request containing all of the necessary parameters, such as indexes, timings and values. The SELECT response from the outstation contains object headers and objects that exactly match those in the request. The master compares the SELECT response with the request, and if they match exactly, then the master issues an OPERATE command with identical object set of headers and objects that it sent in the SELECT message. This approach assures, with miniscule probability of error, that the outstation understands which control the master intended. There are two verifications during a complete, two-step procedure:

- The master must receive a SELECT response that matches the request, and that response must indicate no errors; otherwise, the master must abort the control.
- The outstation is obligated to compare the OPERATE request with the SELECT request, and only if the two match, and if there are no errors detected in the request, should it activate the outputs.

B.4.2 Multiple control objects

SELECT and OPERATE requests may contain multiple objects if the outstation supports having multiple control objects in the same request. For example, it is

permissible to send two or more Control Relay Output Blocks (CROBs), in SELECT and OPERATE messages or two or more analog output blocks (AOBs).

B4.2.1 CROBs and AOBs

Whenever the master sends select-operate commands with multiple objects, it is intended that the outstation will execute them expeditiously. The master must not assume the points will be executed simultaneously or in sequential order as the implementation details are private to the outstation. While some outstations may be capable of executing the controls simultaneously, others cannot and will queue the objects for execution one-after-the-other. Outstations are not required to support more than one DNP3 control object per request message.

B.4.2.2 Pattern control blocks and masks

If the master desires simultaneous execution of controls, it should use Pattern Control Block (PCB) and Pattern Mask (PM) objects respectively. There is no guarantee that multiple controls will execute simultaneously unless a PCB and PM are used and the outstation supports this type of operation. Outstations are not required to implement PCB or PMP.

B.4.2.3 Control-related rules

Rule 1 A master must compare all of the octets following the two IIN (Internal Indications) octets in the SELECT response with all of the octets following the function code octet in the request. If

- the octets do not match exactly,
- the status code returned in any object is non-zero,
- IIN bit 2.0 [NO_FUNC_CODE_SUPPORT] is set,
- IIN bit 2.1 [OBJECT_UNKNOWN] is set,
- IIN bit 2.2 [PARAMETER_ERROR] is set,
- IIN bit 2.4 [ALREADY_EXECUTING] is set, then the master shall not issue the matching OPERATE command.

Rule 2 An outstation must compare all of the octets following the function code octet in the OPERATE request with all of the octets following the function code octet in the SELECT request. If the octets do not match exactly, then the outstation shall not activate any of the outputs specified in either the SELECT or the OPERATE message.

Rule 3 If an outstation returns a non-zero error code in any object in its response to a SELECT request, it shall consider the select invalid.

Rule 4 For the sake of backward compatibility with less strict DNP3 requirements prior to version 2.00, the outstation has two options if a master illegally issues an OPERATE command after receiving an outstation's SELECT response in

which the response had missing objects, non-zero status codes or IIN bits 2-0, 2-1, 2-2 or 2-4 set. The outstation may:

- Choose to ignore the request and not operate any of the outputs.
- Execute those points for which it returned objects with a zero status code.

The outstation's behaviour is not guaranteed when the master violates rule 1 above.

Rule 5 Outstations shall start a selection timer upon receipt of a valid select request. If that timer expires before the outstation receives a valid OPERATE request, the outstation shall immediately terminate the selection.

Rule 6 If a selection is in effect at the outstation, upon receipt of the next request, the outstation shall perform the action as listed in Table B-1depending upon the function code and sequence number in the application control octet.

Rule 7 When multiple control objects are included in a SELECT and OPERATE messages, the outstation has the option to stop parsing the remainder of a request upon detection of the first error or continuing to the end of the request.

Rule 8 When an outstation receives a SELECT and OPERATE request, and operations to one or more of the points specified by the objects in the request are unsuccessful, its response shall include one of these

- No DNP3 objects if the request contains an unsupported function code or object variation.
- All of the DNP3 objects.

- Objects for all of the points up to and including the first unsuccessful point. This is called a “truncated response”.

Rule 9 Each DNP3 object returned in the response shall contain the appropriate status code indication. The IIN bits 2.0, 2.1, 2.2 and 2.4 shall be set or cleared as applicable. The IIN bits only need to reflect the state of the first error detected.

The example in Figure B-5 shows SELECT- OPERATE messages for a Control Relay Output Block (CROB).

The example in Figure B.5 shows SELECT- OPERATE messages for a Control Relay Output Block (CROB). In the first exchange, the master sends a request with the SELECT function code.

Keys for understanding Table B-1.

N is sequence number from *SEQ* field in application control octet of the original selection message.

!= means “Not Equal To”; e.g., !=N means the sequence number is not equal to N.

Table B-1: Action to perform with next request following a Select Request

Next Request Contains			Outstation Action
Request Function Code	Sequence Number modulo 16	Octets in the message following the function code octet match those in the original select request.	
SELECT	N	Yes	This is a valid retry. Repeat the response to the original ***select*** request – do not restart the selection timer.
SELECT	N	No	Discard fragment. Take no further action.
SELECT	!=N	No	This is a new selection that overrides the current selection. Terminate the original selection, initiate a new selection, restart selection timer.
OPERATE	N + 1	Yes	Check for other errors or other discrepancies, and if none are found, initiate the control execution.
OPERATE	N + 1	No	Non-matching octets. Terminate original selection and perform no control action.
OPERATE	!=(N + 1)	Don't Care	Improper sequence number. Terminate original selection and perform no control action.
Neither SELECT nor OPERATE	Don't Care	Don't Care	Operate did not follow select. Terminate original selection and perform no control action.

►►► **Select** Request Message (beginning)											
	C3	03	0C	01	17	01	0A	41	01	FA	00
	AC	FC	Grp	Var	Qual	Range	Prefix	←			CROB

►►► Continuation of **Select** Request Message											
	00	00	00	00	00	00	00				
	CROB continued						→				

◄◄◄ **Select** Response Message (beginning)											
	C3	81	00	00	0C	01	17	01	0A	41	01
	AC	FC	IIN_1	IIN_2	Grp	Var	Qual	Range	Prefix	←	

◄◄◄ Continuation of **Select** Response Message											
	FA	00	00	00	00	00	00	00	00		
	CROB								→		

►►► **Operate** Request Message (beginning)											
	C4	04	0C	01	17	01	0A	41	01	FA	00
	AC	FC	Grp	Var	Qual	Range	Prefix	←			CROB

►►► Continuation of **Operate** Request Message											
	00	00	00	00	00	00	00				
	CROB continued						→				

◄◄◄ **Operate** Response Message (beginning)											
	C4	81	00	00	0C	01	17	01	0A	41	01
	AC	FC	IIN_1	IIN_2	Grp	Var	Qual	Range	Prefix	←	

◄◄◄ Continuation of **Operate** Response Message											
	FA	00	00	00	00	00	00	00	00		
	CROB								→		

Figure B-5: SELECT- OPERATE messages for CROB

The octets in SELECT response message after the IIN octets match the octets in the SELECT request after the function code. This is the expected response, therefore, the master may send an OPERATE request message.

The OPERATE request message is almost identical to the SELECT message, except the sequence number in the application control octet is incremented by one, and the function code is OPERATE. The outstation must compare the OPERATE and SELECT messages, and if all of the octets following the function code octets match, it is permitted to actuate the output.

Table B-2 shows example responses from Control Relay Output Block or analog output requests containing four objects. These objects are identified as A, B, C and D. The responses are identical for requests having the SELECT, OPERATE or DIRECT_OPERATE function codes.

B.5 Function Codes 5 (0x05) *and* 6 (0x06) - DIRECT OPERATE *AND* DIRECT OPERATE – NO ACKNOWLEDGEMENT

These direct operate functions are similar to the OPERATE function code except that no preceding SELECT command is required. They are used for outputting Control Relay Output Blocks, Pattern Control Blocks and analog outputs when the extra security provided by a two-step control command is not necessary. Another use is to optimize bandwidth utilization in closed loop control when other feedback is present.

DIRECT OPERATE request messages look identical to *SELECT and OPERATE* request messages except for the function code. They contain one or more objects that describe the desired output state or level.

Table B-2: Example responses from control relay output block

Conditions in Outstation When Request is Received	Response								
	Status Codes				IIN Bits				
	Obj A	Obj B	Obj C	Obj D	1.5	2.0	2.1	2.2	2.4
No errors are detected, all points successful.	0	0	0	0	0	0	0	0	0
The function code is not supported regardless of which indexes the objects have.	NR	NR	NR	NR	0	1	0	0	0
The outstation does not support the specific variation code in the request.	NR	NR	NR	NR	0	0	1	0	0
Indexes for objects C and D are beyond the maximum number of points installed in the outstation.	0	0	4	4	0	0	0	1	0
	0	0	4	NR					
The point in object B is already executing when this request arrives.	0	5	0	0	0	0	0	0	1
	0	5	NR	NR					
The outstation is not able to control more than one point at a time.	0	8	8	8	0	0	0	0	0
	0	8	NR	NR					
The point in object C is tagged or blocked to prevent its control.	0	0	9	0	0	0	0	0	0
	0	0	9	NR					
The Remote/Local Switch is in the Local position.	7	0	7	7	1	0	0	0	0
	7	NR	NR	NR					
A control output is requested and the Control Relay Output Block in object D's request contains an illegal control code.	0	0	0	3	0	0	0	0	0
An analog output is requested and the value in object D's request exceeds the permitted level.	0	0	0	3	0	0	0	0	0

Keys: NR means Not Reported.

DIRECT OPERATE responses contain the identical set of object headers and objects, and in the same order as appear in the master's request unless it determines an error condition exists. In the case of an error, the outstation sets an error code within an object, possibly omits objects and/or sets IIN bits.

The response to a DIRECT_OPERATE command does not guarantee that execution actually occurred. It only indicates that the request was received. For this reason, systems employing either of these function codes are encouraged to provide another means for detecting that execution did happen.

The DIRECT_OPERATE_NR function code is similar to the DIRECT_OPERATE function code except that the outstation does not send a response message; it does however, execute the control if no errors are detected in the request. This function code is suitable for broadcasting a control request from one master to multiple outstations, where each outstation is identically equipped. It is important to realize that when employing function code DIRECT_OPERATE_NR in a request, there is no direct feedback for assuring that an error-free request was received.

Rules

There are a few rules regarding DIRECT OPERATE functionality:

Rule 1 Every master and outstation device that supports direct operate operation must also provide support for select – operate operation. This allows the

system owner or user to choose the security level appropriate for the installation.

Rule 2 A master must never retry sending a message with a DIRECT_OPERATE function code as this can result in duplicate control actions when, unknown to the master, an outstation restarts. The definition of a retry is a repeated request having the same sequence number in the application control octet as the previous request. If a repeated operation is acceptable or desired, the master should send a similar, but new message with the sequence number properly incremented.

B.6 Function Codes 7 (0x07) and 8 (0x08) - IMMEDIATE FREEZE *AND* IMMEDIATE FREEZE – NO ACKNOWLEDGEMENT

The purpose of this function is to copy the current value of a counter or analog point to a second, separate memory location associated with the same point. The copied value is referred to as the frozen value and remains constant until the next freeze operation to the same point. These commands do not affect the current values of the counter or analog points.

For the IMMED_FREEZE function code, the response is a null response. For the IMMED_FREEZE_NR function code, no response is sent, and for this reason, the IMMED_FREEZE_NR function code is recommended for broadcast freezing.

B.7 Function Codes 9 (0x09) and 10 (0x0A) - FREEZE-AND-CLEAR AND FREEZE-AND-CLEAR – NO ACKNOWLEDGMENT

These function codes are similar to function codes IMMED_FREEZE and IMMED_FREEZE_NR in all respects except that after copying the current value to the frozen value, the current value is immediately cleared to 0. An example is a counter that accumulates pulses and is frozen at periodic time intervals. At each freeze, the counter is cleared and resumes its counting from zero. In an electrical system if the counts represent energy, then the frozen value represents demand. In a water system if the counts represent volume, then the frozen count represents a flow rate. For function code FREEZE_CLEAR, the response is a null response. For function code FREEZE_CLEAR_NR, no response is sent and for this reason, function code FREEZE_CLEAR_NR is recommended for broadcast freezing.

B.8 Function Codes 11 (0x0B) and 12 (0x0C) - Freeze-at-Time and Freeze-at-Time – No Acknowledgement

These function codes initiate periodic freezing of the specified points. The request message contains a Time-Date-and-Interval object header and object followed by object header(s) for the point(s) that are to obey the freezing schedule. Multiple schedules may be sent in the same request. Upon receipt of this type request, an outstation automatically performs the freeze operations according to the schedule without further commands from the master station. The schedule may require the outstation to perform either a single freeze operation or an infinite number of freeze operations.

The general formats of function code FREEZE_AT_TIME or FREEZE_AT_TIME_NR requests and the FREEZE_AT_TIME function code response messages are shown in Figure B-6. No response is sent with function code FREEZE_AT_TIME_NR.

►►► Request Message (beginning)											
	AC	FC	TDH_0	TDO_0	DOH_{00}	DOH_{01}	•••	DOH_{0i}	TDH_1	TDO_1	DHO_{10}

►►► Continuation of Request Message											
	DHO_{11}	•••	DHO_{1j}								

◄◄◄ Response Message											
	AC	FC	IIN_1	IIN_2							

Figure B-6: FREEZE_AT_TIME or FREEZE_AT_TIME_NR requests and the FREEZE_AT_TIME function code response format

where

AC is the Application Control octet.

FC is the function code octet.

IIN_1 and IIN_2 represent the Internal Indication octets.

TDH_x is the xth **T**ime-**D**ate-and-Interval object **H**eader (shown shaded).

TDOx is the xth **T**ime-**D**ate-and-Interval DNP3 **O**bject (shown shaded).

DOH_{xy} is the yth **D**ata **O**bject **H**eader specifying a point that is to be frozen according to schedule in the xth Time-Date-and-Interval object.

A Time-and-Date-with-Interval DNP3 object has a time-date field and an interval field. These two fields are used in a binary code-like scheme to indicate when to freeze the points. This is shown in Table B-3.

Table B-3: Freezing schedule interpretation

Time - Date Field	Interval Field	Freeze Timing
zero	zero	Freeze once immediately.
non-zero	zero	Freeze once at the specified time.
zero	non-zero	Periodically freeze at intervals relative to the beginning of the current hour. Use the time interval from the interval field. Continue freezing forever or until a new function code FREEZE_AT_TIME or FREEZE_AT_TIME_NR freeze request is received.
non-zero	non-zero	Periodically freeze at intervals relative to the time and date in the time-date field. Use the time interval from the interval field. Continue freezing forever or until a new function code FREEZE_AT_TIME or FREEZE_AT_TIME_NR freeze request is received.

B.9: Function Codes 13 (0x0D) *and* 14 (0x0E) - COLD RESTART *AND* WARM RESTART

A COLD_RESTART function code forces the outstation to perform a complete restart similar to what the device would do upon powering up after a long-term power loss. Many devices clear all output hardware to a safe state and re-initialize themselves with configuration information and/or default values and clear all queues. The specific actions performed are device dependent and not defined herein.

A WARM_RESTART function code forces the outstation to perform a partial reset. Only the DNP3 application needs to reset and no affect to other subsystems and processes within the outstation is required. Some, devices re-initialize the DNP3 application with configuration information and/or default values and clear all event and control queues.

When an outstation receives a COLD RESTART or WARM RESTART request, it must immediately respond with a Delay Time DNP3 object and then initiate its restart activities. The delay time in the object specifies the length of time during which the outstation expects to be busy and unable to respond to requests which is illustrated in Figure B-7.

►►► Request Message											
	C3	0D									
	AC	FC									

◄◄◄ Response Message											
	C3	81	00	00	34	01	07	01	2D	00	
	AC	FC	IIN_1	IIN_2	Grp	Var	Qual	Range	Time Delay		

Figure B-7: Example of COLD RESTART or WARM RESTART function code

B.7 Function Code 15 (0x0F) - INITIALIZE DATA (OBSOLETE)

This function code is obsolete and new designs shall not implement it[1]. Originally, it was intended to tell the outstation to set configurable data to the default, or initial start-up, settings. The response to an **INITIALIZE DATA** request is a null response.

B.8 Function Codes 16 (0x10) *and* 17 (0x11) *and* 18 (0x12) - INITIALIZE APPLICATION and START APPLICATION and STOP APPLICATION

[1] *The reason for obsoleting function code 15 was because previous versions of this specification did not provide sufficient details about how to use the function code or clearly define the behavior of an outstation upon receipt of such a request.*

These function codes initialize, start and stop the application(s) specified in the request. Applications are unique to the outstation device and not defined in the DNP3 protocol. A local closed-loop control is an example of such an application. Applications are specified in the request with Application Identifier objects. When referencing a specific application in a message, the object qualifier octet must be 0x5B. Qualifier 0x06 is used to specify all applications without identifying a specific one.

The INITIALIZE APPLICATION function is optional for an outstation application and depends upon the requirements of the specific application in the outstation. Nevertheless, even though there may be nothing to initialize, outstations that have DNP3-controllable applications must parse and respond to this function. Figure B-8 shows an example how to control an outstation application named CL6. Application identifier objects do not have a defined format. For this example, the application name, “CL6”, is used.

B9: Function Code 19 (0x13) - SAVE CONFIGURATION

This function specifies that the outstation should store into non-volatile memory the contents of a configuration file located in volatile memory. When an outstation receives a Save Configuration request, it must immediately respond with a Delay Time DNP3 object and then initiate its storage activities.

B10: Function Code 20 (0x14) *and* 21 (0x15) - ENABLE UNSOLICITED RESPONSES and DISABLE INITIATION OF UNSOLICITED RESPONSES

A master uses these functions to dynamically enable and disable which points may, or may not be included in a spontaneous, unsolicited message. Outstations that do not support unsolicited messages are not obligated to implement these functions. Outstations that do support unsolicited messages must implement these two function codes.

►►► Request Message – Initialize Application											
	C3	10	5A	01	5B	1	03	00	43	4C	36
	AC	FC	Grp	Var	Qual	Range	Size Prefix		‘C’	‘L’	‘6’

◄◄◄ Response Message											
	C3	81	00	00							
	AC	FC	IIN_1	IIN_2							

►►► Request Message – Start Application											
	C3	11	5A	01	5B	1	03	00	43	4C	36
	AC	FC	Grp	Var	Qual	Range	Size Prefix		‘C’	‘L’	‘6’

◄◄◄ Response Message											
	C3	81	00	00							
	AC	FC	IIN_1	IIN_2							

⋯ Application running ⋯

►►► Request Message – Stop Application											
	C3	12	5A	01	5B	1	03	00	43	4C	36
	AC	FC	Grp	Var	Qual	Range	Size Prefix		‘C’	‘L’	‘6’

◄◄◄ Response Message											
	C3	81	00	00							
	AC	FC	IIN_1	IIN_2							

Figure B-8: Control an outstation application named CL6

An outstation may only include event objects in an unsolicited response message from points that have been enabled by an ENABLE UNSOLICITED RESPONSES request. Events that were generated before a point is enabled, must not be reported in unsolicited responses until after the point is enabled and if those events have not already been read and confirmed by a master poll (solicited request, response and confirmation).

As a minimum, an outstation accept commands to enable and disable unsolicited responses by event class even if the device does not have class 1, 2 or 3 data when the request arrives.

Enabling and disabling unsolicited messages on a per point type and index is optional. When this is implemented, the object headers in the request message specify the group number corresponding to static data of a point type and variation 0 – the request message shall not use event type object headers. Masters must send variation 0, but to accommodate legacy systems, outstations may ignore the variation number.

Regardless of the cause, when an outstation is reset or restarted, all of its points must be disabled from initiating unsolicited responses. This does not mean the points do not generate events, just that the points cannot initiate unsolicited reporting. An outstation shall not report unsolicited events until its points are explicitly enabled by a request from the master, and then only data from the enabled points are permitted to be included in the response. Devices transmit a data-less null message upon restarting according to the requirements.

When an outstation receives a function code DISABLE_UNSOLICITED request to disable initiation of unsolicited responses from points identified by the object headers in the request, it no longer transmits any data via an unsolicited response for those points. The request also cancels any pending expectation of confirmation for an unsolicited response that has already been sent from the outstation, but for which confirmation has not yet been received.

An outstation must not lose or discard event data as a result of receiving the DISABLE_UNSOLICITED function code; the outstation must report events if they are requested in a master poll for those points that were disabled from reporting in unsolicited responses.

B.11 Function Code 22 (0x16) - ASSIGN CLASS

A master uses this function code to assign the events generated by points to event classes. Present assignments may be altered using this function code. Every device have a default event class for each and every point for which it supports events. This is necessary so that when a master requests events by class, an outstation only reports events from those points whose class assignments match the request.

When an event is created, it is classified as a class 1, 2 or 3 event. The convention used by DNP3 to disable event generation is to specify an assignment to class 0. The events are not really assigned to class 0 because that class specifies static data, but

using class 0 in the request allows DNP3 to employ a consistent object format. Table B-4 shows which object header groups and variations are used for specifying the points whose events are to be re-assigned.

Table B-4: Object header groups and variations

Point Type or Data Type	Object Headers in the Assignment Message		Applies to Events Reported Using Group
	Group	Variation	
Binary Input	1	0	2
Analog Input	30	0	32
Frozen Analog Input	31	0	33
Counter	20	0	22
Frozen Counter	21	0	23
Binary Output Status	10	0	11
Binary Output Control	12	0	13
Analog Output Status	40	0	43
File	70	0	70 (variations 4, 5, 6 & 7)
Octet String	110	0	111
Virtual Terminal	112	0	113

Events receive their class attribute at the time they are created. Thus, a point that is requested to assign its events to another class does not have to change already buffered events to the new class; only events generated after the ***assign class*** request are assigned to the new class. The response to an ASSIGN_CLASS function code request is always a null response. Outstation devices that are able to store the most recent class assignments in non-volatile memory may use those assignments after a device restart; otherwise, devices must revert to their default class assignments. Figure B-9 shows an example which illustrates assignment of binary input events to class 1,

analog input events to class 2 and frozen counter events for indexes 0 to 2 to class 2, and disabling frozen counter events for indexes 3 to 10.

►►► Request Message (beginning)											
	C3	16	3C	02	06	01	00	06	3C	03	06
	AC	FC	Grp	Var	Qual	Grp	Var	Qual	Grp	Var	Qual
			←	Assignment set				→	←		

►►► Continuation of Request Message											
	1E	00	06	15	00	00	00	02	3C	00	06
	Grp	Var	Qual	Grp	Var	Qual	Range		Grp	Var	Qual
	Assignment set							→	←		

►►► Continuation of Request Message											
	15	00	00	03	0A						
	Grp	Var	Qual	Range							
	Assignment set				→						

◄◄◄ Response Message											
	C3	81	00	00							
	AC	FC	IIN_1	IIN_2							

Figure B-9: Assignment of binary input events

B.12 Function Code 23 (0x17) - DELAY MEASUREMENT

The master uses this function code to measure the communication channel delay time. It is most often used in the time synchronization process. The master must know what the delay exists in the modems and communication media so that it can send a time value that will be accurate when it arrives. The request message contains no objects.

The response message contains a single Fine Time Delay DNP3 object. The Fine Time Delay object holds the outstation processing delay, which is valid for a single, one-time-only request and is defined as the number of milliseconds.

The master record two times in order to compute the communication delay. The first is the exact instant when the leading edge of the start bit of the first octet in the transmitted request message leaves the master device (generally at the interface where the bit is placed onto the physical media, such as at the input of the master modem if so equipped. The recorded time is at the end of clear-to-send timing.) This time is identified as TO (time out).

The second time that the master must record is the exact instant when the leading edge of the start bit of the first octet in the received response message arrives at the master device (generally at the interface where the bit is detectable from the physical media, such as at the output of the master modem if so equipped.) This time is identified as Ti (time in).

The master calculates the communication channel delay time as follows[2]:

Communication channel delay time = $(T_i - T_o$ – processing delay) / 2

B.12.1 Rules

Rule 1 Masters does not retry DELAY MEASUREMENT requests and outstations does not retry corresponding response messages at either the Application or Data Link layers.

[2] *There are several assumptions implicit in this computation. First is that the outbound communication delay is the same as the inbound communication delay. The second is that the master and outstation Application Layers have a means of working together with the lower layers in order to obtain the times when start bits are received and transmitted. Thirdly, the computed communication delay is applicable for the synchronizing message used to write the time; that is, the software design is such that other un-predictable processing delays (e.g., network delays and task switches) do not affect the accuracy.*

Rule 2 Any outstation that requests a time synchronization from the master must support this function code.

Rule 3 All masters that require time-stamped events must support this function code.

B.13 Function Code 24 (0x18) - RECORD CURRENT TIME

This function code is used in the procedure for time synchronizing outstation devices that communicate over a LAN/WAN. It requests a receiver to record the time of receipt of the last octet in a message having this function code. Later, the receiver will compare this time with the time sent by the master in a subsequent write message having a Last Recorded Time object. The receiver uses these two pieces of information to correct its internal time clock.

A master that sends this message must also record the time of transmission when it sends the last octet of a message with this function code. The master will use that time value in a subsequent message to the same outstation, having a Last Recorded Time object.

B13.1 Rules

Rule 1 Masters does not retry RECORD CURRENT TIME request messages at either the Application or Data Link layers.

Rule 2 Any outstation that has a TCP/IP interface and sets IIN.4 [NEED_TIME] to request a time synchronization from the master must support this function code.

Rule 3 All masters that require time-stamped events and support TCP/IP must also support this function code.

B.14 Function Codes 25 (0x19), 26 (0x1A), 27 (0x1B) *and* 30 (0x1E) - OPEN FILE, CLOSE FILE, DELETE FILE *AND* ABORT FILE

The purpose of the OPEN_FILE function code is to make a file available for reading or writing by the master and specifically locking it so that no other process may access the file during this time. When the master is finished, it uses the CLOSE_FILE or ABORT_FILE function code to unlock the file, thereby making it available to another process. A master uses the DELETE_FILE function code to remove a file.

OPEN and DELETE are secure transactions. A valid authentication key is required to successfully perform these transactions and expires as soon as it is used. A zero value for the authentication key implies world (or guest) permissions. Two DNP3 objects exist to support the OPEN, CLOSE, DELETE and ABORT functionality.

- A File Command object
- A File Command Status object

A File Command object is used to initiate open and delete operations.

A File Command Status object is used to indicate the success of OPEN, CLOSE, DELETE and ABORT commands and to return a file handle during opens. It is also used to initiate a file close and abort operations using a previously acquired file handle.

B.15 Function Code 28 (0x1C) - GET FILE INFORMATION

The purpose of the GET_FILE_INFO function code is for the master to retrieve information about a file. The file type, file size, time of creation and permissions are returned.

A master obtains the information by issuing a GET_FILE_INFO function code with a File Descriptor object in the request. The *filename offset*, *file name size*, *request ID* and *file name octet* fields are filled in with appropriate values.

The *file type*, *file size*, *time of creation* and *permissions* fields in the request object are cleared to zero. If the file exists, the outstation responds with a File Descriptor object. This object is an event object when it is used in a response, but it is not an event object when used in a request.

The *filename offset*, *file name size*, *request ID* and *file name octet* fields are filled in with the same data as in the request, and the *file type*, *file size*, *time of creation* and *permissions* fields are completed with their actual values.

B.16 Function Code 29 (0x1D) - AUTHENTICATE FILE

This function code is used to obtain an authentication key that may be needed to open or delete a file. When implemented, an authentication key provides a form of security that assures the requestor can provide a user name and password acceptable to the outstation.

The master requests an authentication key using an Authentication object. The *user name offset*, *user name size*, *password offset*, *password size*, *user name octet* and *password octet* fields must contain appropriate values. The *authentication key* field is cleared to zero in the request.

The outstation responds with an Authentication object. If the request is acceptable to the outstation, the *authentication key* field contains a unique value that may be issued in an open or delete request, otherwise, if unacceptable, a zero appears in the *authentication key* field. The *user name offset*, *user name size*, *password offset* and *password size* fields contain zeros and there are no user name octets or password octets included in the response for security reasons.

B.17 Function Code 31 (0x1F) - ACTIVATE CONFIGURATION

This function instructs the outstation to begin using the contents of the specified file for configuration. After this function code has been executed in the outstation, the file data become the active configuration from that time onward. This infers that the file

configuration data is currently located in, or, during execution will be stored into non-volatile memory. This function code shall not be used for configuration data that remains in volatile memory and could be lost upon device restart or power failure. When an outstation receives an ACTIVATE CONFIGURATION request, it immediately respond with a Delay Time object and then initiate its reconfiguration. The Delay Time object specifies the length of time during which the outstation expects to be busy and will not respond to requests. The master honour this time and not attempt sending any requests until the delay period has elapsed. It is permissible for an outstation to restart during this time period.

B.18 Function Code 129 (0x81) – RESPONSE

All response messages except for unsolicited response messages use function code RESPONSE. Whenever the master issues a request, regardless of what function code appears in the request, the response must always use function code RESPONSE.

B.19 Function Code 130 (0x82) - UNSOLICITED RESPONSE

Unsolicited responses always use function code UNSOLICITED_ RESPONSE without regard to which DNP3 objects are included.