Delay modelling and synchronisation of telecontrol networks

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“The only reason for time is so that everything doesn’t happen at once.” – Albert Einstein

Abstract

Eskom, South Africa's largest supplier of electricity, uses a vast telecommunication network to control and monitor all operations in remote locations such as substations. As Eskom expanded the electricity network across South Africa, the telecommunications network expanded as well. With changing technology in the telecommunications industry, the telecontrol network of Eskom uses different protocols and communication mediums.

This paper covers the study of these different protocols and mediums and the interconnectivity between them. The purpose of the study is to enable the network administrators of Eskom to easily time-synchronise all nodes on the network. Even more importantly, the study is done to better understand the setup of the Eskom telecontrol network and the delays that occur between different protocols and using different communication mediums. The study quantifies all delays that occur between nodes, considering distance between nodes, switching between mediums and processing time within systems. A network simulation tool is established that enables the network administrator to simulate the network and find all delays that occur in the network before the network is actually implemented.

Opsomming

Eskom, Suid Afrika se grootste verskaffer van elektrisiteit, gebruik 'n telekommunikasienetwerk vir die monitering en beheer van prosesse op verafgeleë plekke soos substasies. Met die uitbreiding van Eskom se elektrisiteitsnetwerk is die telekommunikasienetwerk ook uitgebrei. As gevolg van die reuse tegnologiese ontwikkeling in die telekommunikasiebedryf gebruik Eskom se telekommunikasienetwerk verskillende kommunikasiemediums en protokolle.

Die tesis dek die studie van hierdie verskillende protokolle en mediums en die koppelvlak tussen hierdie protokolle. Die doel van die studie is om die Eskom netwerkoperateurs in staat te stel om maklik alle nodes in die netwerk te tyd-sinkroniseer. Dit is verder baie belangrik vir Eskom om die telebeheernetwerk se opset en koppelvlakke tussen mediums en protokolle beter te verstaan. Die studie help om tydvertragings tussen nodes te bepaal deur middel van die inagneming van die afstande tussen nodes en die oorskakeling van een medium na 'n ander se verwerkingstyd binne stelsels. 'n Netwerksimulasiepakket word opgestel om netwerkoperateurs in staat te stel om alle tydvertragings binne die netwerk te bepaal voordat die netwerk geïmplementeer word.

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1. Introduction

1.1. Overview

Eskom, South Africa's largest supplier of electricity, has a vast distribution network across South Africa, with a large number of substations delivering electricity to towns and large factories. Communication with these substations is of the utmost importance to ensure reliable electricity supply with minimum interruptions.

Connecting the substations to the master stations, from where most of the substation control is done, Eskom uses a control network that consists of various protocols and communication mediums. The most well-known protocol is Eskom's own proprietary protocol, "Estel". Eskom is also moving towards using the new international standard protocol "DNP3". Most other protocols that are in use by the telecommunication network are based on the well-known TCP/IP protocol. The existing network infrastructure uses radio frequency as well as fibre optics as transmission medium. Many of the substations are also geographically distant from the regional control centres.

1.2. Time stamps in fault analysis

A time stamp on an event log is commonly regarded as the most important piece of information of the log. The logging of faults would mean nothing if it was not possible to at least pinpoint a day, hour or minute an event happened. The accuracy of this data becomes even more crucial when specialised equipment such as protection relays are used. These protection relays act within milliseconds of one another and the time stamps should thus be accurate to within milliseconds.

A common problem that arises when storing and analysing time-stamped data is that of telemetry skew [1]. Telemetry skew occurs when propagation delays and scan rates prevent events from being logged in real time, and thus an inaccurate sequence of events would be derived from the data.

Consider the following scenario:
When two breakers in two different substations open within a few milliseconds of each other due to a fault on the line, the event will be logged with time stamps by the protection equipment that monitor the line conditions and breakers. As the RTUs continuously poll this equipment, the RTUs will detect the state changes a few 100 milliseconds later and log the event. Later the SCADA central server will poll the RTUs and detect the state changes of the two breakers. The SCADA central server will record the event, update the changes on the database and generate an operation alarm. Each unit in this chain of events will record a different time as the events happen.

If the two breakers both detect a fault on the line, the fault analysers are assisted by the time stamps to locate the origin of the fault. It is therefore extremely important that the protection equipment's internal clocks are synchronised. If the two breakers open within 30 ms of each other and the second breaker's clock is ahead with 31 ms, it would seem as if the second breaker opened first and the time stamp data would thus not aid the analysis at all, but actually make it more difficult.

1.3. Problem statement

Eskom's protection department relies heavily on the telecontrol network to communicate with relays and switches to provide specific protection capabilities. One of the biggest problems on the control network is that of accurate time stamping.

Because of the large scale of the network and the different protocols and mediums used in the network, certain time delays are generated between nodes in the network. From a protection point of view, all these nodes have to be time-stamped to assist the investigation into faults that occur on the distribution network. The synchronisation of time-stamping of all nodes in the telecommunications network is so important that Eskom Transmission uses GPS (Global Positioning Satellite) systems in all Transmission substations (substations from 786kV-132kV), specifically for accurate time-stamping. Unfortunately, to install a GPS system in every Distribution substation (substations of 132kV and below) would be very expensive, due to the large number of Distribution substations.

Another way of time-stamping all nodes in the network is possible by sending the time/date from the master station to all the nodes, but because of the time delays that occur between nodes, the time stamps would differ. A solution to this problem would be to adjust the time stamps according to the time delays between nodes, then exact time-stamping would be possible. If it is impossible to completely time-synchronise the time stamps on certain nodes, the time delays on these nodes should at least be quantified to a certain degree of accuracy.

GPS time-synchronisation systems can time-stamp a node with an accuracy of 10 ms. For Eskom purposes a minimum accuracy of 30 ms is needed as the protection relays would operate with a minimum time delay of 30 ms from one another. It would, however be desirable to have an accuracy of 10 ms, that would be on a par with the GPS-time stamping targets.

1.4. Benefits and feasibility of the project

The project is done in conjunction with Eskom Distribution Northern Region. The problem of accurate time-stamping is a practical problem and solving it would result not only in academic knowledge, but in financial benefits for Eskom as well.

Inaccurate time stamps on certain nodes cause investigations to be more difficult and it often contradicts the findings. Eskom already invests an enormous amount of time and money into investigating faults that occur on the network. In some cases these faults can not be prevented from recurring, due to the time-synchronisation problem. Eskom also loses a lot of money when the electricity network is down due to a fault.

The new knowledge that this project introduces should be used on the current Eskom control network, as well as on the expanded future network. This project should save Eskom valuable resources, as well as securing a more reliable way of communication between substations and master stations.

1.5. Method of approach

The project will be divided into a number of smaller projects. The first is to make a thorough study of the different protocols and mediums used in the Eskom control network. This study is very important, because some information about delays that occur across these protocols and mediums is already well-documented.

Where information about certain protocols and mediums is not available, the protocol or medium itself should be studied. The approach to this study would be to study the working of the protocol or medium itself and then to set up a small network using the protocols and mediums in question. Testing the network in real time would reveal a lot about the strengths and weaknesses of each protocol and medium, as well as what delays occur across the network.

Once all information about the Eskom control network has been studied and all delays that might occur in the network have been considered, a model for each protocol and transmission medium can be created. The model is created in such a manner that each node in the network can be set up as a black box. All known information about the node is entered and all unknown information about the node can be generated by the model.

A software package that simulates networks will be used to implement these models and simulate the full network. Once the results of the simulation has been verified and changed, if necessary, the information can be used to adapt the real Eskom control network to make provisions for delays that might occur. *Figure 1-1* shows a schematic diagram of the described research cycle.

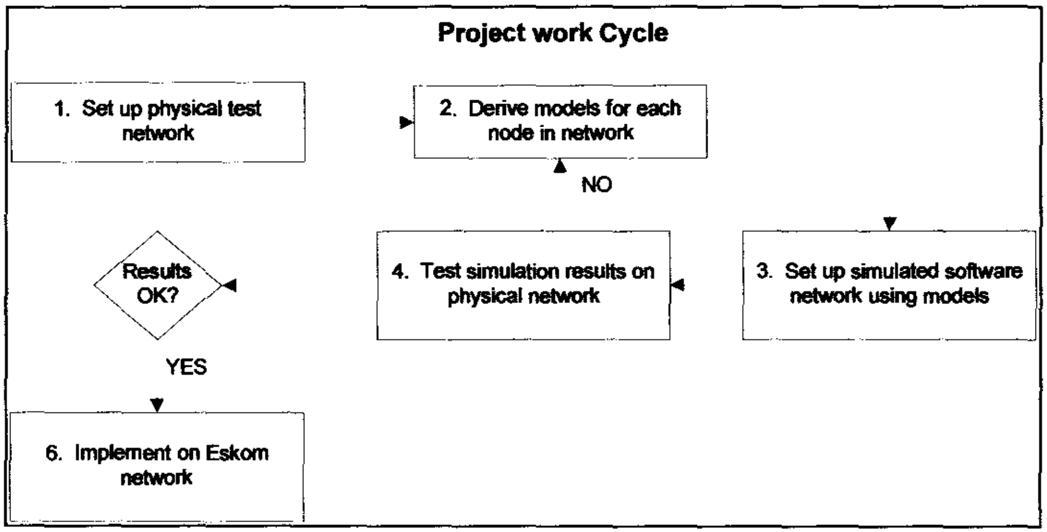


Figure 1-1: Layout of work cycle

To better understand the setup of the Eskom telecommunication network, it is necessary to study all protocols and mediums used in the network.

2. Study of Eskom telecontrol network

The Eskom telecontrol network uses the DNP3 network protocol, as well as the well-known TCP/IP protocol, for communication with computer systems. Eskom uses a Supervisory Control and Data Acquisition (SCADA) system to control processes within a substation. A SCADA system can access and record very large amounts of data, which makes it perfect for control and monitoring of systems. A number of different protocols can run on a SCADA system; most of these protocols are similar to, or based on the OSI (Open Systems Interconnection) model. The OSI model provides a framework for protocols to be developed.

2.1. Eskom telecommunications network considerations

The Eskom telecommunications network is designed with certain goals in mind. To design a data network, a few important factors have to be taken into account. These factors include bandwidth, reliability and financial feasibility.

2.1.1. Bandwidth

There are three different uses for the Eskom telecommunications network. The first and most important use of the network is to establish telecontrol. When the Eskom electricity network is controlled remotely, it is called telecontrol. All substations need to be controlled from a remote location such as a master station. For this use, only a limited amount of bandwidth is needed. If only telecontrol is needed for a certain node in the network, low bandwidth area radio would suffice.

In most cases the network administrators need to use the telecommunications network for supervisory control. When the Eskom electricity network is monitored and remotely acts upon faults that occur on the electricity network, it is called supervisory control.

Supervisory control needs a lot more bandwidth, because large amounts of data are constantly passing through the network to monitor all voltages and currents at certain nodes in the electricity network. To establish supervisory control, area radio does not have enough bandwidth, so fibre optics, UHF and microwave or Power Line Telecommunication (PLT) transmission are used.

For larger substations and geographically-remote locations, Eskom needs to establish telephone communication. Eskom uses its own telecommunication network for telephone communication. Of course, telephone communication needs a lot of bandwidth and therefore area radio would not suffice. For telephone communication, fibre optics, microwave or PLT transmission are used.

2.1.2. Reliability

In order to deliver a good quality service, it is important that the telecommunications network is reliable. The network should be able to detect errors that occur, and in most cases the network should be able to recover from interruptions by itself.

Modern fibre optic, microwave and PLT transmission provide the needed amount of reliability. Much of the reliability is also established by the protocol that is used. Eskom uses a number of different network protocols. All these protocols are based on the Open Systems Interconnection (OSI) model developed by the International Standards Organization (ISO), and delivers very good reliability.

2.1.3. Financial feasibility

As with all businesses, the most important factor is money. The telecommunications network has to be set up to reliably deliver the required amount of bandwidth at the least expense.

Installation of fibre optic cables is very expensive at about R30000/km. Microwave transmission equipment with the required bandwidth becomes cheaper than fibre optic transmission at around 15 km. For this reason Eskom very seldom uses fibre optic transmission for distances further than 15 km. For the longer distances Eskom would then use microwave transmission. If microwave transmission is impossible – usually because of geographical factors such as mountains, etc. – PLT transmission is used.

2.2. SCADA Systems

SCADA refers to a combination of telemetry and data acquisition. A SCADA system collects a large amount of data via a Remote Terminal Unit (RTU) and transfers it back to a central site where necessary analyses and control are done. The data is then displayed on a number of operator screens. The required control actions are then conveyed back to the process. [2]

The SCADA system needs software to run on. There are two types of software available, namely Proprietary and Open. Proprietary software is developed by companies to communicate with their own hardware. The problem with proprietary software is the reliance on the supplier of the system. Open software systems are very popular, because it allows different manufacturers' equipment to communicate with each other. [2]

2.3. Timing systems in the Electricity sector

Because of the importance of time-stamping of events as they occur in an electrical network, a data format for externally synchronising substation devices was universally adapted. The data format is called the IRIG-B time code. IRIG-B was developed by the Inter-Range Instrumentation Group – hence the name IRIG-B. [3]

The format is specifically designed with the electricity sector's needs in mind and provides month, day, hour and second information. It also provides fraction-of-second information up to 1 millisecond. [3]

The IRIG-B code is usually modulated onto a 1 kHz carrier signal and transmitted from the master station to the substations. Because of undefined propagation delays, this is no longer recommended – it is instead recommended to install a GPS system in every substation, which can then synchronise all clocks for time-stamping purposes. Unfortunately, installing GPS systems in every substation can become very costly; developing an alternative method would therefore be of great value.

2.4. Guidelines to time-stamping of operational data logs

As the use of GPS systems become more common for time-stamping purposes, it is important to set standards for the accuracy of these time stamps. A guideline, set up to address this issue specifically, was recently set up by the NERC (North American Electric Reliability Counsel). The guideline states [1]:

"Internal clocks on all affected devices at all affected functional organizations should maintain an accurate coordinated time, and that time shall be similarly coordinated with accepted international time sources."

With details:

"A: All specific geographic sites containing applicable devices (e.g., control center, plant, or substation) shall include a coordinated time synchronization service. This coordinated service should have a demonstrated availability of 99.9%. This may be accomplished through redundant hardware so long as the accuracy of the time service is maintained at all times.

B: The coordinated time synchronization service shall be directly traceable to the international time standard maintained in the United States by the US Naval Observatory on behalf of US Government, or the equivalent Canadian or Mexican government entity, with an accuracy of 1ms. Common services providing such a time signal include GPS, WWV, WWVB, CHU, and GOES satellite.

C: All applicable in-service devices co-located at a specific geographic site should maintain demonstrable and constant communication to either a local coordinated *time synchronization service, or a remote coordinated time synchronization service as defined in guideline detail B.*

D: *All applicable in-service devices should internally store time using the UTC time zone.*

E: *All applicable devices shall automatically adjust their internal clocks according to the NTP specification (RFC1305), which, at the time of this writing, states that the internal time shall not deviate from the coordinated time source by more than 128 ms.*

F: *At no time should any applicable device for a specific operational entity (e.g., control area, ISO/RTO) have an internal time that deviates from any other applicable device within the same operational entity by more than 256 ms. (The rationale for this is to keep the maximum deviation between an in-specification slow clock and an in-specification fast clock to less than approximately one quarter second.)*

G: *All applicable IRIG-B connected devices should maintain an internal clock with a maximum error of 50 ms. All NTP/SNTP connected devices should maintain an internal clock with a maximum error of 100 ms.*

H: *All operational events should be communicated and stored with time stamps. The time stamps should use the UTC time zone. In the even use of UTC is impractical, the time zone employed shall be clearly stated. If multiple time stamps are available for a given event other standards or guidelines shall determine which time stamp (or time stamps) shall be stored for the event.*

I: *The time stamps shall have a resolution of at least 1ms. Sources of time uncertainty should be known and reportable.*

J: *Operational events that are logged to hard copy or screens, or events that are presented to operators may be displayed using the local time zone, and may be represented to any resolution needed to properly operate the system, so long as the internal time stamps are maintained with the specified time zone and resolution as defined in preceding guideline details.*

K: *In the event that operational event recording requiring more resolution than otherwise specified in this guideline is required, equipment compatible with the IRIG-B protocol shall be used to ensure that the accuracy and resolution of the time stamping is maintained."*

It is important to note that the above guideline is intended to be used only as a guideline by electrical companies under the jurisdiction of the NERC. Although Eskom uses CIGRE standards, which is the European equivalent to NERC standards, Eskom does not at this time have a similar guideline or standard to measure the quality of the time stamps in the telecontrol network. Eskom does, however, conform to the IRIG-B time stamp format. It is therefore acceptable to view these guidelines as international guidelines until such time as Eskom could establish its own standards for this specific function.

2.5. Open Systems Interconnection (OSI) model

The development of the Open Systems Interconnection (OSI) model has had a tremendous impact on the design of communication systems. The OSI model was developed by the International Standards Organization (ISO) to provide a framework for the coordination of standards development. The OSI model allows existing and evolving standards' activities to be set within a common framework. [4]

The OSI model consists of seven layers that define a system for two processes to communicate with each other. The OSI model is not a protocol or a set of rules for how a protocol should be written. The OSI model is an overall framework in which to define protocols. *Figure 2-1* depicts the architecture of the OSI model. [4]

Each of the seven layers in the model can be briefly described as follows:

- Application – the provision of network services to the user's application programs.
- Presentation – takes care of the data representation (including encryption).

- Session – controls the communications (sessions) between users.
- Transport – manages the communications between two end systems.
- Network – responsible for the routing of messages.
- Data Link – assembles and sends frames of data from one system to another.
- Physical – Defines the electrical signals and connections at the physical level.

The OSI model uses peer-to-peer processes. Each layer calls on services of the layer directly below it, and provides services to the layer directly above it. Between machines the layers communicate directly to corresponding layers. At the physical layer communication is direct – physical A communicates directly to physical B. At higher levels the communication moves down through the layers on process A (each layer adding information) and then back up through the layers on process B (each layer removing information). In this way each layer knows nothing about information used by layers below it, and delivers only relevant information to the layer above it. A schematic diagram of the OSI layers is depicted in *Figure 2-1.*

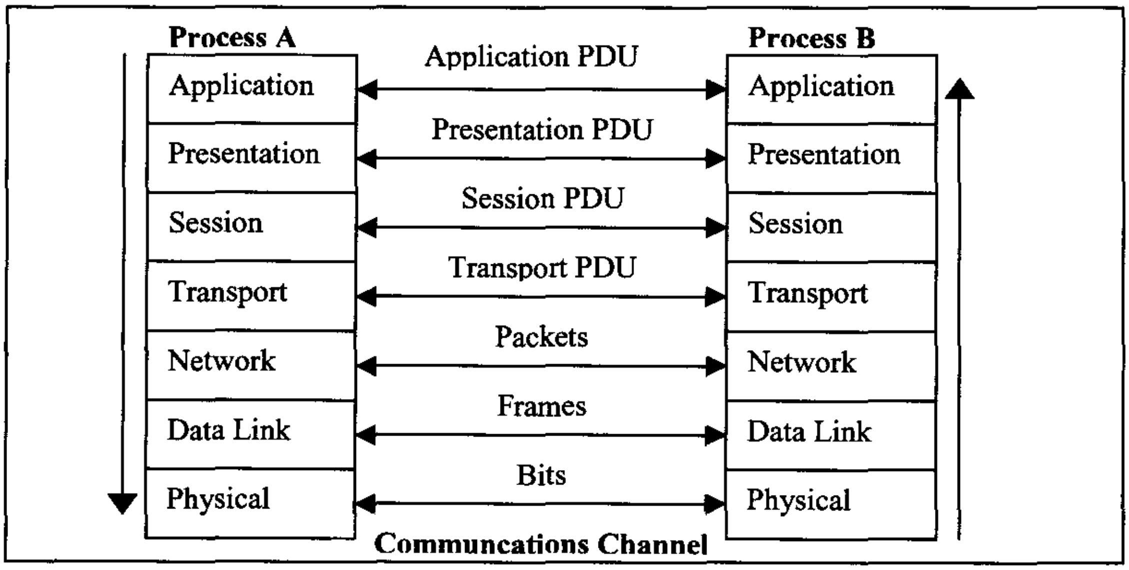


Figure 2-1: Full architecture of OSI model

2.6. TCP/IP

TCP/IP was developed by the US Department of Defence. The goal of the project was to connect a number of different networks, designed by different companies, into a large network – the Internet. TCP/IP supports all the basic network functions – file transfer, remote logon and electronic mail. TCP/IP is also very robust and can automatically recover from any node or telephone line failure. [5]

TCP/IP was developed before the OSI model, therefore the layers of TCP/IP differ slightly from the layers of the OSI model. TCP/IP is made up of five layers: physical, data link, network, transport and application. The transport layer defines two protocols: TCP (Transmission Control Protocol) and UDP (User Datagram Protocol). The network layer defines the IP (Internetworking Protocol). The physical layer and data link layer do not define any specific protocol, but support all standard and many proprietary protocols. [5]

The application layer can be said to encapsulate the top three layers in the OSI model: application, presentation and session. The application layer provides services such as SMTP (Simple Mail Transfer Protocol), FTP (File Transfer Protocol), TELNET, DNS (Domain Name System), SNMP (Simple Network Management Protocol) and TFTP (Trivial File Transfer Protocol). The functionality of these services is beyond the scope of this thesis. [3]

TCP/IP consists of two layers, the IP layer and the TCP layer:
The IP (Internetworking Protocol) layer forwards each packet based on a four-byte destination address – IP address. Authorities assign ranges of numbers to different organisations. The organisations assign different ranges of their numbers to certain departments. IP operates on gateway machines that move data from department to organisation, to region, to the rest of the world. [5] [6]

The TCP (Transmission Control Protocol) layer has the responsibility of verifying the correct delivery of information from client to server. TCP detects errors and lost data and can trigger retransmission until the information is complete and correctly received. [5]

TCP/IP supports Local Area Networks (LANs) and Wide Area Networks (WANs). TCP/IP is not dependent on any transmission medium. [3]

2.7. *Distributed Network Protocol Version 3.00 (DNP3)*

DNP3 was developed during the early 1990s by Harris Controls Division and Distributed Automation Products. DNP3 is an open protocol. It is a telecommunications standard that defines communication between a master station, Remote Telemetry Units (RTUs) and Intelligent Electronic Devices (IEDs). DNP3 was developed to achieve interoperability among systems in an electric utility (such as Eskom), oil or gas, water and security industries. [2]

DNP3 is designed specifically for SCADA applications. This involves the acquisition of information and the sending of control commands between physically-separate computer devices. DNP3 sends relatively small data packets in a reliable manner with the messages involved arriving in a determinable manner. It is different from TCP/IP in this respect, because TCP/IP can send relatively large files, but in such a way that it is not as suitable for SCADA control applications. [2]

DNP3 implements the Enhanced Performance Architecture (EPA) model. The EPA model is a 3-layer subset of the 7-layer OSI model. EPA uses only the application, data link and physical layers, with limited transport and network layer capabilities.

2.8. *RF and Microwave transmission*

Radio frequency is the term used for transmitting signals, using atmosphere as transmission medium. This is done by propagating electromagnetic fields. The information for transmission is modulated with a carrier signal. The carrier signal's frequency is very high to make it possible to be transmitted through the atmosphere.

Radio propagation waves are electromagnetic waves. The frequencies range from Very Low Frequency (VLF) to Extremely High Frequency (EHF). When the frequency changes, the characteristics of the propagation through the atmosphere change. [2]

Some of the very lowest frequency transmitters (about 17 kHz – just above the audible range) can transmit low speed data halfway around the world. These low frequencies can penetrate water and "see" around corners. The problem with such low frequencies is that it has a very limited bandwidth. It is often used by submarines to transmit a single low grade voice channel.

Eskom often uses UHF in the 400 – 450 MHz range to establish a reliable, cost-effective connection between substations and the master station. This allows relatively high bandwidth transmission that is capable of supporting Eskom's SCADA needs.

An EHF system, on the other hand, uses microwave transmission and operates in the region of 1,2 GHz up to 50 GHz. Microwave transmission often has a range of only a few kilometres and cannot "see" around corners, as moisture in the atmosphere tends to absorb a lot of the energy of the transmission. The reason why microwave is a popular transmission medium is that it has a very large bandwidth. A radio system operating in the 8 GHz band can transmit digital data over 30km. Microwave transmission's bandwidth is large enough to transmit high quality voice, data and video information.

Above the 50 GHz range, the electromagnetic spectrum moves towards the visible range, where infrared and fibre optics are used.

2.9. Fibre Optic

The use of light as communication medium is probably the oldest way of communicating. The first proper use of light as transmission medium was that used by the military. A light was flashed across a distance, making up a code (usually the Morse code) and the receiver decoded the light flashes to understand the message. [8]

Laser was invented in the late 1950s which sparked of new interest into light as a transmission medium. Fibre optic technology was invented in 1970 with a loss of only 20dB per km. [8]

The optical fibre is made of a dielectric (glass or plastic) and the signal it carries is light. This is a major advantage, because there is no conductive path or metallic connection between two nodes. Glass and plastic fibres are lightweight and flexible.

The signal is transmitted by a flashing LED (light-emitting diode), or a flashing high power laser light source. At the other end of the fibre the signal is picked up by a photo detector, which changes it back to an electrical signal. [9]

Optical fibre technology allows high bandwidth transmission, because the attenuation of optical fibre is not frequency-dependent. The transmission is also not affected by electrical interferences. [9]

2.10. Power Line Telecommunication

Power Line Telecommunication (PLT) refers to the use of electricity power lines to transmit telecommunication data. The use of power lines to transmit control data was developed in the 1950s. The method then used was called Ripple Control and was characterised by the use of low frequencies (100 – 900 Hz), giving a low bit rate and demanding a very high transmission power. [10]

In the early 1980s, a new method was developed with a slightly higher bit rate. With these systems, frequencies in the range of 5 to 500 kHz are used. Both mentioned systems provided one-way communication. The main driving force behind the study and development of PLT systems was the implementation of SCADA technology. [10] [11]

Bi-directional communication used today was first developed in the late 1980s to 1990s. These systems used much higher frequencies and a substantial reduction of noise levels. With this technology and advanced protocol techniques, proper data transfer can be established. The main advantage of PLT systems to Eskom is that it already has a very large power line grid throughout South Africa. This means that it reduces the cost of telecommunication infrastructure considerably.

2.11. Modelling of delays in a network

All digital networks make use of data packets to send information. Data packets are small groups of data that is sent as a stream. After each packet is received by a network buffer, a check is done to ensure that data has been received correctly. If an error occurred during the sending process, the packet has to be resent. This is one of the main causes of delays in a network and as the amount of data that is sent increases – as an error occurs on the Eskom network – the delays would increase as well.

If packets arrive from a number of sources at λ packets per second, and the average size of a packet is $D = \frac{1}{\mu}$ data units per packet, then data packets in a buffer is transmitted at C data units per second. A delay in the network can then be described as T = *processing time + waiting time,* with the waiting time the time a packet waits in the buffer. [12]
This data queue is depicted in *Figure 2-2.*

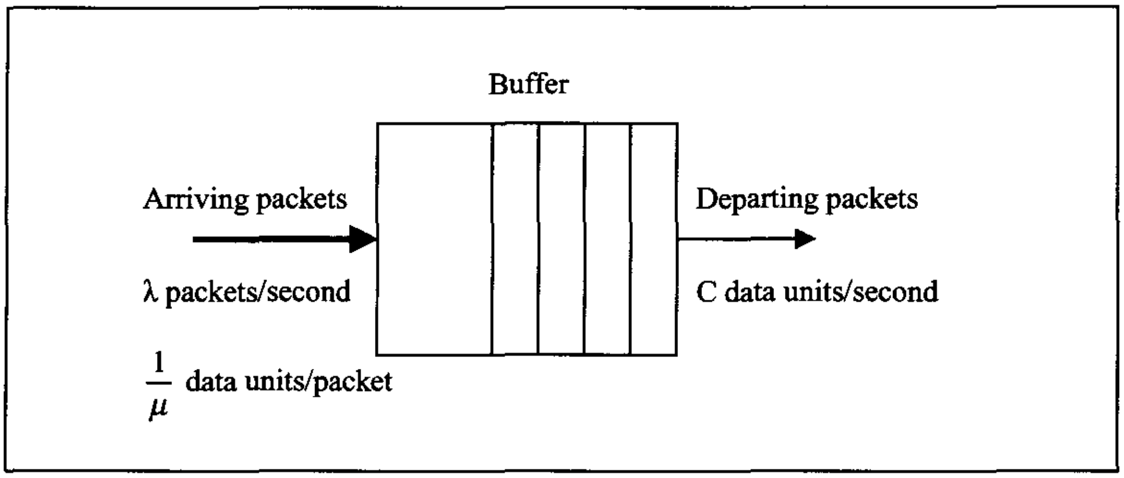


Figure 2-2: Schematic diagram of delays occurring in network

If all packets are of the same size, the delay is:

$$T = \frac{1}{\mu C} + \frac{n}{\mu C} s \qquad (2.1)$$

where n is the number of packets in the queue. This means that the delay T is dependent on the packet size, the outgoing transmission rate C, as well as the state n of the buffer. [12]

If the number of packets in the queue, the packet size and the transmission rate are known, the time delays that occur in the network can easily be predicted. This can also be used on a physical network to find different time delays for different situations. [13]

2.12. Synchronisation of time stamps

The different mediums should now be studied to find the delays that occur over distances and in switching between mediums. Some of the information is available as specifications of the different mediums, and other can only be found by setting up a small network and testing the delays that occur.

All the separate entities that work together in the telecontrol network has its own characteristics and could, because of a number of factors, influence the transmission of data negatively.

One of these negative factors is that of lengthy transmission delays. These delays result in inaccurate time-stamping which, in turn, results in inaccurate event logs. If each entity in the network's characteristics is studied and the delays that it introduces into the network can be isolated, the sum of those delays should result in the total delay in the network. The total delay in the network can then be used to adapt time stamps to be more accurate.

3. Delays occurring in mediums

In a fully configured network, time delays occur because of the way protocols are configured. Switching between different protocols takes up some time as well. Another way delays occur is because of the medium that is used.

The delays that occur in mediums are very closely related to the distance that the medium spans. For instance, fibre optic transmission uses light to transmit data, and light can only travel at a certain speed. Consequently the delay in fibre optic would be larger if longer fibres were used.

3.1. Fibre optic

At a first glance this seems simple, as light travels at a constant speed *c* ($3x10^8$ m/s). The problem arises when different thicknesses of optical fibres are used. The optical fibres are designed to reflect light hitting the edges of the fibre (at a certain angle) back into the fibre. This results in some of the light particles (in this case light is assumed to be particles) travelling longer distances than others. This is called pulse spreading, as transmitted pulse is spread out in time as it travels along the communication link.

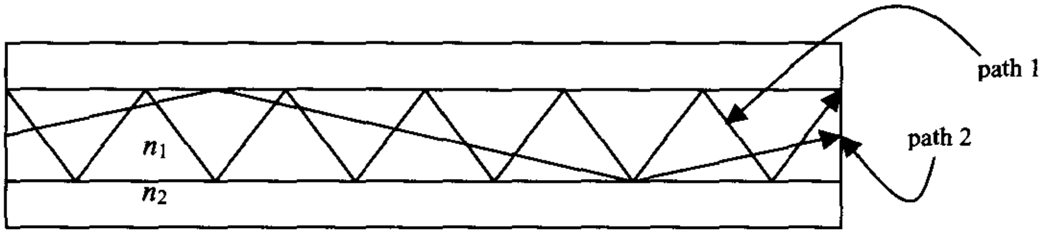


Figure 3-1: Modes in an optical fibre

The different paths (called modes) that the light takes are depicted in *Figure 3-1*. It is clear that path 1 would take a much longer time to reach the destination than path 2. Pulse-spreading causes a limited bandwidth to be used in fibre optic transmission. In single mode fibre, only a single path is available for the light to travel, this would mean that pulse-spreading would be eliminated. The time it takes for a full pulse to arrive at the destination also causes a time delay larger that that of light travelling at c m/s. The speed of light c m/s is measured in a vacuum. Light can not travel at full speed inside an optical fibre. The quality of the optical fibre in use also plays a role in the time delays and the pulse spread that occur in optical fibre transmission. The velocity v of light inside the optical fibre is given as:

$$v = \frac{c}{n_1} \text{ m/s} \tag{3.1}$$

with n_1 the index of refraction of the optical fibre (typically in the order of 1,5). The time t_1 it takes for a particle of light to traverse a distance l is given as:

$$t_1 = \frac{l.n_1}{c} \text{ seconds.} \tag{3.2}$$

The time it takes for a full pulse to reach the destination is dependent on the angle θ that the highest-order mode hits the edge of the fibre. This time $t_{\max}$ is given by:

$$t_{\max} = \frac{l.n_1}{c \sin\theta} \text{ seconds.} \tag{3.3}$$

The pulse spread is given by the difference in $t_{\max}$ and t_1:

$$\tau_{ps} = t_{\max} - t_1 \text{ seconds} \tag{3.4}$$

Substituting equations (3.2) and (3.3) in (3.4) equates:

$$\tau_{ps} = \frac{l.n_1}{c}(\sin\theta - 1)\,\text{seconds.} \qquad (3.5)$$

For multimode fibre, where the core is of refraction index n_1 and the cladding has a refraction index of n_2, equation (3.5) can be simplified to:

$$\tau_{ps} = \frac{l.n_1}{c}\left(\frac{n_1}{n_2} - 1\right)\text{seconds.} \qquad (3.6)$$

The maximum time delay of the optical fibre line can then be expressed as:

$$t_{del} = \frac{l.n_2}{c} \qquad (3.7)$$

For a simulation to be set up using these equations, only the length of the fibre and the indexes of refraction is needed. Optical fibres have specifications that describe all indexes in the fibre.

Example:

A 15-km, 50μm diameter multimode optical fibre with n_1 = 1,5 and n_2 = 1,485 is to transmit data pulses. Determine the pulse spreading and the consequential time delay:

The pulse spread can easily be calculated by substituting the specifications of the optical fibre into equation (3.6). This results in a pulse spread of 757,6 ns. This means that a single pulse will be received for 757,6 ns. If a second pulse is transmitted within 757,6 ns from the first, the two pulses will be received as one pulse of 1515,2 ns.

The time delay can now be found by substituting the optical fibre's specifications into equation(3.7). This results in a time delay of 74,25 μs. This means for a full pulse to be transmitted across a 15-km fibre optic line, it takes 74,25 μs.

3.2. Microwave transmission

The transmission delays caused in microwave transmission is theoretically the same as fibre optics, except for one crucial difference: the signal is not limited to a physical medium such as a section of cable. This creates a few problems when transmitting data at high speeds. Most of these problems also have a large effect on the time it takes for a signal to reach its destination.

Microwave transmission is often used to transmit over rough terrain, because no cables have to be installed across the terrain. *Figure 3-2* shows a microwave transmission across a mountain range.

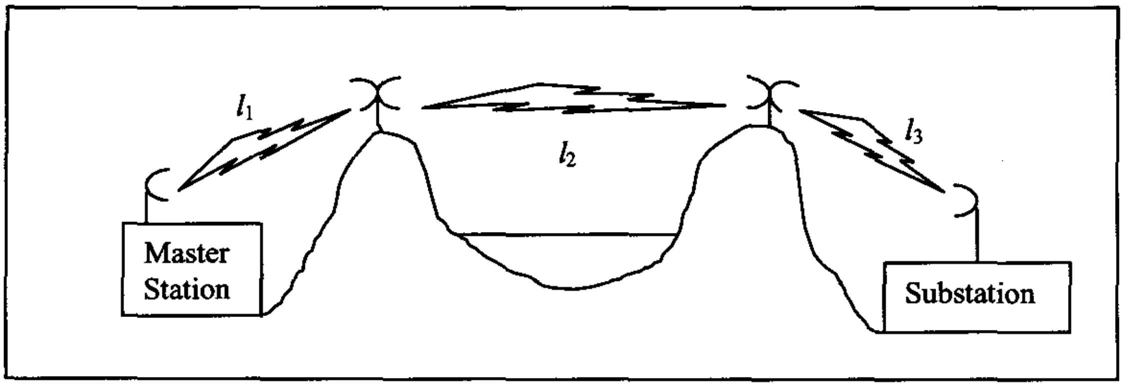


Figure 3-2: A radio link traversing rugged terrain

In many cases all transmission between transmitters or repeaters occurs in straight lines. In these cases, computing the time it takes for a message to arrive is simple. Information is transmitted at the speed of light through the atmosphere, thus, as with fibre optics:

$$t_1 = \frac{l.n_1}{c} \text{seconds.} \qquad (3.8)$$

Using the earth's atmosphere as transmission medium, n_1 can be taken as 1 and l is the distance between transmitters. Unfortunately, in most cases the signal does not travel in a straight line, and, in some cases, travels in two or more paths towards the destination. These paths influence *l*. If the paths are known, *l* can be changed to compensate for these problems.

3.2.1. Reflectors

Sometimes large objects obstruct the line of sight of the transmitter to the receiver. To avoid the cost of using repeaters to retransmit the signal, large metal reflectors are often used. A reflector reflects signals in much the same way as a mirror reflects light – as with a mirror, signals can only be transmitted at certain angles. At frequencies above 6 GHz, reflectors are very effective, as reflectors for lower frequency signals become too large to be practical. A reflector of about 6m x 9m would reflect close to 100% of the incoming signal in the UHF band. [2]

The use of reflectors is part of the network design, and thus the new path length would be known to the system designer. If this new path length is taken into account in equation (3.8), the use of reflectors is not a problem in computing the delays in microwave systems.

3.2.2. Passive repeaters

In some cases reflectors are very ineffective (below 2 GHz). At these frequencies, passive repeaters are often used. A passive repeater consists of two parabolic antennas connected via a short piece of coaxial cable. This creates three effective paths where two paths use atmosphere as medium and the other uses coaxial cable as medium. The time delays occurring in the coaxial cable have to be computed separately from that occurring in the atmosphere. [2]

3.2.3. Multipath propagation

The effect that occurs in radio waves, where the radio waves curve a little with the curve of the earth and the changes in the curve that appear when the atmosphere changes in temperature or humidity, is called multipath propagation. [2]

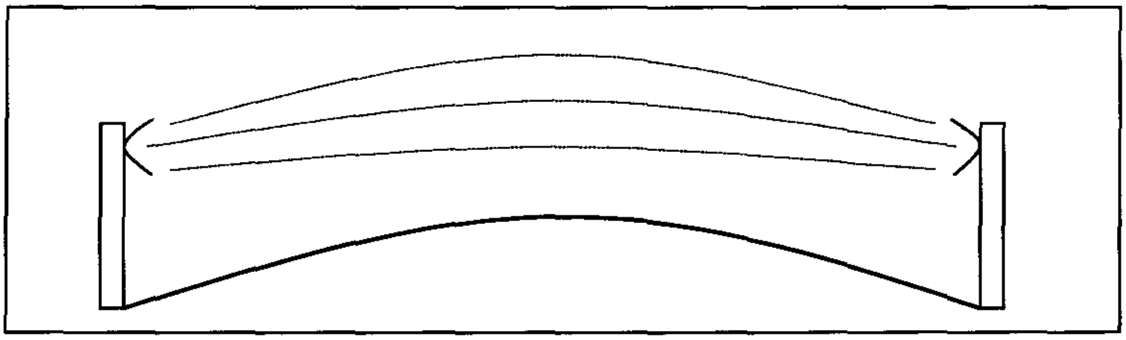


Figure 3-3: Three different refractive conditions

A way to quantify the refraction of the radio wave is to divide the effective radius of the wave's curve by the radius of the earth:

$$K = \frac{R_{effective}}{R_{true}} \tag{3.9}$$

Generally the value of K is $\frac{3}{4}$.

3.2.4. Diversity

In many cases a network designer allows two or more possible paths for a signal to travel. There are two types of diversity, space diversity and frequency diversity.

Space diversity: Space diversity uses two antennas at the receiving end of the link that are spaced at different heights on the mast. The two heights are chosen in such a way that, if there is a reflected signal, the two waves arriving at one antenna would be in phase, whilst the two waves arriving at the other antenna would be exactly out of phase. Each antenna is then taken to a separate receiver where the bit error rate (BER) is monitored. The receiver output with the best BER is taken as the output.

Frequency diversity: In the case of frequency diversity, the same signal is transmitted on two different frequencies. As two different frequencies have different behavioural characteristics, if one of the signals is corrupted at the destination, the other should be intact.

3.2.5. Effect of diversity on calculation of delays

Space diversity does not pose such a big problem when dealing with time-stamping. As long as a little bit of intelligence is built into the system, the delay can be found by using the path length of the chosen signal.

Frequency diversity poses a larger problem, as it is not known which path was taken. A possible solution is to time-stamp nodes only at certain times, when the precise path length can be established. This, however, would not necessarily help the systems administrator in investigating a chain of events, as it is not known which path was taken when a network error occurred.

4. Modelling delays in DNP3

The protocol that the network uses can also introduce certain delays into the network. These delays are predominantly because of processing time as the data moves through the different layers (such as the seven ISO layers). In some cases the protocol is also designed to help find and quantify delays that occur in the network. It is therefore important to understand each protocol.

4.1. DNP3

In order to correctly use the DNP3 protocol to predict delays that may occur in the medium, it is important to understand the working of the protocol.

As stated earlier, DNP3 utilises only three of the seven ISO layers; these are the application, data link and physical layers. The limited transport functionality can be seen as a fourth layer, often called the pseudo-transport layer. [2]

4.1.1. Application layer

The application layer is the first layer that receives data input from the user or other means of data input. The purpose of the application layer is to form the data into manageable size blocks called Application Service Data Units or ASDUs.

The application layer adds a header to each block of data; the header is referred to as Application Protocol Control Information, or APCI. The APCI is either 2 bytes or 4 bytes in length, depending on whether the message is a request or a response. If the input is a command or other request that does not require any other data, only the header is transmitted, with no ASDU. [14]

The whole fragment of data, consisting of the ASDU and APCI, is called the Application Protocol Data Unit or APDU. Each APDU may not be larger than 2048 bytes.

4.1.2. Pseudo-transport layer

The pseudo-transport layer does not have the full functionality of a full transport layer, in fact, it has very little functionality and is often not regarded as a layer. The APDU is passed from the application layer, onto the pseudo-transport layer. [14]

The pseudo-transport layer interprets each fragment as pure data and breaks it down into smaller fragments called Transport Protocol Data Units or TPDUs. A TPDU consists of 249 bytes of data with a 1-byte header.

4.1.3. Data link layer

The data link layer receives the TPDU fragment from the pseudo-transport layer. The data link layer then adds a 10-byte header to each fragment. The data link layer also adds Cyclic Redundancy Check (CRC) error correcting data to each fragment. With all additions, each fragment now has a length of 292 bytes. The format of this new fragment is known as the FT3 frame format. [14]

4.1.4. Physical layer

The physical layer is responsible for transmitting the data over the physical medium. Usually DNP3 uses a bit-serial asynchronous physical layer. It calls for 8-bit data, 1 start bit and 1 stop bit. [14]

4.1.5. DNP3 time synchronisation

An important feature of DNP3 is that it provides time-stamping of events that take place in the SCADA network. For this time-stamping of events to be effective, all nodes in the network should have the same system clock. This means that all system clocks on the network should be synchronised with the master station clock.

The synchronisation of these clocks can be done by sending a time and date signal to all nodes in the network. The accuracy of this time-setting on all nodes depends on the delays that occur between the master station and the systems on the network. As often stated, the delays occur because of mediums in use, waiting time in transmission buffers and processing time of data.

Fortunately, DNP3 has certain functions that can help determine the delay that occur in the network. These functions can be used to test certain configurations of the network in order to set up software models to predict delays in the network.

Delay measurement procedure:

- Master station sends Code 23 Delay Measurement and records time: *MasterSendTime*
- Outstation records received time as *RtuReceiveTime*
- Outstation sends a response and records the time as *RtuSendTime*
- The master station freezes its clock on receipt and records *MasterReceiveTime*

Using this time record, the total delay in the network can be found using the following procedure:

- *RtuTurnAround = RtuSendTime – RtuReceiveTime*
- *Delay = (MasterSendTime – MasterReceiveTime – RtuTurnAround)/2*

It is important to note that the delay found by using the above procedure takes into account the delay that occurs in the medium. [2]

4.2. Testing Methodology

Using the method described above, an accurate model of all delays that occur in the network can be derived. The largest and most obvious delays are those that occur in processing (when data moves through the different layers of the protocol), and those that occur in transmission (when data is carried by a certain medium over long distances).

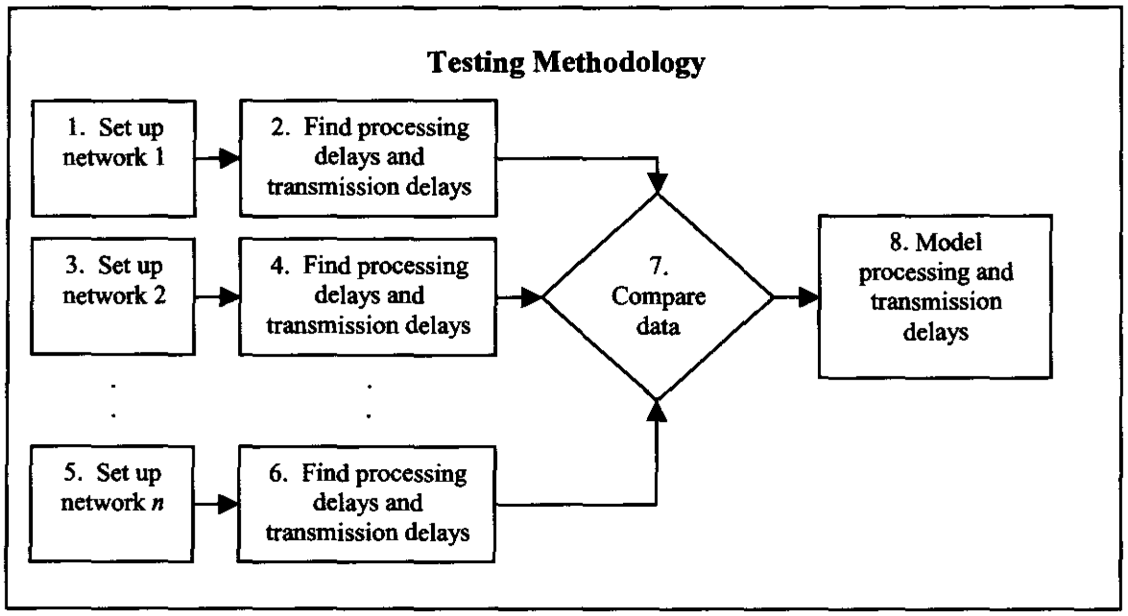


Figure 4-1: Modelling delays in DNP3

Using the methodology shown in *Figure 4-1*, the exact delays that occur in each part of the network can be found.

The DNP3 network can be set up using four different topologies, each of which would have different delays that should be found. The four different topologies are depicted in *Figure 4-2*. It is important that all tests that are carried out are well-defined. It is also very possible that new problems may arise while the tests are carried out. For this reason the tests must be flexible to change if it is needed.

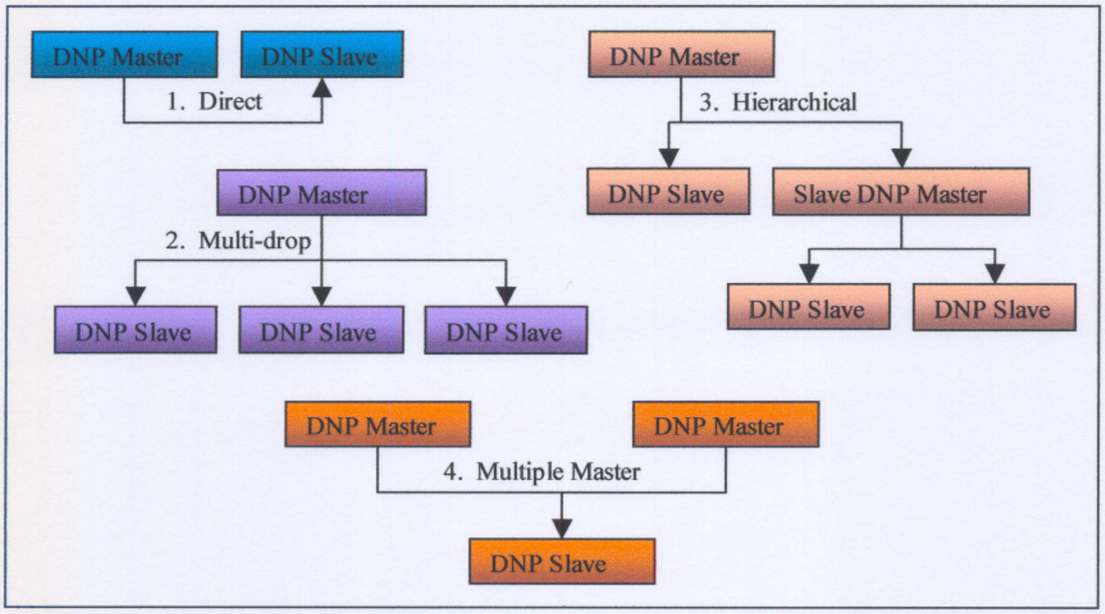


Figure 4-2: DNP3 network topologies

4.2.1. Test 1

The first test has to be the simplest one, namely to find all basic delays that might occur in the network. As the tests become more complex, it becomes more difficult to isolate different delays. For this reason, a simple point-to-point architecture (*Figure 4-2*: 1. Direct) is used for the first test.

An appropriate medium, such as fibre optic, should be used. If possible another medium such as microwave, should be used as well to find the delay component of the transmission medium.

- Configure network over short distance to eliminate transmitting medium delays
- Run command Code 23 on master station

After command Code 23 has been executed, all the processing times should have been recorded by the master- and substation. The full delay can then be calculated as:

$$Delay = (MasterSendTime - MasterReceiveTime - RtuTurnAround)/2$$

To analyse the components of the delay, other time stamps can be used.

Propagation delay 1 = RtuReceiveTime - MasterSendTime

Propagation delay 2 = MasterReceiveTime - RtuSendTime

RTU processing time = RtuTurnAround

4.2.2. Test 2

For the second test, the network will be configured with transmission units such as fibre optic switches or TAIT modem radios. The delays in the transmission units would add to the delays found in Test 1.

- Configure network over short distance to eliminate transmitting medium delays
- Run command Code 23 on master station

After command Code 23 has been executed, all the processing times should have been recorded by the master- and substations. All delays on all substations can then be calculated as:

Delay = (MasterSendTime – MasterReceiveTime – RtuTurnAround)/2

To analyse the components of the delay, other time stamps can be used.

Propagation delay 1 = RtuReceiveTime - MasterSendTime

Propagation delay 2 = MasterReceiveTime - RtuSendTime

RTU processing time = RtuTurnAround

4.2.3. Test 3

In the third test, the network will use a hierarchical (*Figure 4-2*: 3. Hierarchical) configuration. With the hierarchical network, any station can act as a master station. It is important to determine if any new delays are caused in the network as a result of this. These anticipated new delays could be because of a waiting time in buffers.

- Configure network over short distance to eliminate transmitting medium delays

- Configure master station and 1 master/slave station with its own slave station to use half-duplex
- Run command Code 23 on master 1 station

After command Code 23 has been executed, all the processing times should have been recorded by the master- and substations. All delays on all substations can then be calculated as:

Delay = (MasterSendTime – MasterReceiveTime – RtuTurnAround)/2

To analyse the components of the delay, other time stamps can be used.

Propagation delay 1 = RtuReceiveTime - MasterSendTime

Propagation delay 2 = MasterReceiveTime - RtuSendTime

RTU processing time = RtuTurnAround

4.3. Delays in a live SCADA network

Before the first tests are done, it is important to define exactly how the delays in the network are going to be found. A typical setup of a live SCADA network is depicted in *Figure 4-3.*

As can be seen in *Figure 4-3,* the setup can be divided into 4 sections. Looking from the RTU in the field, the first section would be the RTU. In this case the RTU uses a UHF radio link (second section) to communicate to a repeater that gathers information via the Bandwidth Management Equipment (BME) (third section) from a number of RTUs and sends this information through to the SCADA control centre (fourth section).

If the RTU is connected directly to the SCADA master station, all delays that occur in sections two and three are eliminated. This should then be how the first test should be done – to only find the processing delays in the master station and slave station.

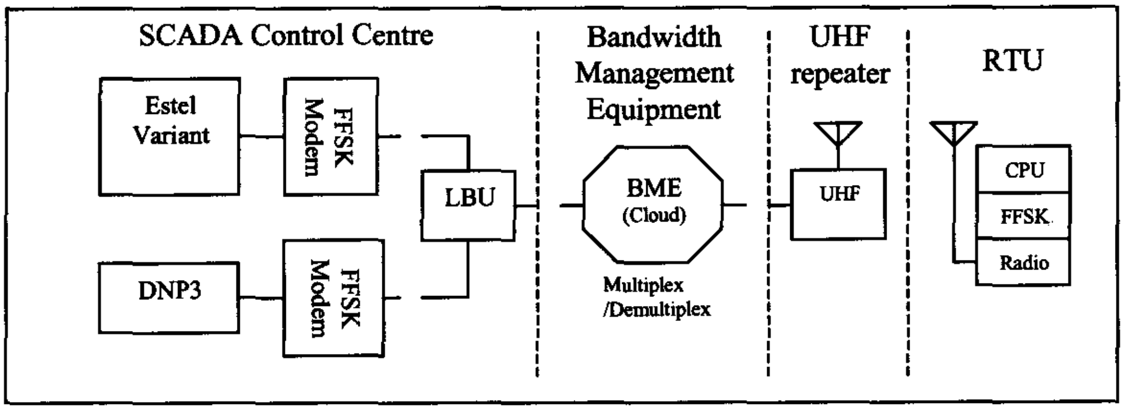


Figure 4-3: Single UHF repeater communication diagram

In *Figure 4-3* it is possible to connect the RTU any place where there is an IDF – the IDF serves as an intermediate connection. Running a function Code 23 on the master station with the RTU connected to all the different places where an IDF exists, all the delays that occur in each part can be calculated.

4.4. Setting up the DNP3 model

To model the delays that occur in a DNP3 network, a lab network is first set up. The simplest type of network is configured first – a direct link between the master- and slave station. Using a direct link eliminates propagation delays and ensures that the only delays that are recorded are delays that occur in the processing of the master station and the slave station.

The master station is a simple desktop computer with specific DNP3 software running on it. The slave is a RTU. Once connected, the slave can be configured and put online. With the master station and the slave station communicating, the Code 23 - delay measurement is run on the master station. The delay measurement is done a few times to ensure that the delays are in the same order every time. The results of this first test dictate the next step. It is important to make sure that all delays that could occur are accounted for before continuing.

4.5. Test Results

4.5.1. Test 1: Nulec recloser to master via direct link.

The first tests that were done were done on a Nulec RTU connected to a recloser simulator. The device is made specifically for test purposes – the RTU is a real Nulec RTU, but the alarms coming from the recloser are simulated. The master station is set up on a personal computer running FieldCom software. FieldCom analyses the DNP3 protocol and converts the messages into an easily-understandable form. The raw bits can also be accessed via FieldCom as hexadecimal values.

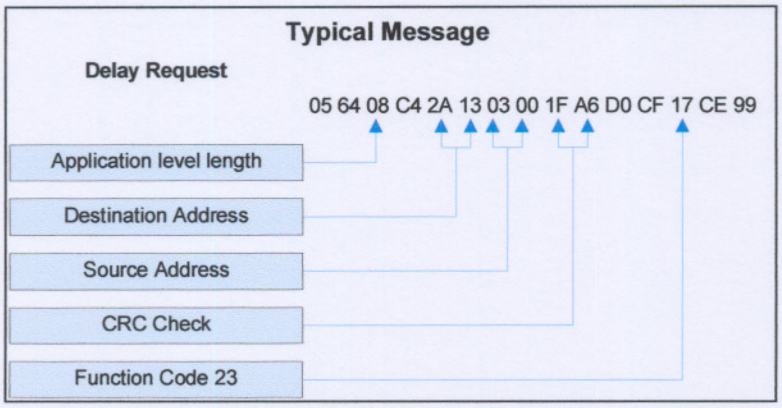


Figure 4-4: Function Code 23 message analyzed from Hex

The function Code 23 message analysed from FieldCom is depicted in *Figure 4-4*. The response to this message from the DNP3 slave is depicted in *Figure 4-5*.

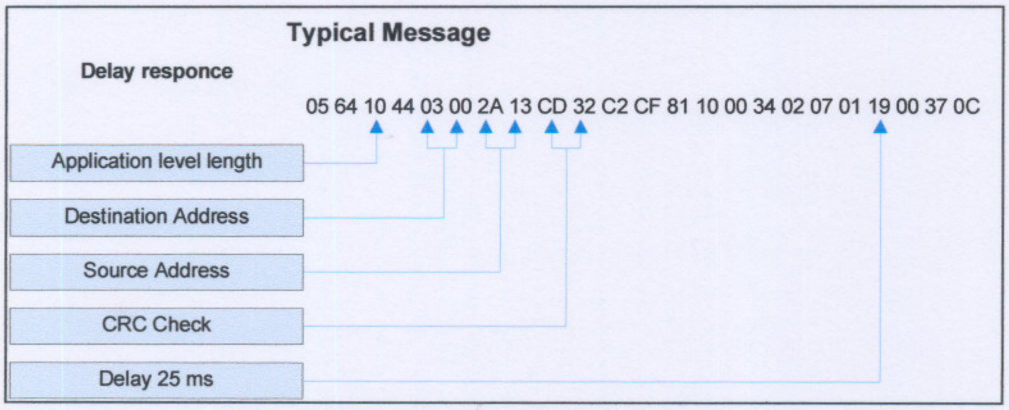


Figure 4-5: DNP3 slave response to FC23 analysed in Hex

Once the message containing the delay is received from the DNP3 slave, the master station adds the delay to its system clock and sends this adapted time to the DNP3 slave. The message sent to the DNP3 slave is depicted in *Figure 4-6*.

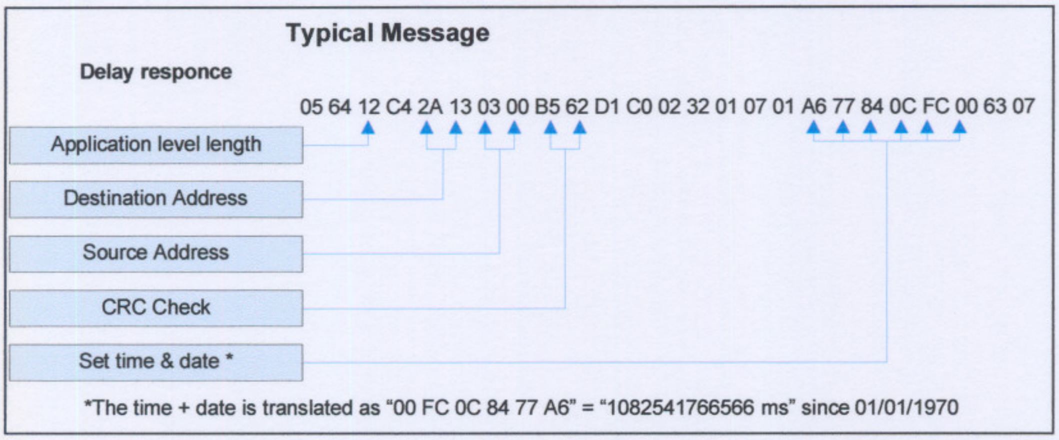


Figure 4-6: Updated set time message analysed in Hex

Function Code 23 was run 50 times - with communications set up to a baud rate of 9600, 4800 and 2400 respectively.

Figure 4-7: Delay request message as a bit stream

The results of these tests where analysed to not only give the average delay that occurs, but also how much the consecutive delays are within certain boundaries of one another.

This is of some significance, because the delay should be the same when the delay's measure message is transmitted and when the set time message is transmitted.

Test results:

9600 baud – The results of the delay tests, done with a direct link from the master station to the Nulec recloser, produced the following data:

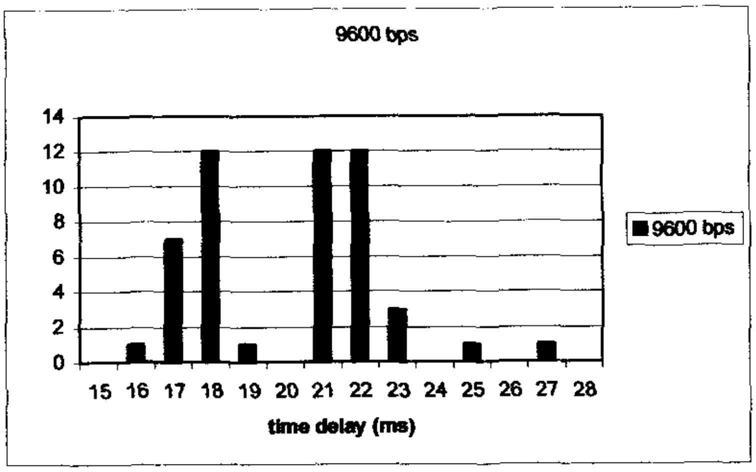


Figure 4-8: Test results of direct link Nulec at 9600bps

The average delay of the above tests is 20.14 ms. The minimum delay is 16 ms and the maximum delay is 27 ms. If the delay is set to 21.5 ms, with a maximum error of 5.5 ms, we are still well within the limits of a maximum error of 10 ms.

Statistical Analysis – 9600 bps	
Mean	20.14
Median	21
Standard Deviation	2.424450285
Range	11
Minimum	16
Maximum	27

Table 4-1: Statistical analysis – 9600 baud

Statistical analysis is shown in *Table 4-1*. Note that the mean and median differ with less than 1 ms. This is an indication that the spread of the delays is fairly even. The full data recordings and analysis are shown in **Appendix B.**

4800 baud - The results of the delay tests done, with a direct link from the master station to the Nulec recloser, produced the following data:

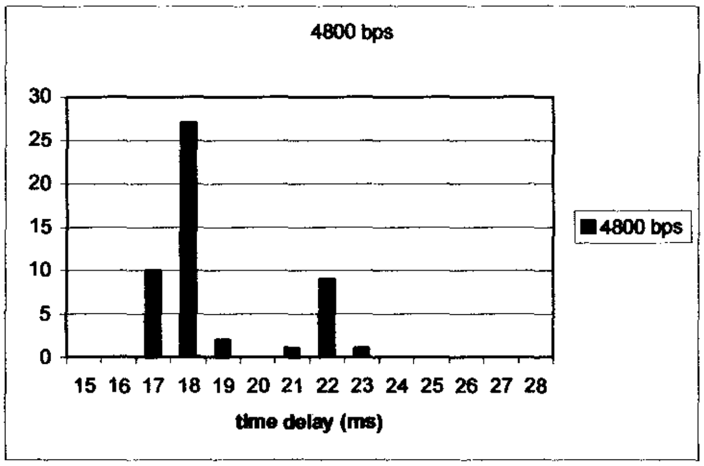


Figure 4-9: Test results of direct link Nulec at 4800bps

The average delay of the above tests is 18.72 ms. The minimum delay is 17 ms and the maximum delay is 23 ms. If the delay is set to 20 ms with a maximum error of 3 ms we are still well within the limits of a maximum error of 10 ms.

Statistical Analysis – 4800 bps	
Mean	18.72
Median	18
Standard Deviation	1.829910224
Range	6
Minimum	17
Maximum	23

Table 4-2: Statistical analysis – 4800 baud

Statistical analysis is shown in *Table 4-2.* Note that the mean and median differ with less than 1 ms. This is an indication that the spread of the delays is fairly even. The full data recordings and analysis are shown in **Appendix B.**

2400 baud - The results of the delay tests, done with a direct link from the master station to the Nulec recloser, produced the following data:

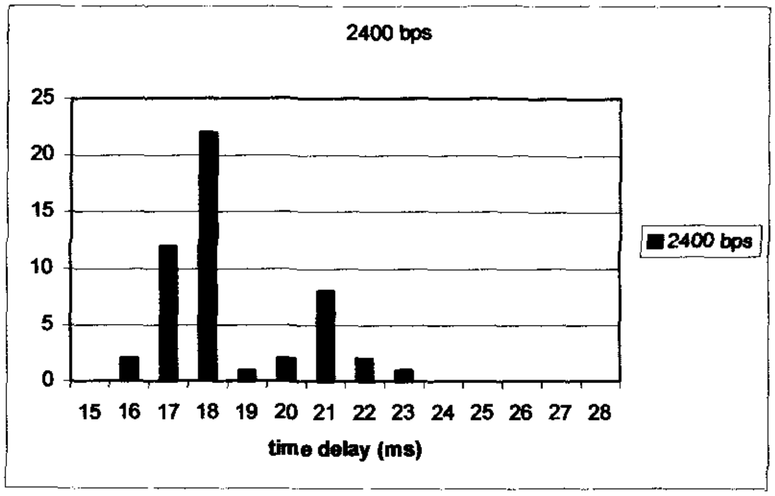


Figure 4-10: Test results of direct link Nulec at 2400bps

The average delay of the above tests is 18.52 ms. The minimum delay is 16 ms and the maximum delay is 23 ms. If the delay is set to 19.5 ms with a maximum error of 3.5 ms we are still well within the limits of a maximum error of 10 ms.

Statistical Analysis - 2400 bps	
Mean	18.52
Median	18
Standard Deviation	1.71714048
Range	7
Minimum	16
Maximum	23

Table 4-3: Statistical analysis – 2400 baud

Statistical analysis is shown in *Table 4-3*. Note that the mean and median differ with less than 1 ms. This is an indication that the spread of the delays is fairly even. The full data recordings and analysis are shown in **Appendix B.**

Because the delays of the three baud rates are so close, it is possible to combine all the data into one to get an average delay at all baud rates that are still within the 10 ms error range. This combined data is depicted in *Figure 4-10*. The combined data has an average delay of 19.127 ms. The minimum delay is 15 ms and the maximum delay is 27 ms. If the delay is set to 21ms, with a maximum error of 6ms, we are within the limits of a 10 ms error level. Taking the combined rate means that a total of 150 samples of delays were taken. Because the mean delays of the 3 separate sets of 50 tests differ with less than 2 ms, it was accepted that 50 samples would be sufficient for future data sets.

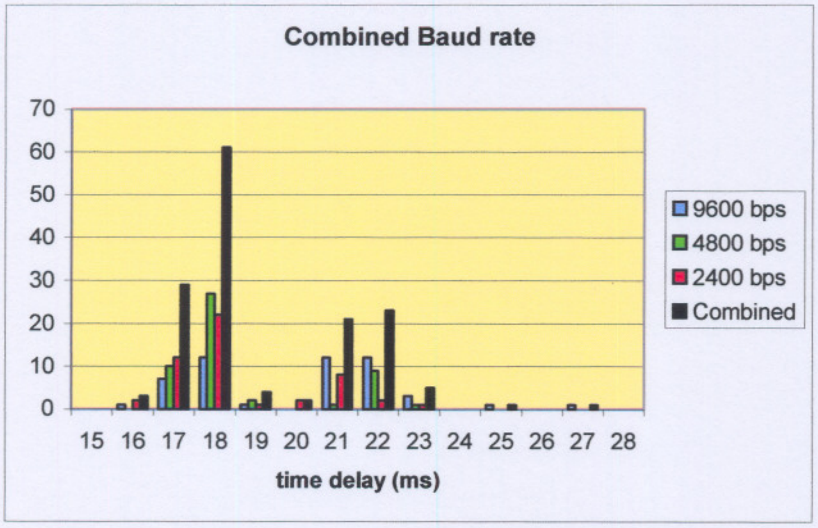


Figure 4-11: Test results of direct link Nulec at a combined bit rate

4.5.2. Test 2: Nulec recloser to master via TAIT radios.

To test the delays that occur in the TAIT radios only, a delay test from the master to the slave must be done, with the radios in between. The delays by the slave can then be subtracted to get the TAIT radio delay only.

The original results of the master-to-slave test with TAIT radios in between are displayed in *Figure 4-12.*

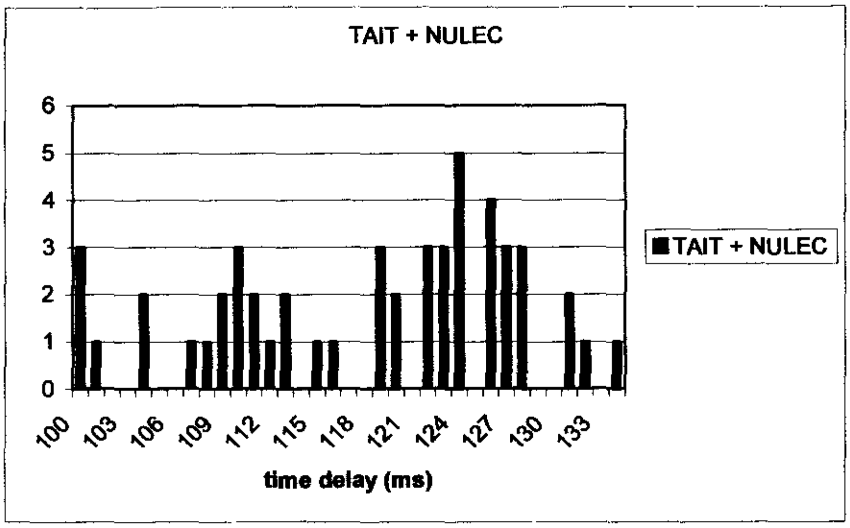


Figure 4-12: Test results of master- to-slave with TAIT radios

It is important to note that these delays include the processing delays that occur in the NULEC recloser. To take these delays into account, the delays caused by the NULEC must be subtracted from the total delay. To allow for a better accuracy, the three sets of direct link data is combined to get 50 average delay samples.

Statistical Analysis - TAIT Radio + NULEC	
Mean	118.24
Median	121
Standard Deviation	9.395092075
Range	34
Minimum	100
Maximum	134

Table 4-4: Statistical analysis – TAIT + NULEC

Statistical analysis is shown in *Table 4-4*. Note that the mean and median differ with less than 3 ms. This is an indication that the spread of the delays is fairly even, even though the spread does have a slight tendency to lean towards the higher delays. The full data recordings and analysis are shown in **Appendix B.**

To allow for worst case and best case scenarios, it can be said that the largest TAIT + Nulec delay is the result of a large TAIT delay combined with a large NULEC delay. The smallest TAIT + NULEC delay is the result of a small TAIT delay combined with a small NULEC delay. For this reason the data must be transformed by subtracting the smallest direct link delays from the smallest TAIT radio delays. The result of this transformation is depicted in *Figure 4-13.*

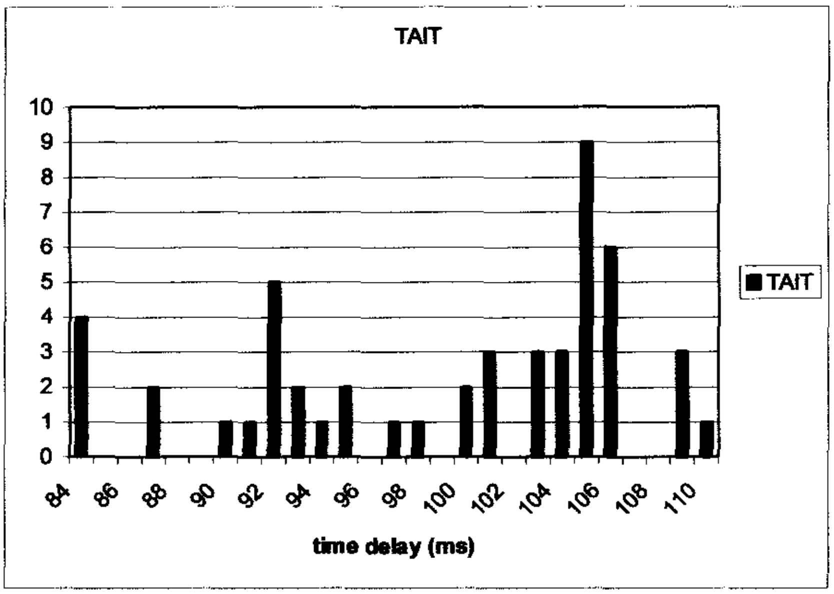


Figure 4-13: Test results of TAIT radios only transformation

After the transformation it is clear that the range of the different delays is now between 83 ms and 110 ms (a difference of 27 ms). This is down from between 100 ms and 134 ms (a difference of 34 ms). If a set delay of 98 ms is chosen, the largest error is 15ms, with an 80% chance of the delay being between 90 ms and 106 ms, which translate to a maximum error of 8 ms.

Statistical Analysis - TAIT Radio	
Mean	99.12
Median	102
Standard Deviation	7.758181988
Range	27
Minimum	83
Maximum	110

Table 4-5: Statistical analysis - TAIT

Statistical analysis is shown in *Table 4-5*. Note that the mean and median differ with less than 3 ms. This is an indication that the spread of the delays is fairly even, even though the spread still does have a slight tendency to lean towards the higher delays. The full data recordings and analysis are shown in **Appendix B.**

If we assume that each radio contributes to half of the total delay, each radio contributes 49 ms to the total delay, with a maximum error of 8 ms and an 80% chance of a maximum error of 4 ms. When the same tests are conducted on a live network through a repeater, the reason for this assumption will become clear.

4.5.3. Test 3: Nulec recloser to master via MDS radios

Eskom is at the moment in the process of implementing MDS radios to replace the TAIT radios. MDS radios are digital communication devices, as opposed to analogue TAIT radios. The same tests and transformations as with the TAIT radios have to be done with the MDS radios. The results of the original data, with the Nulec recloser delays included are depicted in *Figure 4-14*.

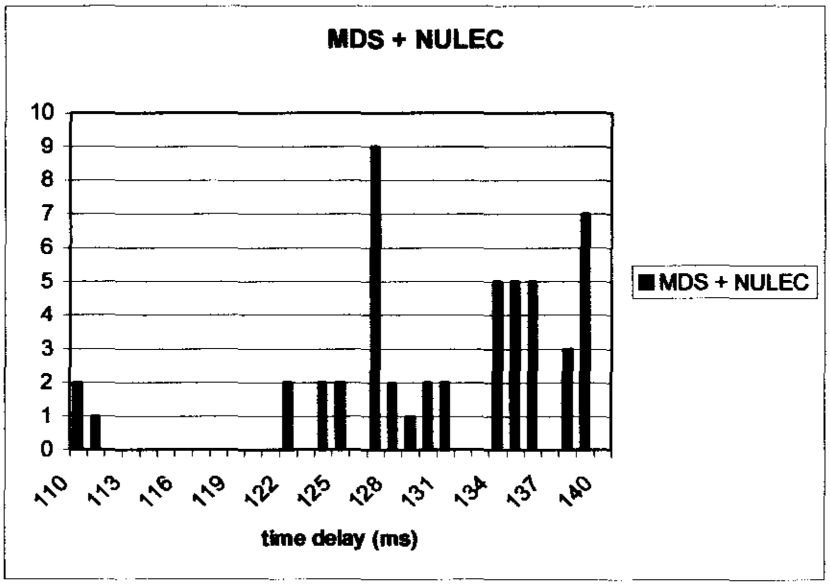


Figure 4-14: Test results of master-to-slave with MDS radios

As with the TAIT radio, note that these delays include the processing delays that occur in the NULEC recloser. To take these delays into account, the delays caused by the NULEC must be subtracted from the total delay.

Statistical Analysis - MDS Radio + NULEC	
Mean	130.54
Median	132.5
Standard Deviation	7.827763253
Range	36
Minimum	103
Maximum	139

Table 4-6: Statistical analysis – MDS + NULEC

Statistical analysis is shown in *Table 4-6.* Note that the mean and median differ with less than 2 ms. This is an indication that the spread of the delays is fairly even, even though the spread still does have a slight tendency to lean towards the higher delays. The full data recordings and analysis are shown in **Appendix B.**

To allow for worst-case and best-case scenarios, it can be said that the largest MDS + Nulec delay is the result of a large MDS delay combined with a large NULEC delay. The smallest MDS + NULEC delay is the result of a small MDS delay combined with a small NULEC delay. For this reason the data must be transformed by subtracting the smallest direct link delays from the smallest MDS radio delays. The result of this transformation is depicted in *Figure 4-15.*

After the transformation it is clear that the range of the different delays is now between 87 ms and 117 ms (a difference of 30 ms). This is down from between 103 ms and 139 ms (a difference of 36 ms). If a set delay of 112 ms is chosen, the largest error is 25 ms with a 90% chance of the delay to be between 107 ms and 117 ms, which translate to a maximum error of 5 ms.

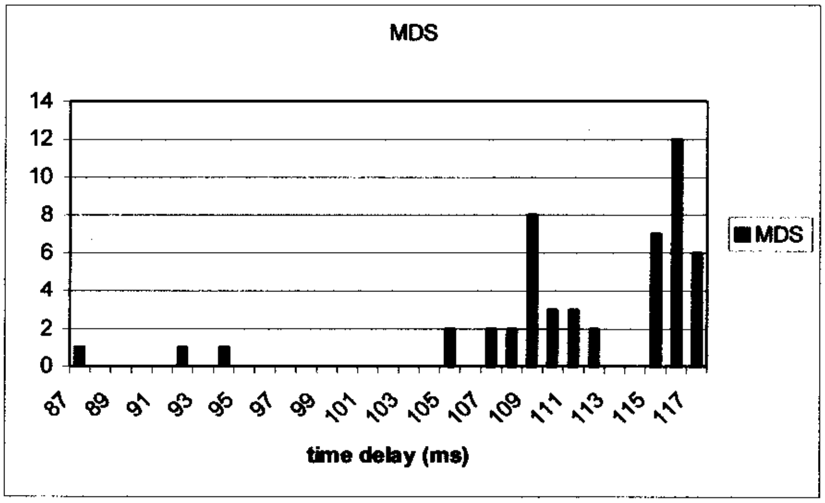


Figure 4-15: Test results of MDS radios-only transformation

An interesting point to note is that the MDS radios introduce a delay of around 10 ms more than the TAIT radios. This is possibly caused by the digital nature of the MDS radios. Digital devices use a data buffer for incoming data before the data is retransmitted onto the next medium.

Statistical Analysis - MDS Radio	
Mean	111.42
Median	113.5
Standard Deviation	6.395438425
Range	30
Minimum	87
Maximum	117
Sum	5571

Table 4-7: Statistical analysis - MDS

Statistical analysis is shown in *Table 4-7*, note that the mean and median differ with less than 3 ms. This is an indication that the spread of the delays is fairly even, even though the spread still does have a slight tendency to lean towards the higher delays. The full data recordings and analysis are shown in **Appendix B.**

If we again assume that each radio contributes to half of the total delay, each radio contributes 56 ms to the total delay, with a maximum error of 13 ms and a 90% chance of a maximum error of 3 ms. When the same tests are conducted on a live network through a repeater, the reason for this assumption will become clear.

4.5.4. Test 4: Full network setup

Now that we have broken up the entire telecontrol network into its various delays, it is important to measure the delays that occur in the network, from the control centre right through to the RTU in the field.

In order to do these tests, a change to the setup had to be done. The SMART© front-end that is used by the control centre to easily open and close breakers remotely, does not allow for ad hoc commands, such as time-delay requests, to be sent. The SMART© front-end was thus replaced by the FieldCom front-end that simulates the master station. FieldCom was used for all preceding tests.

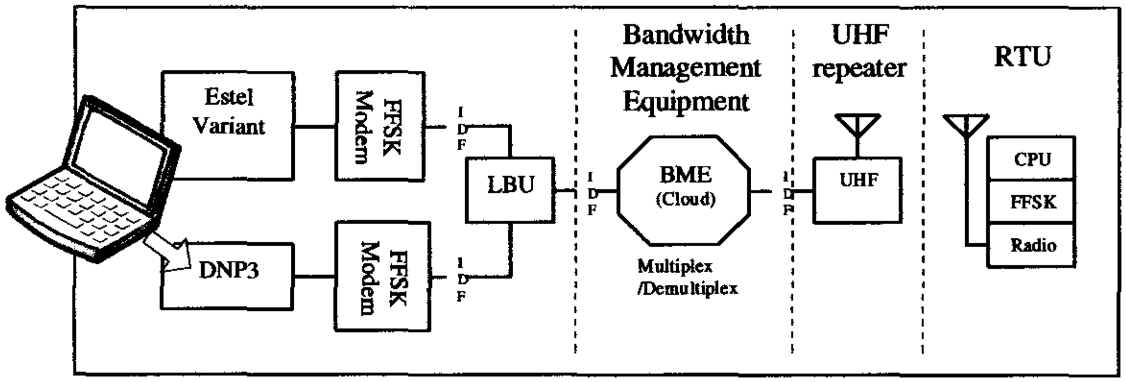


Figure 4-16: FieldCom connected to single UHF repeater

When testing the delays that occur on a live network, it can be expected that a number of other factors could have an influence on the results. In many cases the channel is used by a number of other RTUs to communicate to the master station.

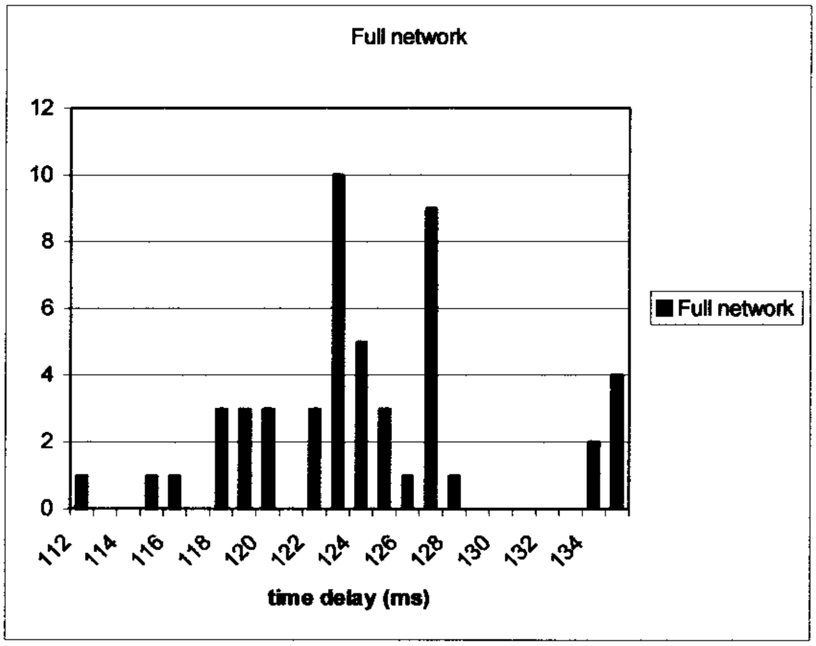


Figure 4-17: Test results of full network setup

The results of the delay test conducted on the full network are depicted in *Figure 4-17.*

Statistical Analysis – Full network	
Mean	124.2
Median	123.5
Standard Deviation	5.205962045
Range	23
Minimum	112
Maximum	135

Table 4-8: Statistical analysis – full network

Statistical analysis is shown in *Table 4-8*. Note that the mean and median differ with less than 1 ms. This is an indication that the spread of the delays is fairly even. The full data recordings and analysis are shown in **Appendix B.**

As with the TAIT and MDS radio test results, we want to isolate the delays that are caused by each component in the network. To isolate these delays, the delays caused by the NULEC must be subtracted from the total delay. As these tests were done with a

TAIT radio connected to the RTU, a single TAIT radio delay must also be subtracted from the total delays. To allow for better accuracy, the three sets of direct link data is combined to get 50 average delay samples. The smallest direct link delays are then subtracted from the smallest full network delays. The smallest TAIT radio delays are also subtracted from the smallest full network delays. The result of this transformation is depicted in *Figure 4-18.*

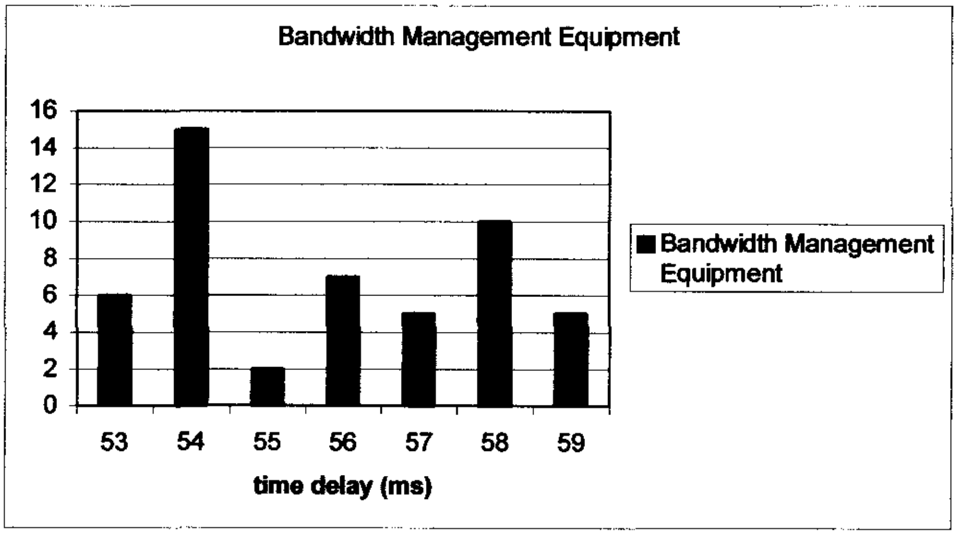
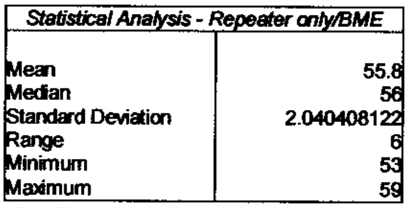


Figure 4-18: Results of the BME/repeater-only transformation

The results in Figure 4-18 show that the bandwidth management equipment with repeater is a very stable system that has very little variation in the delays that are introduced into the system. If the average delay of 56 ms is taken, the maximum error is 3 ms.



Statistical Analysis - Repeater only/BME	
Mean	55.8
Median	56
Standard Deviation	2.040408122
Range	6
Minimum	53
Maximum	59

Table 4-9: Statistical analysis – repeater/BME

Statistical analysis is shown in *Table 4-9*. Note that the mean and median differ with a mere 0,2 ms. This is an indication that the spread of the delays is very even. The full data recordings and analysis are shown in **Appendix B.**

What makes this result even more remarkable is that the tests were conducted while another RTU continuously communicated to the master station on the same channel.

Now that we have analysed all the different delays that are introduced into the network from the master station to the slave station, we can start to model the delays that occur in different network setups. The breakdown of these delays is depicted in *Figure 4-19*.

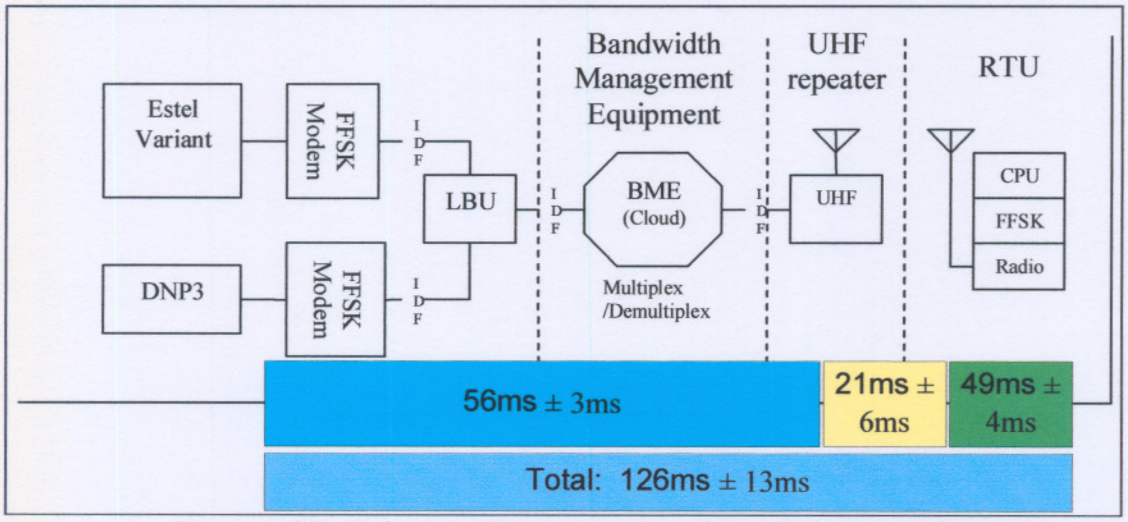


Figure 4-19: Delays as they accumulate through the network.

In *Figure 4-19,* the predefined delays as they occur separately in the network are displayed. The sum of these delays is shown to be 126 ms with a maximum error of 13 ms. This is 3 ms larger than the chosen accuracy of 10 ms. 13 ms is still at an acceptable level for protection and investigation purposes – it is also the highest level of accuracy possible when delays are modelled as downstream accumulations.

To verify the delay models, the total delay (126ms ± 13ms) is compared to the total delay that was found when the full network delay tests were conducted. These tests resulted in an average delay of 124 ms, with a maximum error of 12 ms. The comparison of these two results is remarkably close and shows that this information can be used as the sum of the parts in all different setups of the network.

5. Modelling of delays in mediums

The delays that occur in mediums are always constant for each different transmission line. These delays are dependent only on the type of medium used, the length of transmission and the specifications of that specific medium used.

5.1. *Fibre optic*

To calculate the delays that occur because of the use of fibre optic, only three variables are needed: the length of the optical fibre and the two refraction indexes of the fibre. The mathematical model thus constitutes a simple equation.

$$t_{del} = \frac{l.n_2}{c} \tag{5.1}$$

5.2. *Microwave transmission*

To calculate the delays that occur because microwave transmission is much the same than that of fibre optic, with the difference that the refraction index is taken as 1 for air.

$$t_{del} = \frac{l}{c} \tag{5.2}$$

It is important that the total delay that occurs be calculated as a summation of all the different paths (usually straight lines) that is used by the microwave medium to reach its destination.

6. Implementation of models

The models will be implemented using Matlab© using the SimuLink© functionality. SimuLink© allows the developer to use signal flow diagrams to implement models in block sets. The whole network is then connected to simulate the physical network.

6.1. DNP3

From the delays that were found during the practical testing phase, we can now build a SimuLink© model that takes these delays into account to calculate the entire delay. Each unit of equipment that the signal passes through has to be modelled using its own characteristic delay. The sum of all delays in DNP3 units, as well as the delays in the mediums used, should result in the total delay through the network.

6.2. Fibre optic

The SimuLink© model of a fibre optic line is depicted in *Figure 6-1*. The "Variable Transport Delay" block receives an input signal which is then transformed by means of a formula that the block receives as another input. The formula is specific to the fibre optic line and is determined by the length of the line and the index of refraction.

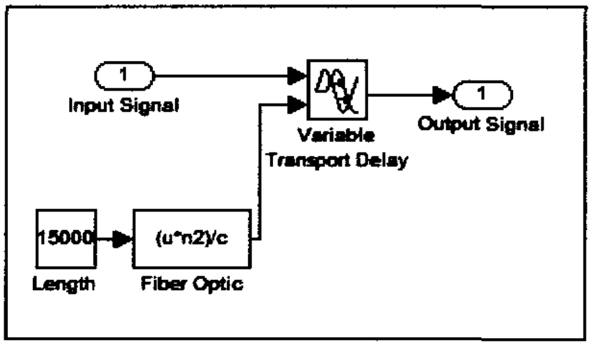


Figure 6-1: Fibre optic SimuLink model

The fibre optic model is then converted into a single subsystem, and connected to a network model (*Figure 6-2*). The outputs – input & delay – can be plotted in Matlab© to show the original signal and the delayed signal.

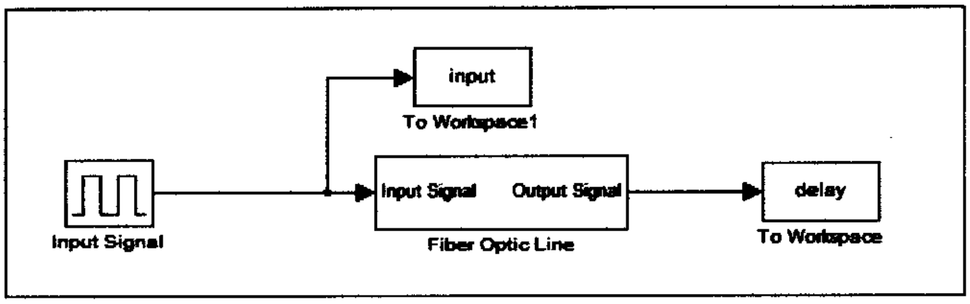


Figure 6-2: Network SimuLink model

With a pulse input, the output should be a pulse as well. The output pulse, however, should be delayed by a certain amount of time. If the same parameters are used than that of the example in Chapter 3.1, the time difference between the two signals should be 74,25μs. The plot of the two signals can be seen in *Figure 6-3*.

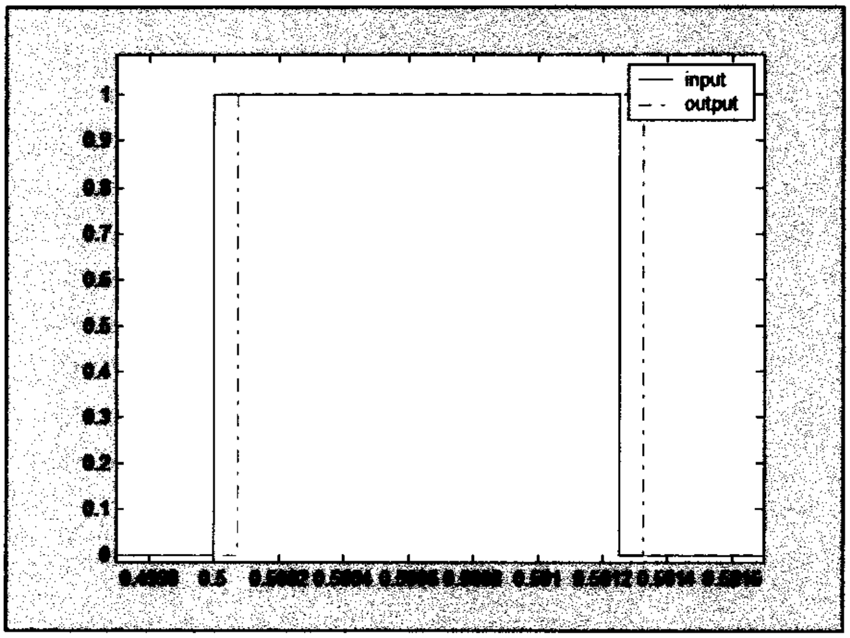


Figure 6-3: Input signal vs. delayed input signal (fibre optic)

After closer inspection of *Figure 6-3*, it can be seen that the time difference between the input and output signal is exactly 74,25µs. This means that the implementation of the model is an accurate description of the theoretical model.

6.3. Microwave transmission

By using the same SimuLink© model than that of optical fibre transmission, and changing the index of refraction to 1(air), the delays in microwave transmission can be measured.

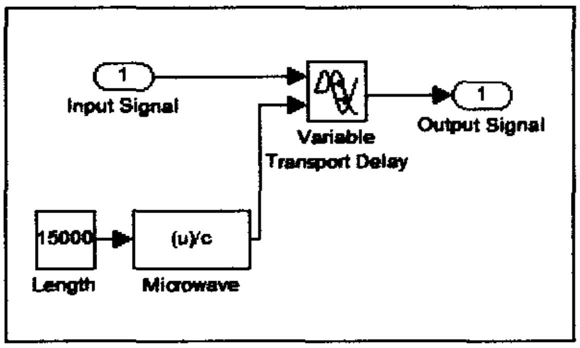


Figure 6-4: Microwave SimuLink model

The new microwave model can now be implemented in a network with an input and output to measure the time difference between the two signals.

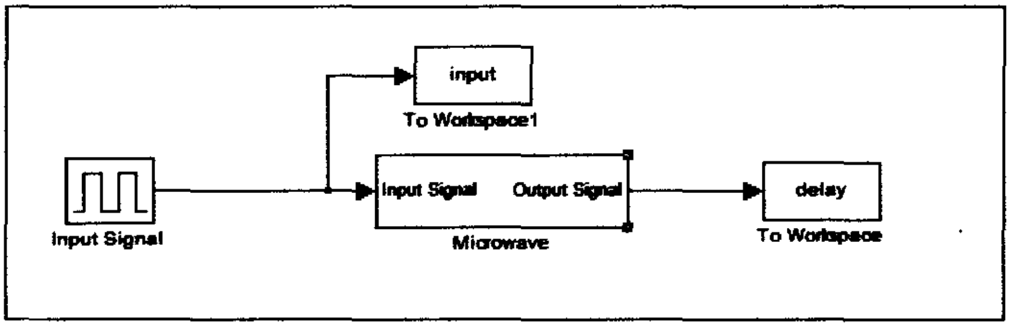


Figure 6-5: Network SimuLink model

The graph of the microwave input signal vs. output signal shows that the delay is smaller than that of fibre optic transmission. The delay on a 15-km microwave transmission is 50 µs.

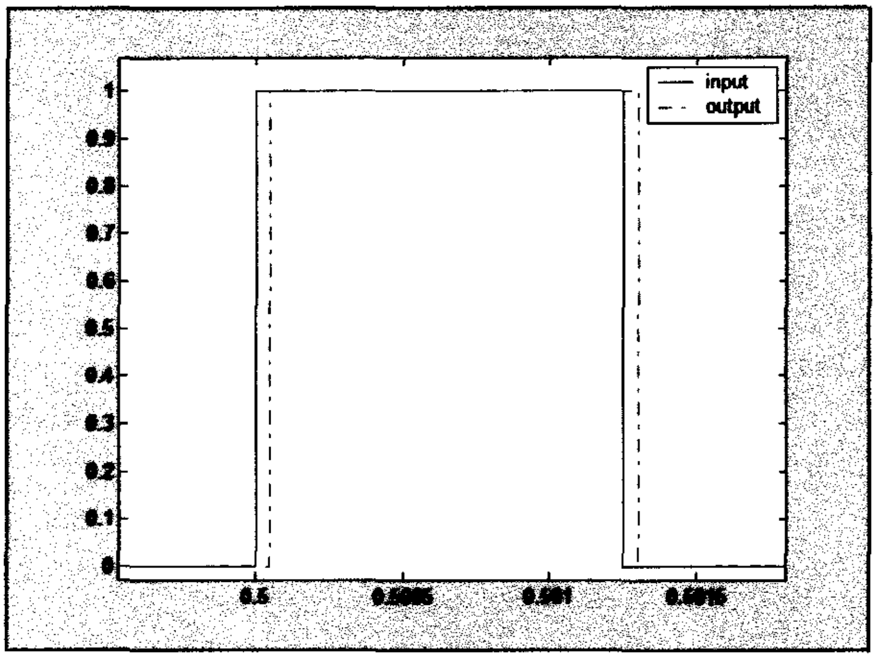


Figure 6-6: Input signal vs. delayed input signal (Microwave)

6.4. Nulec recloser

As the Nulec recloser introduces a constant delay into the network, a SimuLink© block with a constant delay is used. The constant delay is set up to be 21 ms.

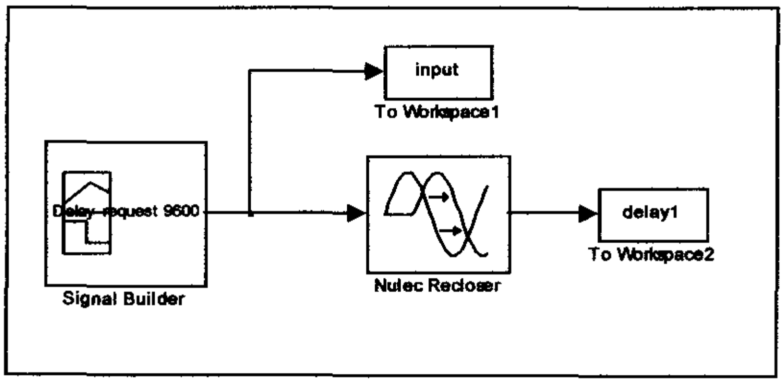


Figure 6-7: Nulec SimuLink model

The input signal into the Nulec is the delay request message, and the output is then compared to the time shift that was derived from the tests.

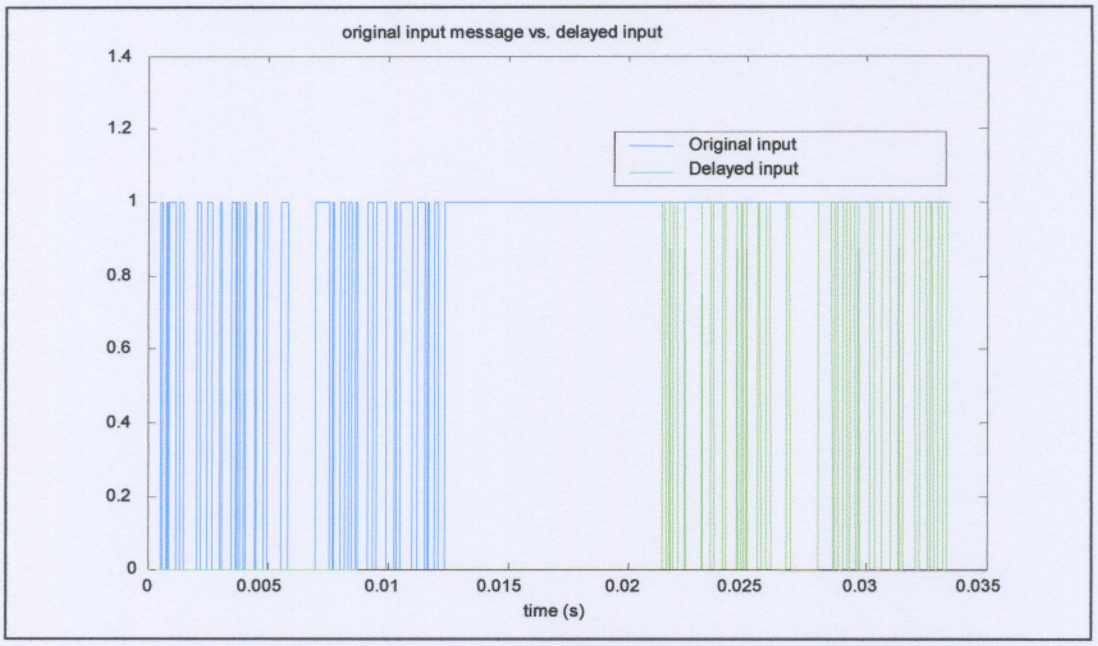


Figure 6-7: Input signal vs. delayed input signal (Nulec)

6.5. TAIT radio modems

As the TAIT radios introduce a constant delay into the network, a SimuLink© block with a constant delay is used. The constant delay is set up to be 49 ms, as it was calculated from the delay measurements done.

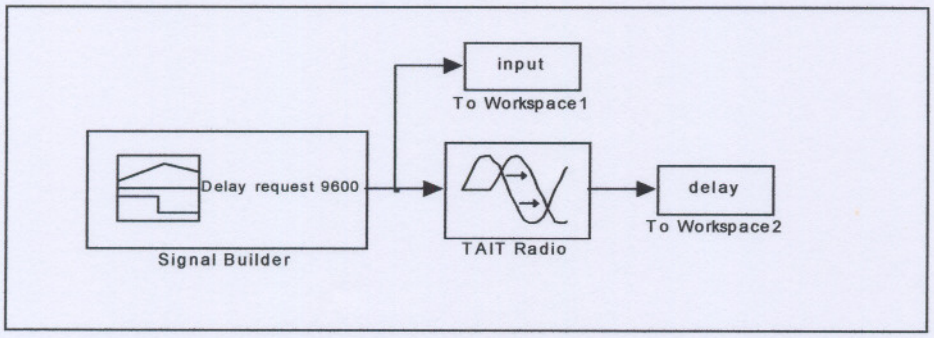


Figure 6-8: TAIT SimuLink model

The input signal into the TAIT is the delay request message, and the output is then compared to the time shift that was derived from the tests.

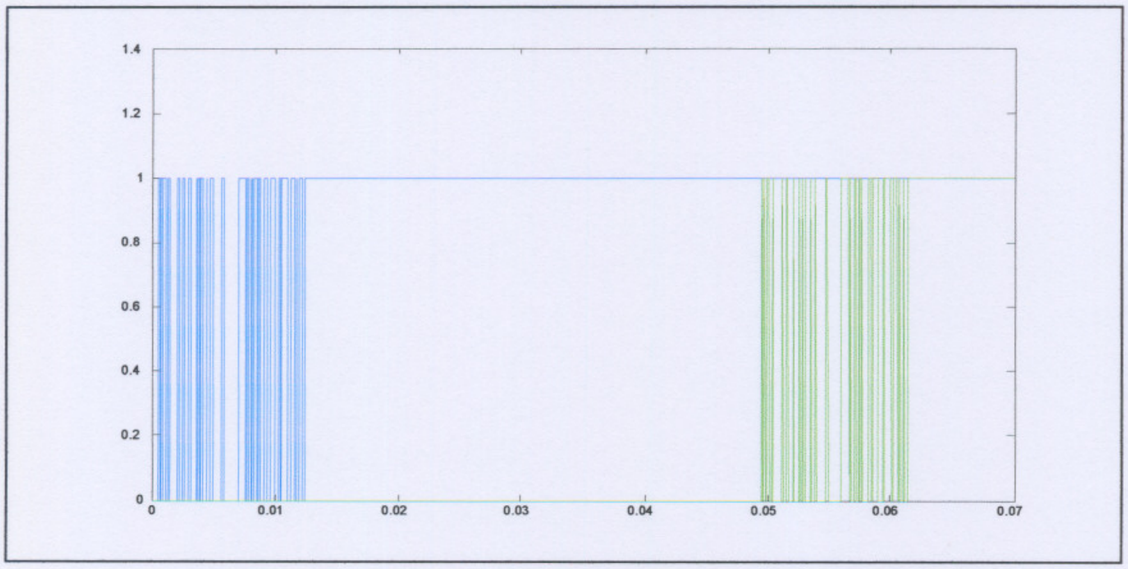


Figure 6-9: Input signal vs. delayed input signal (TAIT radios)

6.6. MDS radio modems

Like the TAIT radios, the MDS radios introduce a constant delay into the network. A SimuLink© block with a constant delay is used. The constant delay is set up to be 56 ms, as it was calculated from the delay measurements done.

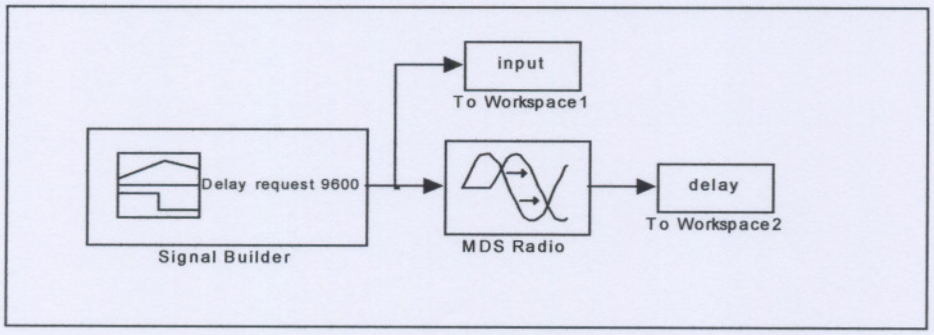


Figure 6-10: MDS SimuLink model

The input signal into the MDS is the delay request message, and the output is then compared to the time shift that was derived from the tests.

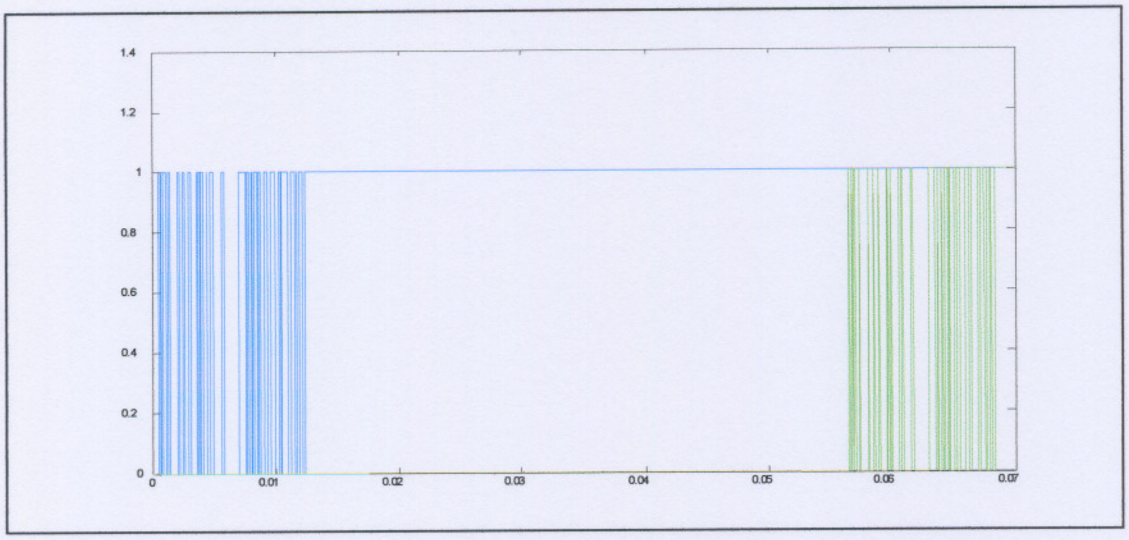


Figure 6-11: Input signal vs. delayed input signal (MDS Radios)

6.7. Bandwidth Management Equipment /Repeater

As the delays calculated on the BME/repeater were the same as with those in the MDS radios (56 ms), the models and implementation would be exactly the same, and the input and output signal would also be the same as in *Figure 6-11*.

6.8. Demonstration telecontrol network

Once all models of the units in the telecontrol network have been set up, it is possible to build and simulate a large part of the network to find the time differences that naturally exist between time-stamps.

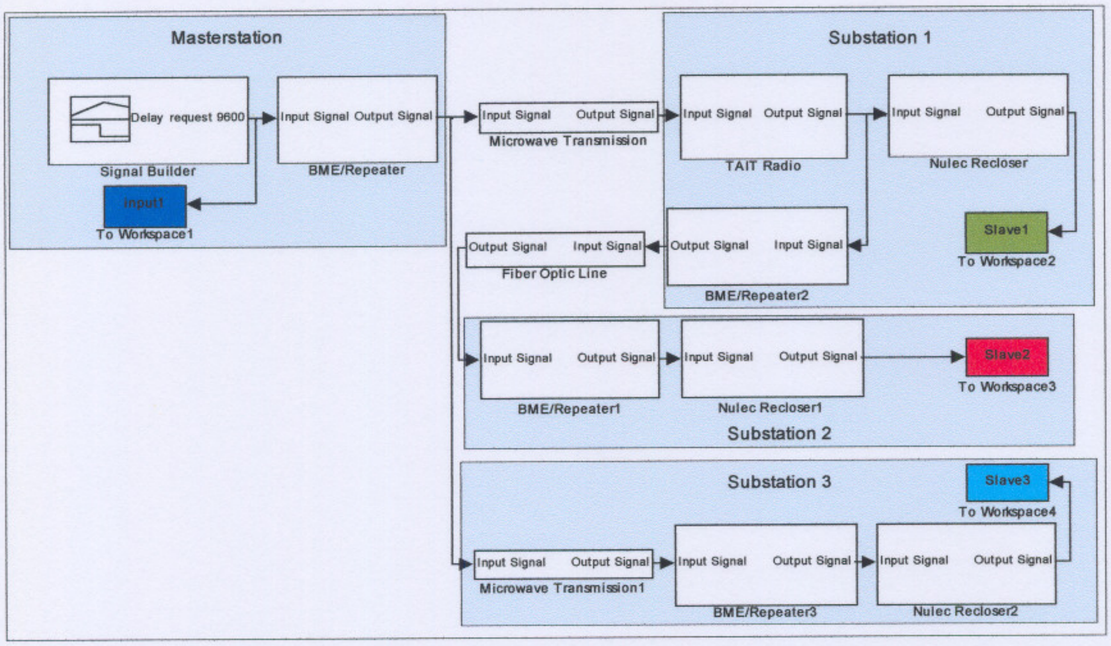


Figure 6-12: SimuLink model of full network

In *Figure 6-12,* an example of a telecontrol network with three RTUs is shown. Two of the RTUs are connected to the master station via TAIT modem radios and the other RTU is connected through another slave RTU that acts as a master station.

The SimuLink model in *Figure 6-12* is very similar to the Eskom Communication Diagram in *Figure 4-3*. This is important, because it means the network can be built up in SimuLink directly from the existing communication diagrams.

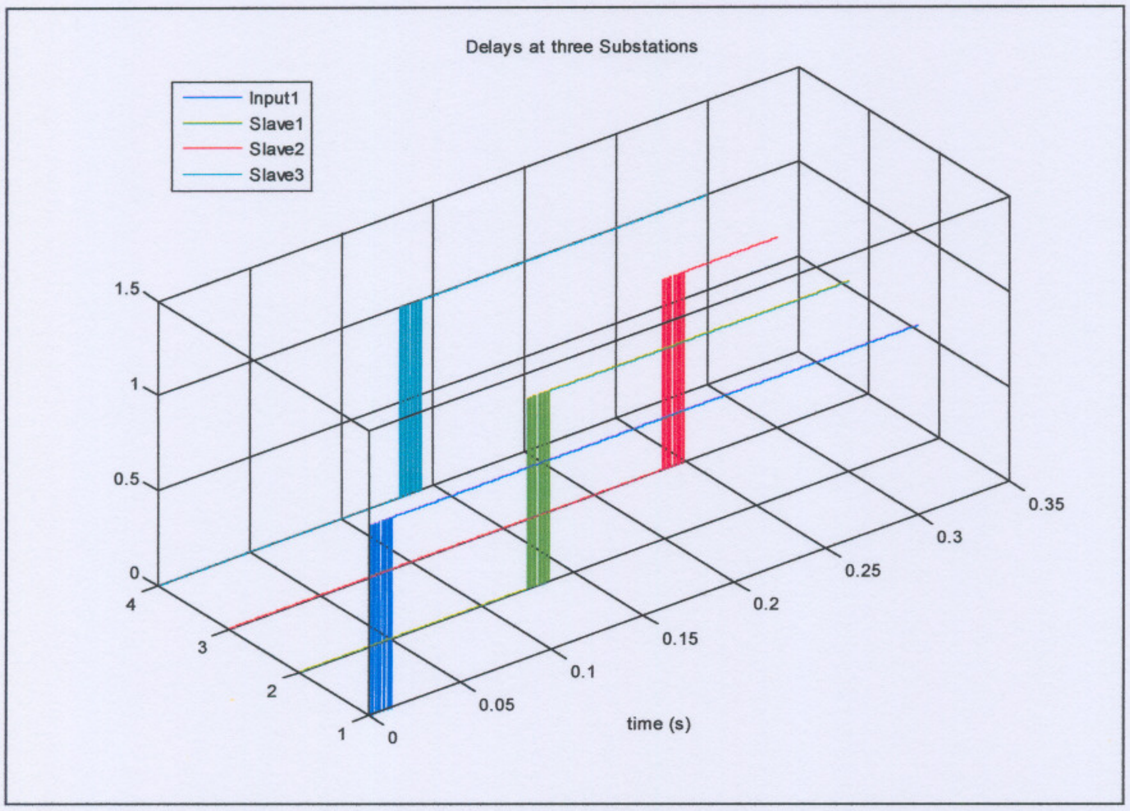


Figure 6-13: Input signal vs. delayed signals at RTUs

Once the network has been built, the simulation can be run and the different delays can be displayed as they occur on their own and as they accumulate from the master station to the slave station.

7. Conclusion

The development of the SimuLink© models for predicting the propagation delays in the telecommunication network now offers a number of alternatives to the GPS clock synchronisation. The GPS system involves installing a GPS system in every substation to synchronise all substations' clocks within 10-ms accuracy.

7.1. *Time-delay model in fault analysis*

The first and most obvious alternative is to keep transmitting the time signal from the master station to all the substations. The time delay model should then be used in fault analysis to recreate the network on which the fault occurred. The propagation delay to each node in the network is then quantified and the time stamps on each event can be corrected to recreate an accurate chain of events.

In this case, the time delay modelling tool would only assist in the analysis of faults and cause no changes in the telecommunications network itself.

7.2. *Time-delay model used for accurate time-stamping*

The time delay modelling tool can be used to determine the propagation delays in the design phase of the network and the time-stamping software could then be updated to take these delays into account when synchronising clocks of substations.

This alternative is then to be used by telecommunication network developers and optimisers. The sequence of events can then be trusted when doing fault analyses.

7.3. *Time-delay model together with GPS system*

It is very important not to forget that using a GPS system for clock synchronisation in every substation is still the easiest and preferred method of ensuring accurate time stamps in event logs. Because of the high cost involved in installing a GPS system in every distribution substation, it is advised to use the time-delay model in conjunction with a GPS system.

Telecommunication network designers could analyse the delays in the network using the delay modelling tool. The tool would be used to pinpoint nodes in the network where a GPS system could be installed to keep the downstream propagation delay to a minimum. This could be shown by analysing the network in *Figure 6-12.* If a single GPS system is installed on a specific RTU within a substation, the propagation delay on one Nulec1 would be halved, and the propagation delay on Nulec2 would be three times less.

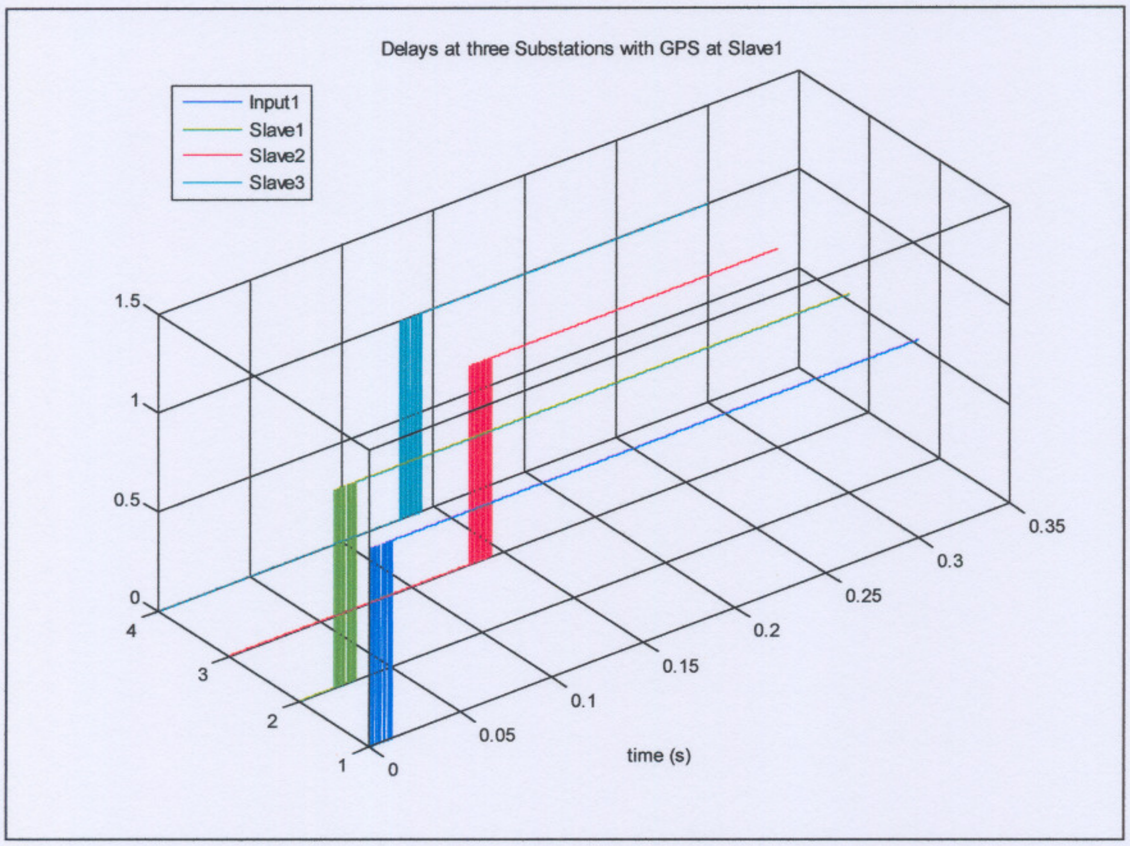


Figure 7-1: Input signal vs. delayed signals at RTUs

The effect of the smaller delay is shown in *Figure 7-1.* When comparing *Figure 6-13* with *Figure 7-1,* it is apparent that Slave3 and Slave4 are the only delays that are still around 130 ms. The Slave1's delay came down from around 130 ms to 20 ms. Slave2's delay is down from 230 ms to 130 ms.

Analysing the telecommunications network in this fashion leaves the accuracy of the time stamps up to the system designer and the budget that is available. A few GPS systems could be installed in certain areas, for instance where the telecommunications network has a hierarchical structure. Where the telecommunication network structure has a star type configuration, a single GPS system in the centre would keep all delays to within the specified limits.

Remember that a protocol such as DNP3 already measures the delay and takes that into account when time-stamping is done. The use of the delay modelling tool would assist these protocols in minimising the delays. In other protocols the accuracy of the time stamps would rely entirely on the delay modelling tool.

To quote Albert Einstein again: "The only reason for time is so that everything doesn't happen at once." Sometimes, though, we want some things to happen at once - or at least change them to seem as if it did.

8. References

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9. Appendices

9.1. *Appendix A – Time-Stamping of Operational Data Logs*

NERC	Guideline
Guideline Title: Time Stamping of Operational Data Logs	Version: 0.9.1 (Draft to Operating and Planning Committees)
Revision Date:	Effective Date:

Purpose:

The purpose of this guideline is to describe minimum recommendations for maintaining time synchronized indications for logged events.

Applicability:

This guideline is focused on all computer or microprocessor based operational devices used to monitor, control, or analyze the bulk electric system where accurate timing has been deemed necessary. These devices include, but are not limited to, Substation Automation Systems, Programmable Logic Controllers (PLC), Intelligent Electronic Devices (IED), sequence of event recorders, digital fault recorders, intelligent protective relay devices, Energy Management Systems (EMS), Supervisory Control and Data Acquisition (SCADA) Systems, Plant Control Systems, routers, firewalls, Intrusion Detection Systems (IDS), remote access systems, physical security access control systems, telephone and voice recording systems, video surveillance systems, and log collection and analysis systems.

It is recognized that for operational reasons protection devices may require more stringent time stamping requirements than specified in this guideline. This increased resolution is beyond the scope of this document.

This guideline is applicable to anyone who owns, manages, or maintains devices, services and/or systems that support the North American bulk electric system.

This guideline does not specify where time stamping recorders or telemetry equipment should be placed within the bulk electric system. Rather, this guideline recommends the characteristics of the time stamps that are created by equipment that is selected and installed for other operational requirements.

This guideline is not, by itself, intended to require equipment upgrades to existing implementations that do not support time stamping of operations. Rather, this guideline is intended to assist in the configuration of time synchronization features on equipment that either already exists or is in the planning stages.

Some of the recommendations in this guideline are more important than others. For this reason the terms "shall" and "should" are used throughout this document. The term "shall" is used in the more important aspects of this guideline to stress their importance to the overall time synchronization process. The term "should" is used to indicate the less important aspects of this guideline.

This guideline describes recommended minimum configurations that are to be used in the absence of installations requiring more accuracy or resolution. Where more stringent requirements may exist (e.g., in other NERC, regional, or company specific requirements) they take precedence over the values specified in this guideline.

Background:

Effective and accurate event logging is crucial to a reconstructed timeline following a disturbance event. Accurate time receiving devices are inexpensive, easy to configure, and require little maintenance. Lack of a coordinated accurate time stamp for recorded events makes any reconstruction of a timeline difficult and time consuming, if not impossible. In addition, the lack of coordinated time stamping of events may cause the recorded event data to be suspect when it is used to reconstruct a timeline of events among systems of different management or administrative domains.

Of specific interest when collecting, storing and analyzing time stamp information is the concept of telemetry skew. Telemetry skew happens when communication delays or scan rates cause the receipt of information to not occur strictly in "real time". For example, when a breaker in a substation opens, monitoring equipment in the substation should capture the time associated with the operation. At some point later, perhaps several hundred milliseconds, the RTU may detect the breaker operation, and capture the time. Later, the SCADA central server will poll the RTU, and detect that the status point associated with the breaker has changed, and store an updated point value in the database, optionally with a time stamp. Then, the SCADA alarm subsystem will generate an uncommanded operation alarm, with an alarm time associated, and present it to the SCADA system operator. Even later, the breaker status may be communicated to an ISO or RTO, and upon receipt of the status point, the updated value will be stored, time stamped, and perhaps alarmed at the ISO or RTO.

Each of these timestamps will be different due to scanning rates, communication delays, and system processor loads and message queue lengths. It is conceivable that the total time skew resulting from a telemetry sequence may exceed a minute. Of prime importance to the analysis of an event is the initial time stamp, which should be preserved for later analysis. Other time stamps may be used to determine when the succeeding systems found out that the point value was changed, but they will not be of primary use in developing an accurate electric system event timeline. Requirements for what events require stored time stamps s beyond the scope of this document.

The details included in this security guideline can generally be implemented with current technology.

For many years, electric utilities have had a requirement to time stamp critical events (e.g. transmission breaker operation) to within approximately 1 millisecond of actual time traceable to an accepted standard. Initially, these installations were very expensive primarily due to the cost of establishing a timing signal at the site with the required accuracy. Now, with the US Navy Navstar Global Positioning Satellite (GPS) system being in place, the cost has been mitigated considerably by deriving actual time (traceable to a government standard) with an accuracy measured in microseconds from the GPS signals. Today a utility can install a commercially available GPS time code receiver producing either a modulated IRIG B or NTP/SNTP output for approximately $2000 - $7000 and one day's labor (reasonably trained person) cost. The IRIG B modulated signal produced by the time code receiver can be distributed to the equipment requiring the time signal by using coaxial cable or fiber optics. Most if not all equipment that would actually time stamp data or events e.g. protective relays, sequence of events recorders, SCADA Remote Terminal Units, etc. are equipped to accept the modulated IRIG B signal. NTP/SNTP output is required for all network connected devices such as routers, firewalls, servers, IDS, etc.

Definitions:

Accuracy: Indication of the amount of error in a measurement or quantity.

Accurate: Free from error; conforming exactly to a standard.

CHU: Radio time service run and maintained by the Canadian Government.

Clock: The internal hardware and software that maintains time in a computer or intelligent microprocessor device

Coordinated Time Synchronization Service: A hardware component or other device, generally local to control centre, plant, or substation, that maintains a traceable, accurate time; and provides a time signal that can be used to synchronize the remaining devices at that location.

GOES: Geostationary Orbit Environment Satellite. A legacy time service to be decommissioned by January 1, 2005, provided by National Oceanic and Atmospheric Administration (NOAA) weather satellites (http://noaasis.noaa.gov/NOAASIS/ml/nisttime.html).

GPS: US Navy Navstar Global Positioning Satellite service. This service provides a time service in addition to location information.

In-service device: A device that: is capable of processing and storing accurate time as specified in this guideline; has had its internal clock automatically or manually set to be within one second of the coordinated time; and, has established a permanent communication link with the coordinated time synchronization service.

IRIG: Inter Range Instrumentation Group, a Department of Defence organization which developed a specification for transmission of time synchronization over wide areas.

NTP: Network Time Protocol: A protocol used to accurately synchronize computer clocks via a network connection.

Resolution: The smallest increment of time to which the measurement is defined.

SNTP: Simple Network Time Protocol: A protocol used to accurately synchronize computer clocks via a network connection.

UTC: Coordinated Universal Time, sometimes called Greenwich Mean Time, nominally reflects the mean solar time along the Earth's prime meridian.

WWV: Radio time service run and maintained by the US National Institute of Standards and Technology (NIST) at Ft. Collins (US) Radio 2.5, 5, 10, 15, 20 MHz.

WWVB: Radio time service run and maintained by the US National Institute of Standards and Technology (NIST) at Boulder (US) Radio 60 kHz.

Guideline Statement:

Internal clocks on all affected devices at all affected functional organizations should maintain an accurate coordinated time, and that time shall be similarly coordinated with accepted international time sources.

Guideline Detail:

A. All specific geographic sites containing applicable devices (e.g., control centre, plant, substation) shall include a coordinated time synchronization service. This coordinated service should have a demonstrated availability of 99.9%. This may be accomplished through redundant hardware so long as the accuracy of the time service is maintained at all times.

B. The coordinated time synchronization service shall be directly traceable to the international time standard maintained in the United States by the US Naval Observatory on behalf of US Government, or the equivalent Canadian or Mexican government entity, with an accuracy of 1ms. Common services providing such a time signal include GPS, WWV, WWVB, CHU, and GOES satellite.

C. All applicable in-service devices co-located at a specific geographic site should maintain demonstrable and constant communication to either a local coordinated time synchronization service, or a remote coordinated time synchronization service as defined in guideline detail B.

D. All applicable in-service devices should internally store time using the UTC time zone.

E. All applicable devices shall automatically adjust their internal clocks according to the NTP specification (RFC1305), which, at the time of this writing, states that the internal time shall not deviate from the coordinated time source by more than 128 ms.

F. At no time should any applicable device for a specific operational entity (e.g., control area, ISO/RTO) have an internal time that deviates from any other applicable device within the same operational entity by more than 256 ms. (The rationale for this is to keep the maximum deviation between an in-specification slow clock and an in-specification fast clock to less than approximately one quarter second.)

G. All applicable IRIG-B connected devices should maintain an internal clock with a maximum error of 50 ms. All NTP/SNTP connected devices should maintain an internal clock with a maximum error of 100 ms.

H. All operational events should be communicated and stored with time stamps. The time stamps should use the UTC time zone. In the event use of UTC is impractical, the time zone employed shall be clearly stated. If multiple time stamps are available for a given event other standards or guidelines shall determine which time stamp (or time stamps) shall be stored for the event.

I. The time stamps shall have a resolution of at least 1 ms. Sources of time uncertainty should be known and reportable.

J. Operational events that are logged to hard copy or screens, or events that are presented to operators may be displayed using the local time zone, and may be represented to any resolution needed to properly operate the system, so long as the internal time stamps are maintained with the specified time zone and resolution as defined in preceding guideline details.

K. In the event that operational event recording requiring more resolution than otherwise specified in this guideline is required, equipment compatible with the IRIG-B protocol shall be used to ensure that the accuracy and resolution of the time stamping is maintained.

Exceptions:

None.

Related Documents:

RFC1305 and RFC2030 Network Time Protocol (NTP) and Simple Network Time Protocol (SNTP) http://www.ietf.org

August 14, 2003 Blackout: NERC Actions to Prevent and Mitigate the Impacts of Future Cascading Blackouts, February 10, 2004 at ftp://www.nerc.com/pub/sys/all_updl/docs/blackout/BOARD_APPROVED_BLACKOUT_RECOMMENDATIONS_021004.pdf

"Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations," U.S.-Canada Power System Outage Task Force, April 5, 2004 at http://www.nerc.com/~filez/blackout.html

IRIG standards are issued by the Inter Range Instrumentation Group of the Range Commanders Council under the authority of the US Department of Defense at http://jcs.mil/RCC/files/200.pdf

Revision History:

Date	Version Number	Reason/Comments
Sept 2003	Version – 0.0.1	Initial draft.
	Version – 0.0.2	Updates.
	Version – 0.0.3	Added Telemetry skew comments
	Version – 0.0.4	Added non-proscriptive comments
Oct 2003	Version – 0.0.5	Shall to should; explain 150ms vs. 250ms time; add definition for forensic
Nov 2003	Version – 0.0.6	Added more non-proscriptive clarifying language
	Version – 0.0.7	PCSS TF Review
	Version – 0.0.8	Additional Review by PCSS TF

	Version – 0.9	Additional Review by PCSS TF, addition of IRIG
April, 2004	Version 1.0	Comments from CIPC, WECC, and DEWG

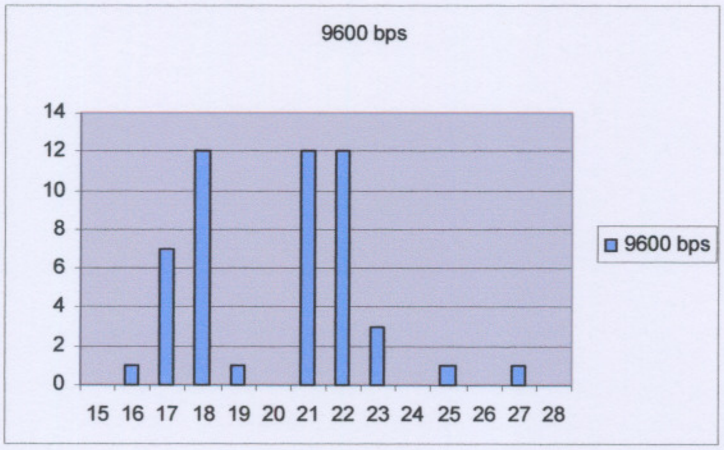
9.2. *Appendix B – Test Data & Statistics*

9.2.1. Direct link at 9600 bps

Number	Delay (ms)
1	18
2	21
3	21
4	21
5	22
6	23
7	22
8	18
9	21
10	22
11	22
12	18
13	22
14	21
15	18
16	19
17	22
18	21
19	18
20	25
21	18
22	22
23	23
24	22
25	17
26	21
27	21
28	21
29	17
30	27
31	21
32	18
33	17
34	21
35	18
36	22
37	18
38	17
39	23
40	18
41	22
42	16
43	17
44	17
45	22
46	22
47	17
48	18
49	21
50	18
	20.14

Delay (ms)	Frequency
15	0
16	1
17	7
18	12
19	1
20	0
21	12
22	12
23	3
24	0
25	1
26	0
27	1
28	0

9600 bps	
Mean	20.14
Standard Error	0.342869047
Median	21
Mode	18
Standard Deviation	2.424450285
Sample Variance	5.877959184
Kurtosis	-0.287847941
Skewness	0.277305922
Range	11
Minimum	16
Maximum	27
Sum	1007
Count	50
Confidence Level(95.0%)	0.689020729

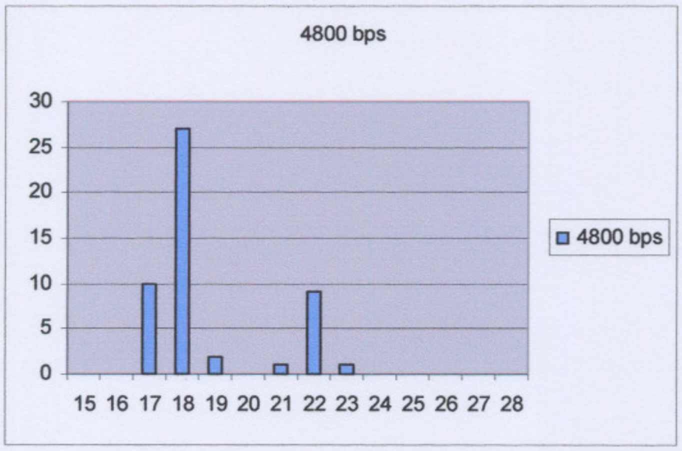


9.2.2. Direct link at 4800 bps

Number	Delay (ms)
1	18
2	17
3	22
4	17
5	22
6	22
7	18
8	22
9	18
10	18
11	18
12	17
13	17
14	19
15	18
16	18
17	18
18	18
19	18
20	18
21	17
22	22
23	17
24	22
25	18
26	22
27	18
28	18
29	18
30	18
31	17
32	22
33	17
34	18
35	21
36	18
37	17
38	18
39	22
40	18
41	18
42	18
43	17
44	18
45	18
46	18
47	23
48	19
49	18
50	18
	18.72

Delay (ms)	Frequency
15	0
16	0
17	10
18	27
19	2
20	0
21	1
22	9
23	1
24	0
25	0
26	0
27	0
28	0

4800 bps	
Mean	18.72
Standard Error	0.258788386
Median	18
Mode	18
Standard Deviation	1.829910224
Sample Variance	3.348571429
Kurtosis	-0.108875759
Skewness	1.20359031
Range	6
Minimum	17
Maximum	23
Sum	936
Count	50
Confidence Level(95.0%)	0.520054416

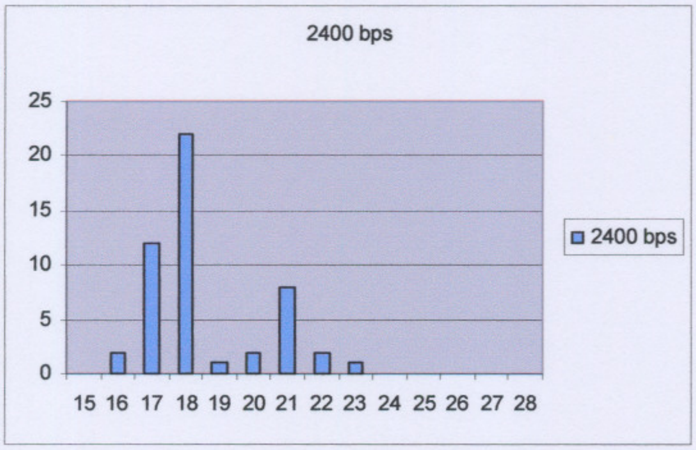


9.2.3. Direct link at 2400 bps

Number	Delay (ms)
1	20
2	17
3	16
4	21
5	18
6	21
7	18
8	17
9	18
10	17
11	20
12	18
13	17
14	18
15	22
16	18
17	18
18	17
19	18
20	19
21	17
22	18
23	18
24	22
25	18
26	18
27	18
28	18
29	18
30	18
31	21
32	18
33	16
34	21
35	21
36	18
37	23
38	18
39	17
40	17
41	18
42	17
43	18
44	21
45	21
46	17
47	18
48	17
49	17
50	21
	18.52

Delay (ms)	Frequency
15	0
16	2
17	12
18	22
19	1
20	2
21	8
22	2
23	1
24	0
25	0
26	0
27	0
28	0

2400 bps	
Mean	18.52
Standard Error	0.242840336
Median	18
Mode	18
Standard Deviation	1.71714048
Sample Variance	2.948571429
Kurtosis	-0.129002187
Skewness	0.947146895
Range	7
Minimum	16
Maximum	23
Sum	926
Count	50
Confidence Level(95.0%)	0.488005629

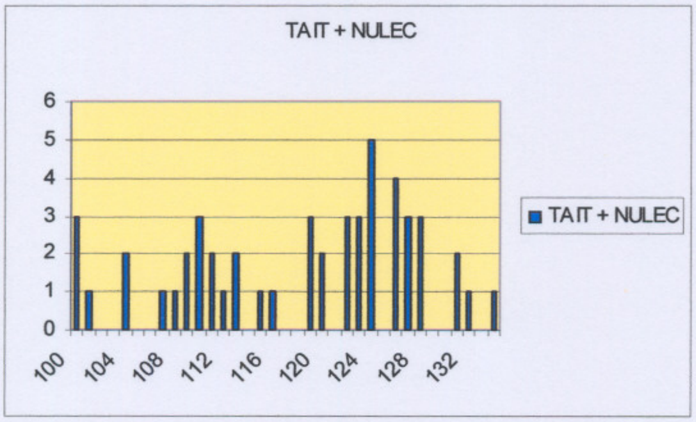


9.2.4. Total TAIT radio and Nulec

Number	Delay (ms)
1	124
2	132
3	124
4	131
5	111
6	123
7	115
8	134
9	128
10	123
11	119
12	101
13	124
14	113
15	107
16	100
17	111
18	119
19	128
20	110
21	104
22	110
23	120
24	113
25	126
26	116
27	127
28	127
29	100
30	119
31	112
32	126
33	122
34	126
35	122
36	110
37	109
38	128
39	124
40	100
41	123
42	108
43	109
44	122
45	127
46	104
47	131
48	126
49	124
50	120
	118.24

Delay (ms)	Frequency
100	3
101	1
102	0
103	0
104	2
105	0
106	0
107	1
108	1
109	2
110	3
111	2
112	1
113	2
114	0
115	1
116	1
117	0
118	0
119	3
120	2
121	0
122	3
123	3
124	5
125	0
126	4
127	3
128	3
129	0
130	0
131	2
132	1
133	0
134	1

TAIT Radio + NULEC	
Mean	118.24
Standard Error	1.328666663
Median	121
Mode	124
Standard Deviation	9.395092075
Sample Variance	88.2677551
Kurtosis	-0.870783807
Skewness	-0.445757458
Range	34
Minimum	100
Maximum	134
Sum	5912
Count	50
Largest(1)	134
Smallest(1)	100
Confidence Level(95.0%)	2.670055575

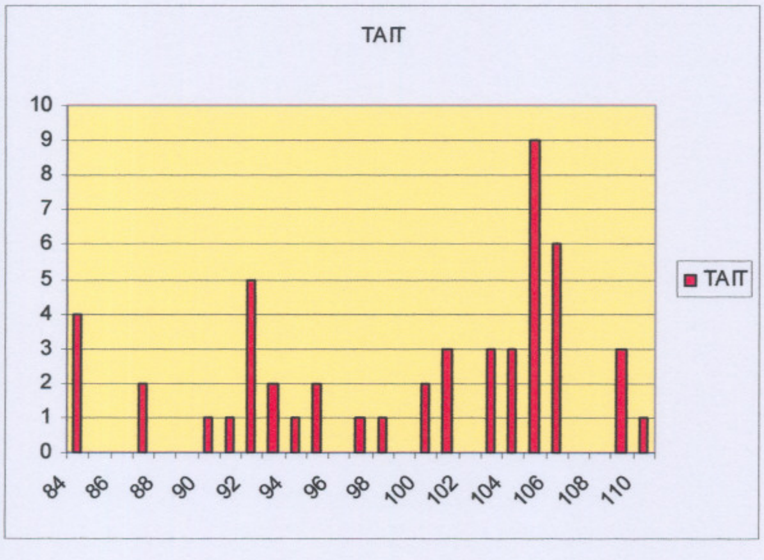


9.2.5. TAIT radio only

Number	Delay (ms)
1	84
2	83
3	83
4	84
5	87
6	87
7	90
8	91
9	92
10	92
11	92
12	92
13	92
14	93
15	93
16	94
17	95
18	95
19	97
20	98
21	101
22	100
23	100
24	101
25	101
26	103
27	103
28	103
29	104
30	104
31	104
32	105
33	105
34	105
35	105
36	105
37	106
38	106
39	106
40	105
41	105
42	105
43	105
44	106
45	106
46	106
47	109
48	109
49	109
50	110

Delay (ms)	Frequency
84	4
85	0
86	0
87	2
88	0
89	0
90	1
91	1
92	5
93	2
94	1
95	2
96	0
97	1
98	1
99	0
100	2
101	3
102	0
103	3
104	3
105	9
106	6
107	0
108	0
109	3
110	1

TAIT Radio	
Mean	99.12
Standard Error	1.097172619
Median	102
Mode	105
Standard Deviation	7.758181988
Sample Variance	60.18938776
Kurtosis	-0.772175293
Skewness	-0.645722962
Range	27
Minimum	83
Maximum	110
Sum	4956
Count	50
Largest(1)	110
Smallest(1)	83
Confidence Level(95.0%)	2.204850884

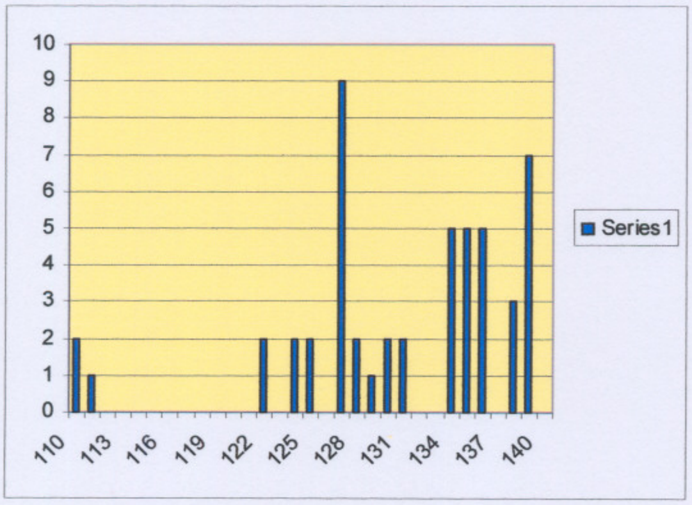


9.2.6. Total MDS radio and Nulec

Number	Delay (ms)
1	134
2	131
3	135
4	139
5	130
6	135
7	127
8	139
9	127
10	127
11	128
12	136
13	103
14	122
15	124
16	139
17	138
18	125
19	127
20	136
21	134
22	127
23	124
24	127
25	136
26	111
27	139
28	134
29	109
30	127
31	139
32	135
33	125
34	128
35	139
36	135
37	127
38	122
39	135
40	136
41	134
42	134
43	138
44	139
45	129
46	136
47	127
48	130
49	131
50	138
	130.54

Delay (ms)	Frequency
110	2
111	1
112	0
113	0
114	0
115	0
116	0
117	0
118	0
119	0
120	0
121	0
122	2
123	0
124	2
125	2
126	0
127	9
128	2
129	1
130	2
131	2
132	0
133	0
134	5
135	5
136	5
137	0
138	3
139	7
140	0

MDS Radio + NULEC	
Mean	130.54
Standard Error	1.107012896
Median	132.5
Mode	127
Standard Deviation	7.827763253
Sample Variance	61.27387755
Kurtosis	2.989742932
Skewness	-1.505831811
Range	36
Minimum	103
Maximum	139
Sum	6527
Count	50
Largest(1)	139
Smallest(1)	103
Confidence Level(95.0%)	2.22462566

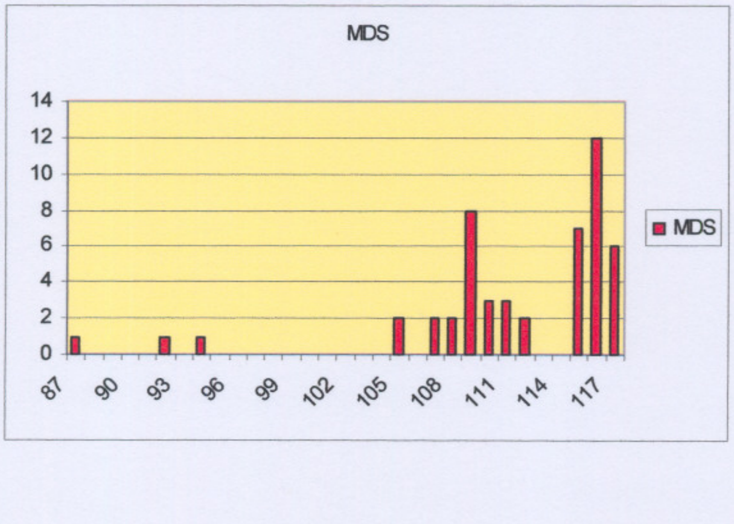


9.2.7. MDS radio only

Number	Delay (ms)
1	87
2	92
3	94
4	105
5	105
6	107
7	107
8	108
9	108
10	110
11	109
12	109
13	109
14	109
15	109
16	109
17	109
18	109
19	110
20	110
21	111
22	111
23	111
24	112
25	112
26	115
27	115
28	115
29	115
30	115
31	116
32	116
33	116
34	116
35	116
36	117
37	116
38	116
39	116
40	115
41	116
42	116
43	116
44	117
45	117
46	117
47	117
48	117
49	116
50	115

Delay (ms)	Frequency
87	1
88	0
89	0
90	0
91	0
92	1
93	0
94	1
95	0
96	0
97	0
98	0
99	0
100	0
101	0
102	0
103	0
104	0
105	2
106	0
107	2
108	2
109	8
110	3
111	3
112	2
113	0
114	0
115	7
116	12
117	6

MDS Radio	
Mean	111.42
Standard Error	0.904451576
Median	113.5
Mode	116
Standard Deviation	6.395438425
Sample Variance	40.90163265
Kurtosis	5.175591458
Skewness	-2.077218019
Range	30
Minimum	87
Maximum	117
Sum	5571
Count	50
Largest(1)	117
Smallest(1)	87
Confidence Level(95.0%)	1.817563456

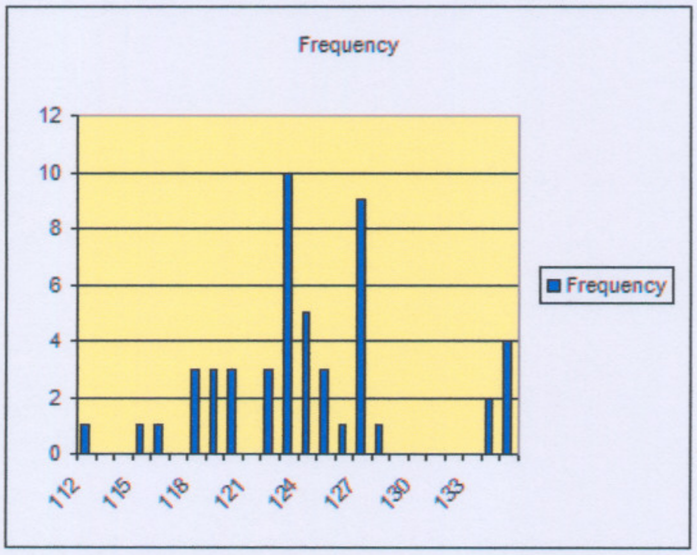


9.2.8. Full network delay

Number	Delay (ms)
1	134
2	127
3	119
4	134
5	120
6	128
7	127
8	124
9	112
10	127
11	135
12	118
13	127
14	123
15	123
16	123
17	118
18	116
19	127
20	123
21	115
22	119
23	125
24	122
25	123
26	124
27	118
28	135
29	124
30	123
31	122
32	125
33	120
34	123
35	127
36	127
37	122
38	125
39	124
40	120
41	123
42	127
43	123
44	119
45	135
46	124
47	135
48	123
49	126
50	127
	124.2

Delay (ms)	Frequency
112	1
113	0
114	0
115	1
116	1
117	0
118	3
119	3
120	3
121	0
122	3
123	10
124	5
125	3
126	1
127	9
128	1
129	0
130	0
131	0
132	0
133	0
134	2
135	4

Repeater + TAIT Radio + Nulec	
Mean	124.2
Standard Error	0.736234213
Median	123.5
Mode	123
Standard Deviation	5.205962045
Sample Variance	27.10204082
Kurtosis	0.422849424
Skewness	0.395782604
Range	23
Minimum	112
Maximum	135
Sum	6210
Count	50
Largest(1)	135
Smallest(1)	112
Confidence Level(95.0%)	1.479518015

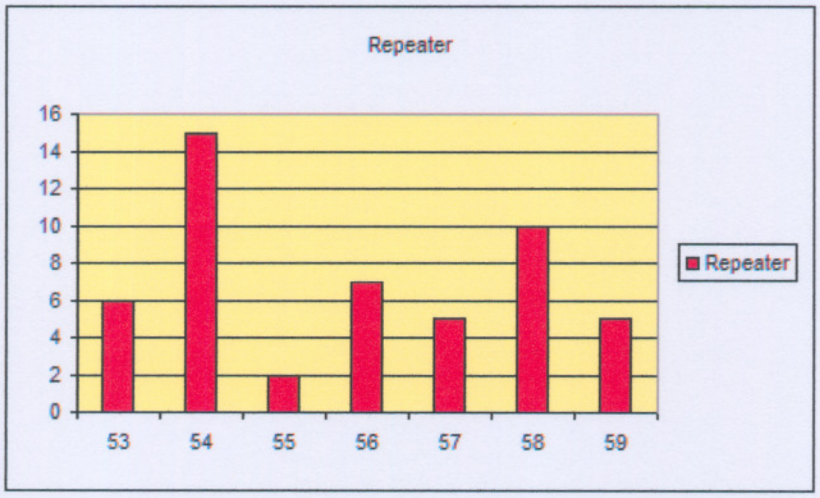


9.2.9. BME/repeater delay only

Number	Delay (ms)
1	54
2	57
3	58
4	59
5	58
6	58
7	57
8	57
9	56
10	57
11	56
12	56
13	58
14	58
15	58
16	58
17	58
18	58
19	57
20	56
21	55
22	54
23	54
24	54
25	54
26	54
27	54
28	54
29	53
30	53
31	54
32	54
33	54
34	55
35	56
36	56
37	54
38	54
39	54
40	54
41	53
42	53
43	53
44	53
45	59
46	59
47	59
48	59
49	58
50	56

Delay (ms)	Frequency
53	6
54	15
55	2
56	7
57	5
58	10
59	5

Repeater only	
Mean	55.8
Standard Error	0.288557284
Median	56
Mode	54
Standard Deviation	2.040408122
Sample Variance	4.163265306
Kurtosis	-1.468006884
Skewness	0.147149531
Range	6
Minimum	53
Maximum	59
Sum	2790
Count	50
Largest(1)	59
Smallest(1)	53
Confidence Level(95.0%)	0.579877561



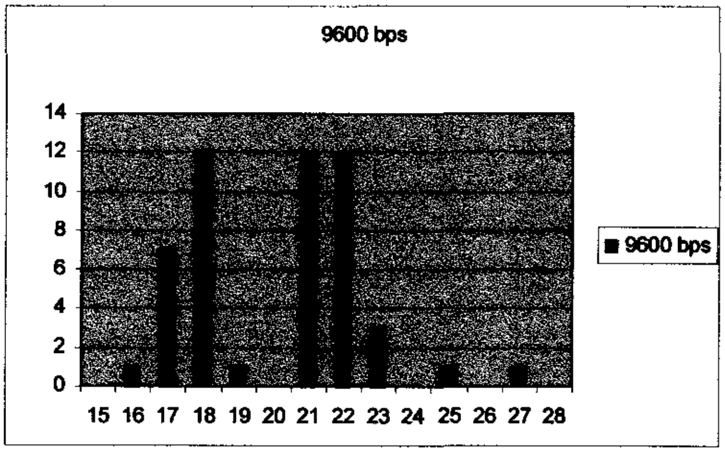
9.2. *Appendix B – Test Data & Statistics*

9.2.1. Direct link at 9600 bps

Number	Delay (ms)
1	18
2	21
3	21
4	21
5	22
6	23
7	22
8	18
9	21
10	22
11	22
12	18
13	22
14	21
15	18
16	19
17	22
18	21
19	18
20	25
21	18
22	22
23	23
24	22
25	17
26	21
27	21
28	21
29	17
30	27
31	21
32	18
33	17
34	21
35	18
36	22
37	18
38	17
39	23
40	18
41	22
42	16
43	17
44	17
45	22
46	22
47	17
48	18
49	21
50	18
	20.14

Delay (ms)	Frequency
15	0
16	1
17	7
18	12
19	1
20	0
21	12
22	12
23	3
24	0
25	1
26	0
27	1
28	0

9600 bps	
Mean	20.14
Standard Error	0.342869047
Median	21
Mode	18
Standard Deviation	2.424450285
Sample Variance	5.877959184
Kurtosis	-0.287847941
Skewness	0.277305922
Range	11
Minimum	16
Maximum	27
Sum	1007
Count	50
Confidence Level(95.0%)	0.689020729

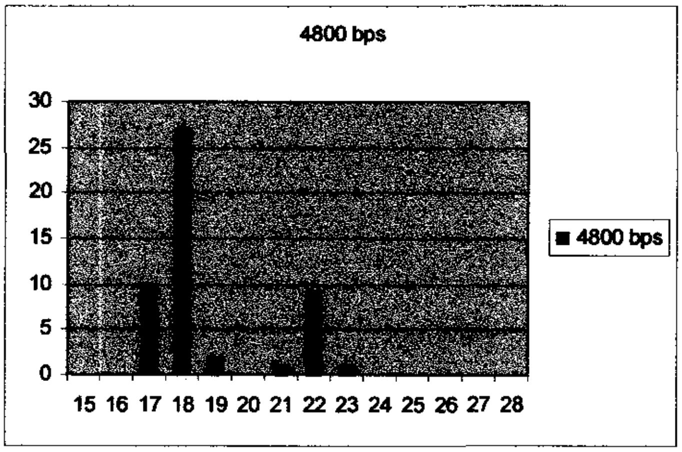


9.2.2. Direct link at 4800 bps

Number	Delay (ms)
1	18
2	17
3	22
4	17
5	22
6	22
7	18
8	22
9	18
10	18
11	18
12	17
13	17
14	19
15	18
16	18
17	18
18	18
19	18
20	18
21	17
22	22
23	17
24	22
25	18
26	22
27	18
28	18
29	18
30	18
31	17
32	22
33	17
34	18
35	21
36	18
37	17
38	18
39	22
40	18
41	18
42	18
43	17
44	18
45	18
46	18
47	23
48	19
49	18
50	18
	18.72

Delay (ms)	Frequency
15	0
16	0
17	10
18	27
19	2
20	0
21	1
22	9
23	1
24	0
25	0
26	0
27	0
28	0

4800 bps	
Mean	18.72
Standard Error	0.258788386
Median	18
Mode	18
Standard Deviation	1.829910224
Sample Variance	3.348571429
Kurtosis	-0.108875759
Skewness	1.20359031
Range	6
Minimum	17
Maximum	23
Sum	936
Count	50
Confidence Level(95.0%)	0.520054416

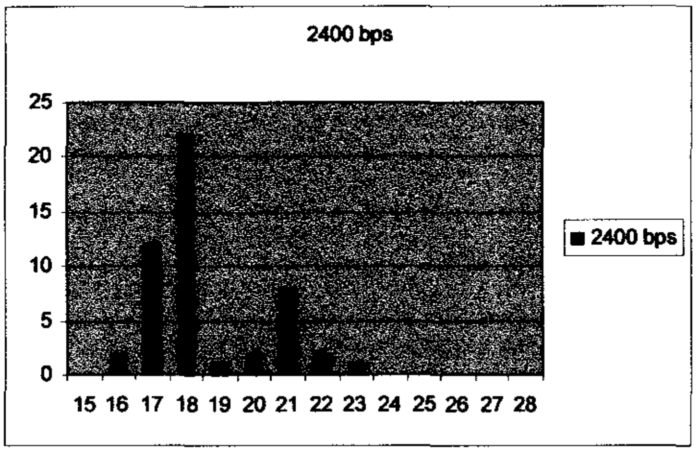


9.2.3. Direct link at 2400 bps

Number	Delay (ms)
1	20
2	17
3	16
4	21
5	18
6	21
7	18
8	17
9	18
10	17
11	20
12	18
13	17
14	18
15	22
16	18
17	18
18	17
19	18
20	19
21	17
22	18
23	18
24	22
25	18
26	18
27	18
28	18
29	18
30	18
31	21
32	18
33	16
34	21
35	21
36	18
37	23
38	18
39	17
40	17
41	18
42	17
43	18
44	21
45	21
46	17
47	18
48	17
49	17
50	21
	18.52

Delay (ms)	Frequency
15	0
16	2
17	12
18	22
19	1
20	2
21	8
22	2
23	1
24	0
25	0
26	0
27	0
28	0

2400 bps	
Mean	18.52
Standard Error	0.242840336
Median	18
Mode	18
Standard Deviation	1.71714048
Sample Variance	2.948571429
Kurtosis	-0.129002187
Skewness	0.947146895
Range	7
Minimum	16
Maximum	23
Sum	926
Count	50
Confidence Level(95.0%)	0.488005629

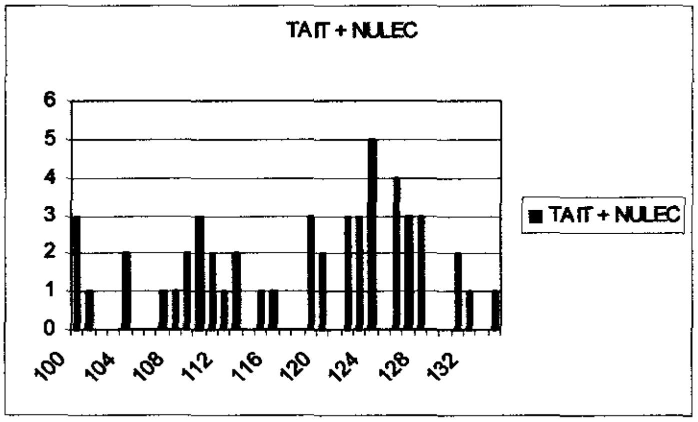


9.2.4. Total TAIT radio and Nulec

Number	Delay (ms)
1	124
2	132
3	124
4	131
5	111
6	123
7	115
8	134
9	128
10	123
11	119
12	101
13	124
14	113
15	107
16	100
17	111
18	119
19	128
20	110
21	104
22	110
23	120
24	113
25	126
26	116
27	127
28	127
29	100
30	119
31	112
32	126
33	122
34	126
35	122
36	110
37	109
38	128
39	124
40	100
41	123
42	108
43	109
44	122
45	127
46	104
47	131
48	126
49	124
50	120
	118.24

Delay (ms)	Frequency
100	3
101	1
102	0
103	0
104	2
105	0
106	0
107	1
108	1
109	2
110	3
111	2
112	1
113	2
114	0
115	1
116	1
117	0
118	0
119	3
120	2
121	0
122	3
123	3
124	5
125	0
126	4
127	3
128	3
129	0
130	0
131	2
132	1
133	0
134	1

TAIT Radio + NULEC	
Mean	118.24
Standard Error	1.328666663
Median	121
Mode	124
Standard Deviation	9.395092075
Sample Variance	88.2677551
Kurtosis	-0.870783807
Skewness	-0.445757458
Range	34
Minimum	100
Maximum	134
Sum	5912
Count	50
Largest(1)	134
Smallest(1)	100
Confidence Level(95.0%)	2.670055575

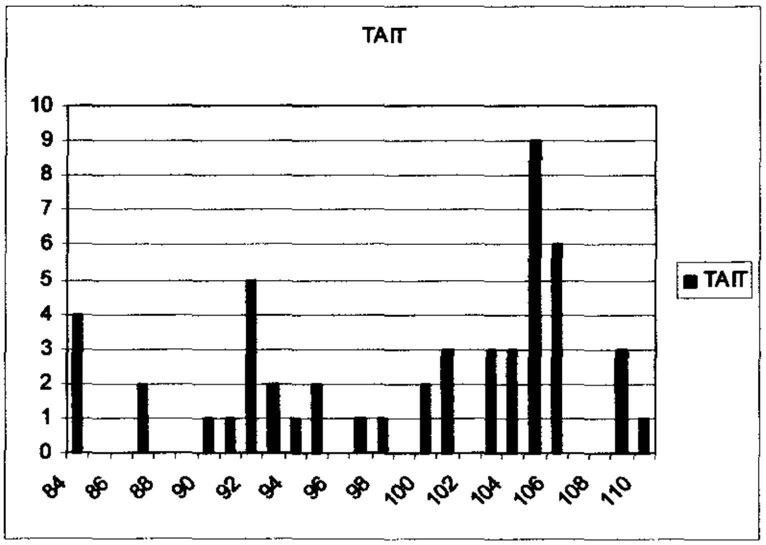


9.2.5. TAIT radio only

Number	Delay (ms)
1	84
2	83
3	83
4	84
5	87
6	87
7	90
8	91
9	92
10	92
11	92
12	92
13	92
14	93
15	93
16	94
17	95
18	95
19	97
20	98
21	101
22	100
23	100
24	101
25	101
26	103
27	103
28	103
29	104
30	104
31	104
32	105
33	105
34	105
35	105
36	105
37	106
38	106
39	106
40	105
41	105
42	105
43	105
44	106
45	106
46	106
47	109
48	109
49	109
50	110

Delay (ms)	Frequency
84	4
85	0
86	0
87	2
88	0
89	0
90	1
91	1
92	5
93	2
94	1
95	2
96	0
97	1
98	1
99	0
100	2
101	3
102	0
103	3
104	3
105	9
106	6
107	0
108	0
109	3
110	1

TAIT Radio	
Mean	99.12
Standard Error	1.097172619
Median	102
Mode	105
Standard Deviation	7.758181988
Sample Variance	60.18938776
Kurtosis	-0.772175293
Skewness	-0.645722962
Range	27
Minimum	83
Maximum	110
Sum	4956
Count	50
Largest(1)	110
Smallest(1)	83
Confidence Level(95.0%)	2.204850884

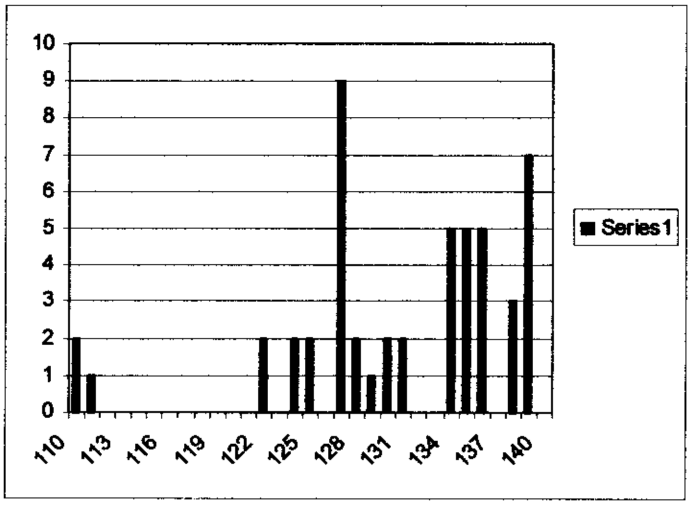


9.2.6. Total MDS radio and Nulec

Number	Delay (ms)
1	134
2	131
3	135
4	139
5	130
6	135
7	127
8	139
9	127
10	127
11	128
12	136
13	103
14	122
15	124
16	139
17	138
18	125
19	127
20	136
21	134
22	127
23	124
24	127
25	136
26	111
27	139
28	134
29	109
30	127
31	139
32	135
33	125
34	128
35	139
36	135
37	127
38	122
39	135
40	136
41	134
42	134
43	138
44	139
45	129
46	136
47	127
48	130
49	131
50	138
	130.54

Delay (ms)	Frequency
110	2
111	1
112	0
113	0
114	0
115	0
116	0
117	0
118	0
119	0
120	0
121	0
122	2
123	0
124	2
125	2
126	0
127	9
128	2
129	1
130	2
131	2
132	0
133	0
134	5
135	5
136	5
137	0
138	3
139	7
140	0

MDS Radio + NULEC	
Mean	130.54
Standard Error	1.107012896
Median	132.5
Mode	127
Standard Deviation	7.827763253
Sample Variance	61.27387755
Kurtosis	2.989742932
Skewness	-1.505831811
Range	36
Minimum	103
Maximum	139
Sum	6527
Count	50
Largest(1)	139
Smallest(1)	103
Confidence Level(95.0%)	2.22462566

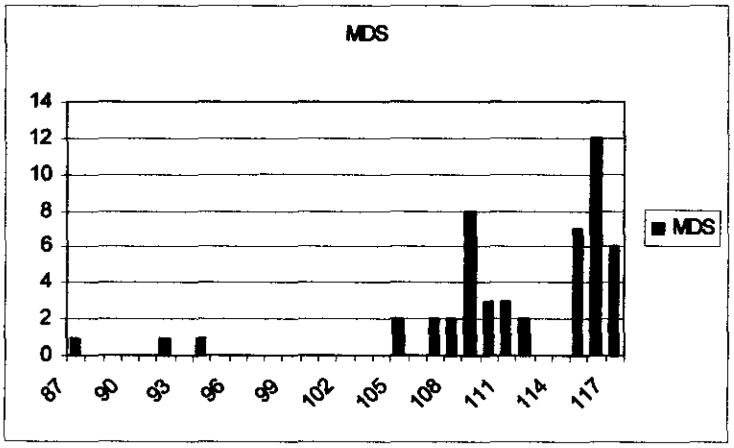


9.2.7. MDS radio only

Number	Delay (ms)
1	87
2	92
3	94
4	105
5	105
6	107
7	107
8	108
9	108
10	110
11	109
12	109
13	109
14	109
15	109
16	109
17	109
18	109
19	110
20	110
21	111
22	111
23	111
24	112
25	112
26	115
27	115
28	115
29	115
30	115
31	116
32	116
33	116
34	116
35	116
36	117
37	116
38	116
39	116
40	115
41	116
42	116
43	116
44	117
45	117
46	117
47	117
48	117
49	116
50	115

Delay (ms)	Frequency
87	1
88	0
89	0
90	0
91	0
92	1
93	0
94	1
95	0
96	0
97	0
98	0
99	0
100	0
101	0
102	0
103	0
104	0
105	2
106	0
107	2
108	2
109	8
110	3
111	3
112	2
113	0
114	0
115	7
116	12
117	6

MDS Radio	
Mean	111.42
Standard Error	0.904451576
Median	113.5
Mode	116
Standard Deviation	6.395438425
Sample Variance	40.90163265
Kurtosis	5.175591458
Skewness	-2.077218019
Range	30
Minimum	87
Maximum	117
Sum	5571
Count	50
Largest(1)	117
Smallest(1)	87
Confidence Level(95.0%)	1.817563456

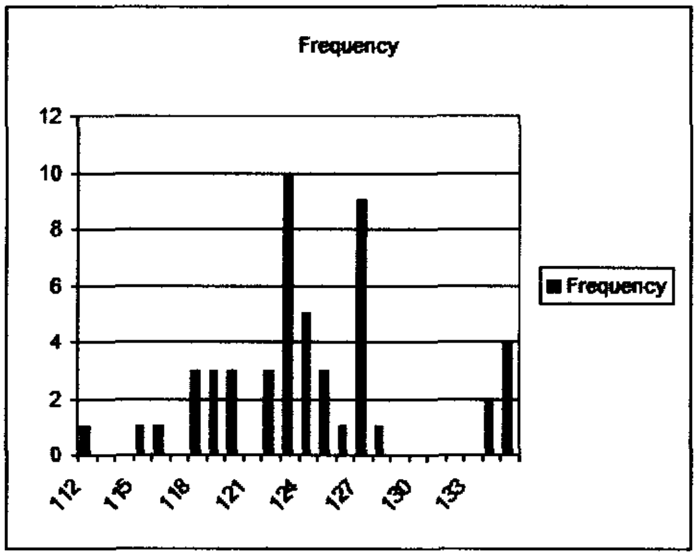


9.2.8. Full network delay

Number	Delay (ms)
1	134
2	127
3	119
4	134
5	120
6	128
7	127
8	124
9	112
10	127
11	135
12	118
13	127
14	123
15	123
16	123
17	118
18	116
19	127
20	123
21	115
22	119
23	125
24	122
25	123
26	124
27	118
28	135
29	124
30	123
31	122
32	125
33	120
34	123
35	127
36	127
37	122
38	125
39	124
40	120
41	123
42	127
43	123
44	119
45	135
46	124
47	135
48	123
49	126
50	127
	124.2

Delay (ms)	Frequency
112	1
113	0
114	0
115	1
116	1
117	0
118	3
119	3
120	3
121	0
122	3
123	10
124	5
125	3
126	1
127	9
128	1
129	0
130	0
131	0
132	0
133	0
134	2
135	4

Repeater + TAIT Radio + Nulec	
Mean	124.2
Standard Error	0.736234213
Median	123.5
Mode	123
Standard Deviation	5.205962045
Sample Variance	27.10204082
Kurtosis	0.422849424
Skewness	0.395782604
Range	23
Minimum	112
Maximum	135
Sum	6210
Count	50
Largest(1)	135
Smallest(1)	112
Confidence Level(95.0%)	1.479518015



9.2.9. BME/repeater delay only

Number	Delay (ms)
1	54
2	57
3	58
4	59
5	58
6	58
7	57
8	57
9	56
10	57
11	56
12	56
13	58
14	58
15	58
16	58
17	58
18	58
19	57
20	56
21	55
22	54
23	54
24	54
25	54
26	54
27	54
28	54
29	53
30	53
31	54
32	54
33	54
34	55
35	56
36	56
37	54
38	54
39	54
40	54
41	53
42	53
43	53
44	53
45	59
46	59
47	59
48	59
49	58
50	56

Delay (ms)	Frequency
53	6
54	15
55	2
56	7
57	5
58	10
59	5

Repeater only	
Mean	55.8
Standard Error	0.288557284
Median	56
Mode	54
Standard Deviation	2.040408122
Sample Variance	4.163265306
Kurtosis	-1.468006884
Skewness	0.147149531
Range	6
Minimum	53
Maximum	59
Sum	2790
Count	50
Largest(1)	59
Smallest(1)	53
Confidence Level(95.0%)	0.579877561