Implementation and Simulation of Communication Network for Wide Area Monitoring and Control Systems in OPNET

Elias Karam

KTH Electrical Engineering

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Abstract

The electricity market is, unlike other markets, unique in the sense that power has to be balanced at all times. New upcoming technology, known as Phasor Measurement Unit (PMU) offers an accurate and timely data on the state of the power system, providing the possibility to manage the system at a more efficient and responsive level.

The PMU systems have been researched extensively in their use for power system management in terms of their contribution to the collected measurements on the states of the power systems. On the other hand, little research has been made on the ability of the current IT infrastructure to meet the demands of the PMUs, and vice versa. One way to contribute to this much needed research is through implementing models of the PMU system in a simulator and observing the behaviour of these models in different network parameters.

In this thesis, the PMU requirements are analyzed and implemented in OPNET, which is a network simulator. Metrics collected from simulations are represented, and evaluated.

Acknowledgements

First, I would like to thank my supervisors, Lars Wallin at Svenska Kraftnät and Moustafa Chenine at KTH for their solid support. Moustafa, I appreciate you patience and your insightful comments. Moreover, I would like to thank both my families; Karam in Lebanon who gave me support all over these years and Sköld in Sweden who made me feel I am a member of their family from the first day. My sincere thanks and love to my partner Evelina Sköld. Last but not least, I would like to thank Sweden for giving us the opportunity to get a high-quality of education.

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1. Introduction

The continuing growth in electricity consumption without a parallel increase in transmission has led to condensed operational margins for many power systems. As a result, they are operating towards unexpected power flow patterns and close to their stability limits. In order to avoid these consequences, the rate of power system efficiency and reliability should be increased [1]. One way to do so is by employing Wide Area Monitoring and Control (WAMC) systems based on Phasor Measurement Unit (PMU) which provides dynamic coverage of the network. The functions of the WAMC systems are generally grouped into two categories. First, functions based on PMUs located in a few key locations of the network. Second, functions based on sufficient numbers of PMUs covering the whole network.

PMU is considered as the most promising measurement technology for monitoring the power systems. This unit is composed of a number of phasors that capture measurements of analog voltage, current waveform and the line frequency.

The Phasor Data Concentrator (PDC), which is located in the control center, gathers all the phasor data received from geographically distributed PMUs via the communication network.

The communication network is one of the components that can be investigated and upgraded, to provide more accurate real-time information between the PMU and the control center. In this way, the observance of the power balance can be facilitated [2]. Without the communication technology, it is difficult, if not impossible, to efficiently automate and control the power system.

The communication network is an important component that supports the IT infrastructure for wide area monitoring and control systems. Communication networks utilized in the power system automations are extremely heterogeneous, ranging from different communication mediums to different proprieties. Demands for faster and more accurate real-time communication for various critical and non-critical operations over wide geographical areas are generally increasing.

1.1 Problem statement

PMU is considered as a promising technology for monitoring the electric systems, however extensive research is lacking within the communication network field of PMUs' requirements which is a predicament that lays as a foundation for this thesis and future research. In general the communication network delays are regarded as a challenging factor that affect the speed and accuracy of PMUs transferred data towards the wide area monitoring and control systems and that will be examined in this thesis.

1.2 Aim and objective

The main aim and objective of this master thesis is to consolidate the performance requirements of PMUs as well as evaluate it in order to improve the performance and reliability to meet the needs of wide area monitoring and reach the capability of applying control functions. Moreover, the data collected are implemented in dedicated and shared network models and then simulated with OPNET modeller with the aim of observing the communication delays from the PMUs to the control center and vice versa.

The workflow is as follows:

- Derive the requirements for PMU systems and correlate these requirements with the possible monitoring and control functions that the PMUs are part of.
- Implement communication networks in OPNET.
- Simulate the communication networks in OPNET.
- Make evaluations on the outcomes.

1.3 Chapter Overview

Chapter 1: Introduction
This chapter presents the focus area, the problem that this thesis tries to solve as well as the aim and objective of it.

Chapter 2: Background
The background chapter introduces a theoretical overview of electric power systems, communication links, protocols and experiences within phasor technology.

Chapter 3: Methodology
This chapter describes the methodology applied to attain the aim of the thesis.

Chapter 4: Implementation
This chapter lists the parameters and presents the OPNET implementations of the dedicated and shared models.

Chapter 5: Simulation results
This chapter lists the End to End delay, throughput and utilization results. Besides, the results regarding the time estimates introduced in the North American SynchroPhasor Initiative (NASPI) section are also discussed.

Chapter 6: Conclusion and future work
This chapter concludes all the work done and draws attention to areas that can be further researched to achieve more accurate times.

2. Background

In this chapter a description of the electric power system components that are directly related to implementing the phasor measurement unit networks is presented. In addition, a brief introduction of protocols and communication links used for design and implementation reasons is included. At the end of this chapter, a description of the experiences in phasor network components is introduced.

2.1 The electric power system

Power systems nowadays are more than just a single generating plant. They play an essential role in the world by providing high reliable energy source. However, infrequently they face outages that affect residential areas and industries around the world. The number of outages has been increasing, due to increasing consumption and no upgrade in generation, transmission and distribution lines for economic costs and environmental reasons. The frequently asked questions are: Are these the real root causes of the blackouts? [1]. Can we prevent outages from happening by upgrading the system generation and grid? Investigations on these questions showed that the reason behind the numerous blackouts in the U.S. and Italy [4] was the lack of information. If power system operators were able to monitor a wide area of the grid, the number of outages would have been reduced, since recent network events showed that anomalies indicating power system instability started to occur days before the instability became critical [4] [5].

2.1.1. Power system automation

Power system automation refers to the various measurement devices connected to the network, intelligent electronic devices and the use of computer. Power system automation offers to utilities a set of benefits in monitoring, remote control, automation power delivery, reduced operation, and maintenance costs. Moreover, the same information gathered can provide better planning, system design enhancement and an increase in customer satisfaction. These benefits also rely on data acquisition, power system supervision and power system control working together. More readings on the subject of power system automation, its architecture and components can be found in [3].

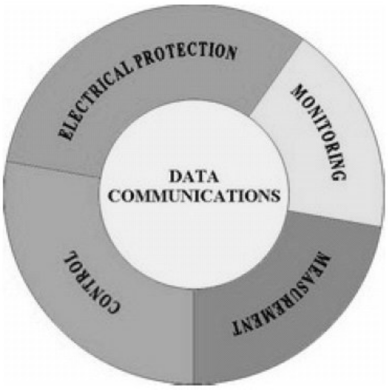


Figure 1: Functional structure of Power System Automation. [6]

2.1.2. Control center

In the 1950s, analogue communications were employed to collect real-time data of MW power outputs from power plants as well as tie-line flows to power companies for operators who used analogue computers to conduct Load Frequency Control (LFC) and Economic Dispatch (ED) [7]. When digital computers were introduced in the 1960s, Remote Terminal Units (RTUs) were developed to collect real-time measurements of voltage, real/reactive powers and status of circuit breakers at transmission substations. This was done through dedicated transmission channels to a central computer equipped with the capability to perform necessary calculations for Automatic Generation Control (AGC) a combination of LFC and ED [8]. The capability of control centers was pushed to a new level in the 1970s with the introduction of the concept of system security, covering both generation and transmission systems [9]. The security purpose was to resist disturbances or contingencies. In the second half of the 1990s, a trend began to fundamentally change the electric power industry. This came to be known as industry restructuring or deregulation [10], the restructuring was done in a manner to be distributed, fully decentralized, integrated, flexible and open. Details about functions and architectures of control centers can be found in [8].

2.1.3. SCADA

Nowadays, the Supervisory Control and Data Acquisition System (SCADA) is the major communication technology used for monitoring and controlling the electric power network. The characteristics of SCADA are star-connected and point-to-point links connecting substations to control centers. Comparing with today's networks, SCADA links are slow. The control center asks each substation for updated data once every 2 to 4 seconds. As a result, the control center's picture of the operational status of the power network is not enough to warn disordered events [11]. SCADA assembles data from various locations through sensors at a factory, plant or in other remote locations and then forwards the data to a central computer which runs different applications. SCADA system architecture is shown in Figure 2. SCADA systems have the following base functions [12]:

- Data acquisition
- Monitoring and event processing
- Control
- Data storage archiving and analysis
- Reporting

Each of these functions is described in details in [12]. SCADA functions are listed in order to compare them with the benefits of a system based on phasor measurements.

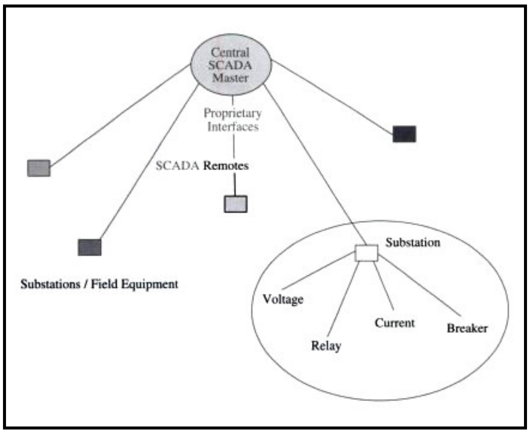


Figure 2: SCADA system architecture [13]

2.2 Phasor Measurement

The phasor technology is considered as the most promising measurement technology for power systems. Although SCADA has been the essential components for monitoring and control in power system for approximately 50 years, phasor technology is considered as the next generation that is needed for increasing the reliabilities of wide area monitoring and control in the network [14].

2.2.1. Phasor technology

Phasor image is the representation of a sinusoidal signal in the form of magnitude and phase with respect to a reference. The phase is the distance between the signal's sinusoidal peak and a specified fix point in time, as a reference. In Figure 3, the reference time is equal to zero and calculated in angular measure. The magnitude is correlated to the amplitude of the sinusoidal signal. The use of phasor technology simplifies the mathematics and electronics required for power systems. This simplification facilitates the PMU monitoring on a wide grid [15]. Moreover, phasors can also be represented in the complex plane by real and imaginary components.

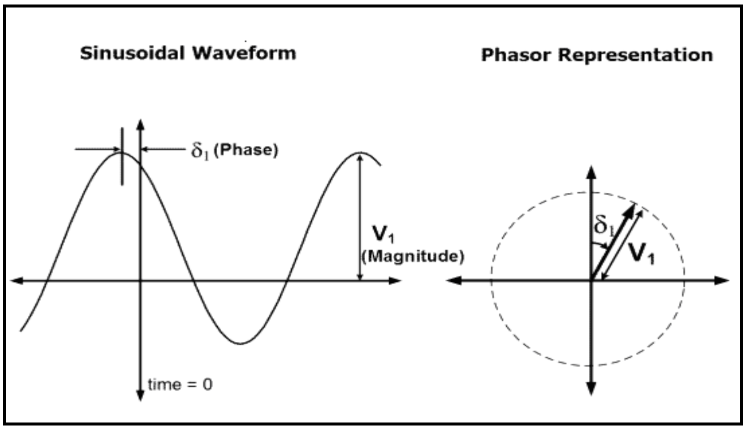


Figure 3: Phase and Magnitude representation from sinusoidal to phasor representation [17]

The expectation beyond the deployment of phasor technology is to have a dynamic view of the system behavior. This reduces the problems that have risen in most of the major blackouts that have occurred around the world. Examples of some major blackouts include: the August 2003 Eastern Interconnection Blackout in the US; the August 16 Western Interconnection Blackout in the US and the summer 2003 and 2004 blackouts in Europe (in Italy specifically) [4] [8].

To calculate two or more phase angles of phasor measurements, one of the phasors should be chosen as a reference and all the others phase angle measurements are computed with respect to the chosen reference [16]. Figure 4 illustrates phasor measurements with respect to a reference.

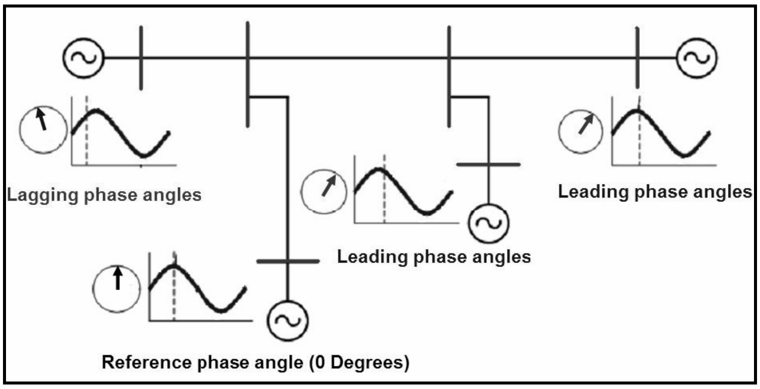
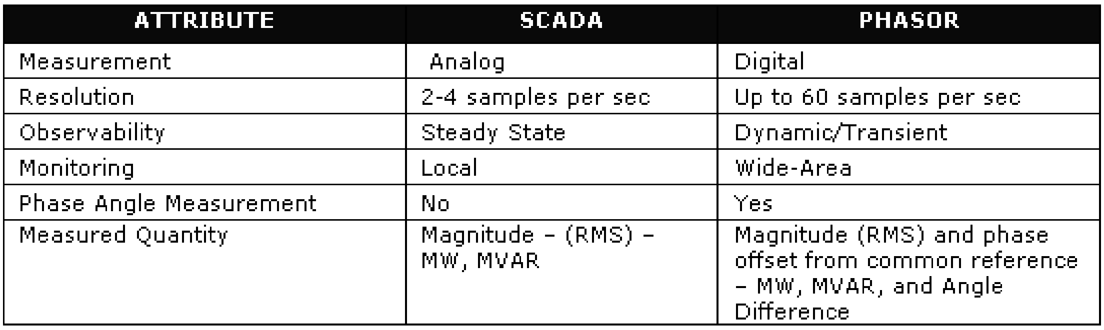


Figure 4: Phasor measurements with respect to a reference [17]

Figure 5 below shows a comparison between SCADA system and phasor technology. The parameters that each attribute can hold with the two different systems are presented. It is important to know that the phasor technology was not developed to replace the SCADA system, but to complement it.



ATTRIBUTE	SCADA	PHASOR
Measurement	Analog	Digital
Resolution	2-4 samples per sec	Up to 60 samples per sec
Observability	Steady State	Dynamic/Transient
Monitoring	Local	Wide-Area
Phase Angle Measurement	No	Yes
Measured Quantity	Magnitude - (RMS) - MW, MVAR	Magnitude (RMS) and phase offset from common reference - MW, MVAR, and Angle Difference

Figure 5: Comparison of SCADA and phasor capabilities [17]

2.2.2. Time synchronization

Signal synchronization is needed to supply a common timing reference for the phasor measurements in an electric system network. It can be provided by two sources, local or global. The signal reference should be, according to Coordinated Universal Time (UTC), with a repetition of 1 pulse per second at all measurement sites through synchronism accuracy within 1 microsecond of UTC.

Local source signal synchronization is broadcasted from a central station through transmission systems like AM radio broadcast microwave and fiber optics. Details about local broadcasting are not covered in this paper since it is not deployed in PMUs, due to the fact that these transmission systems either have low accuracy, or acquire high installation cost [10].

Global source signal synchronization is broadcasted from satellites, to be more exact, by Global Positioning System (GPS). "The GPS is a U.S. Department of Defense (DoD) satellite based on radio-navigation system. It consists of 24 satellites arrayed to provide a minimum worldwide visibility of four satellites at all times. Each satellite transmits a timed navigation signal from which a receiver can decode time synchronized to within 0.2 ms of UTC. The inherent availability, redundancy, reliability and accuracy make it a system well suited for synchronized phasor measurement systems" [18]. Figure 6 illustrates the locations of the satellites around the earth.

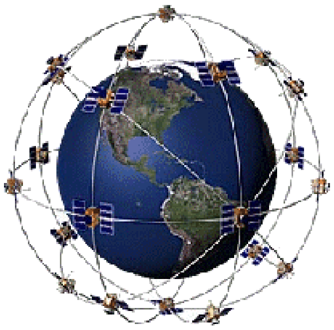


Figure 6: Satellites location for GPS [18]

More details about PMU synchronization, on whether they receive signal directly or from an independent receiver, and PMUs that use fixed frequency synchronized sampling can be found in [18].

2.2.3. Phasor measurement unit

Installation of this unit is in its experimental stage in many power systems. The unit is composed of a number of phasors that capture measurements of analog voltage, current waveform and the line frequency. After that, the phasor measurements are digitized by an analog to digital converter and stamped with the creation time provided by a GPS clock. GPS clocks are used for synchronization of multiple PMUs with a precision of maximum 1 microsecond difference. Afterwards, the data are transferred to a phasor data concentrator, which is explained in the next section. PMU provides a dynamic system observation of the network, because the measurements are taken with a high sampling rate from geographically distant locations and they are then grouped together according to the time stamp provided by the GPS. Phasor measurement unit transmits samples in different sizes. The sample size depends on the number of phasors in a unit. Sample and packet have the same meaning when talking about PMU transfer rate. The required transfer rate differs from a 50 Hz system to a 60Hz system. For example, a 60 Hz system has a rate up to 60 samples per second, while the 50 HZ one has up to 50 samples per second [19]. Figure 7 shows the block diagram of a PMU.

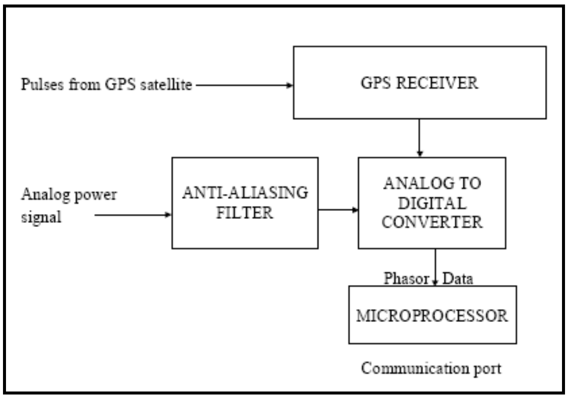


Figure 7: Phasor Measurement Unit block diagram [20]

2.2.4. Phasor data concentrator

It is at a PDC that collection, concentration, correlation and synchronization of phasor data samples take place. Samples with the same creation time are encapsulated in one packet, and then transmitted as a single stream to the phasor data server. In addition to that, PDC performs a number of quality checks, such as inserting the appropriate flag in the correlation of data, checking for disturbance flags and recording the data for offline analysis. The PDC information can also be an input to the SCADA system. Super PDC collects data from all PDCs in the network, and then treat the collected data the same way as a normal PDC does [17]. Figure 8 shows the placement of a PDC in a phasor network.

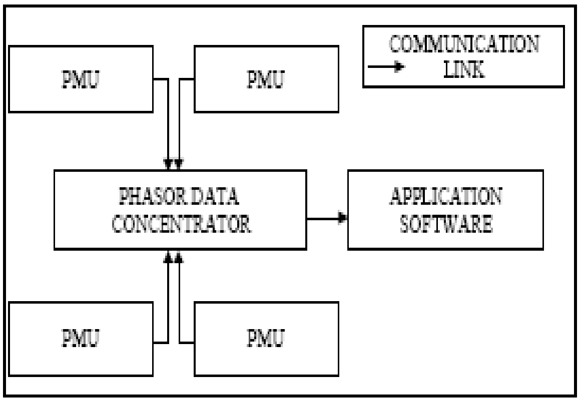


Figure 8: PDC placement in a network [20]

2.2.5. Typical network of phasor measurement units

PMUs located at various locations of the electric system network gather real-time data and transmit them. A PDC at the control center receives the data and aggregates them. A computer which is connected to the output of the PDC provides the users with software applications that display measured frequencies, primary voltages, currents and MWs for the operators [17]. Figure 9 shows phasor network architecture.

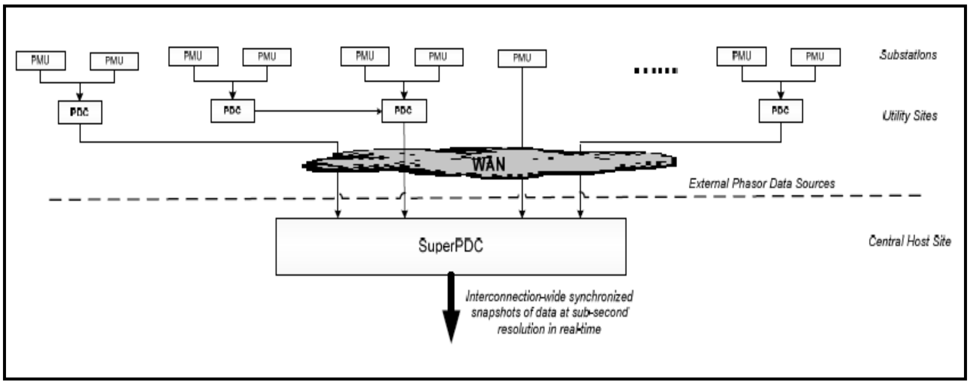


Figure 9: Phasor network architecture [17]

2.2.6. Standards for phasor measurement communication

To be able to interchange phasor measurements between a variety of devices and users that utilize PMU bought from different vendors and different communication protocols, standards need to be set up for all vendors to follow. The standard for phasor network messaging is called “synchrophasor for power system”.

Synchrophasors address issues like [18]:

- Synchronization of data sampling
- Data to phasor conversions
- Formats for timing input and phasor data output

The synchrophasor standards for power systems give us the opportunity to synchronize input and output data for phasor measurements as well as anticipate in adding assessments to developers and users of digital computer-based substation system. Two types of synchrophasors standards are available, the IEEE 1344 and the IEEE C37.118. Both standards have a common base to start with, such as time synchronization and phasor calculation, but with the latter one coming as an updated version to enhance the accuracy of measurements. The message format has been modified in IEEE C37.118 in order to improve information exchange with other systems and to add more value to the total process.

IEEE C37.118 improves PMU interoperability with the following three major contributions [16]:

- Refined definition of an “Absolute Phasor” referring to GPS-based and nominal frequency phasors, as well as time-stamping rule;
- Introduction of the TVE (Total Vector Error) to quantify the phasor measurement errors;
- Introduction of the PMU compliance test procedure.

For more reading about these topics, refer to IEEE publications concerning standards for synchrophasors (can be found in [18] [21]).

2.3 Wide Area Monitoring and Control systems

The usage of electric power system is a major concern of the utilities and grid operators, due to a continuous load growth without an increase in transmission resources. Many of the power systems are operating close to their stability limits [22] and unexpected power flow patterns. Implementation of advanced control and supervision systems could prevent such events, which was where the idea of WAMC came from. WAMC functions depend on different application requirements, thus these applications depend on the number and locations of the PMUs installed in the system.

WAMC system networks are exclusive for each electric power system company. WAMC system technology platform enables the development of new applications for enhancement of power system control and operation. A WAMC system is considered exclusive because it is designed based on the needs of the company, taking into consideration the available technology, the economical constraints, the number of PMUs installed in the power system and which applications have the priorities to be improved [23].

WAMC applications are divided into two different types:

First, applications implemented based on PMUs installed in few key locations of the network, given by that a partial observation of the power system state. Examples of applications:

- Voltage stability monitoring for transmission corridors [25]

- Oscillatory stability monitoring [26]
- Coordination of FACTS control using feedback from remote PMU measurements, to enhance transmission capacity restricted by, for instance, voltage stability [27].

Each application has its own requirements in terms of the number of required measurement samples. However, the same measurements can often be used for more than one application.

Second, a range of more advanced applications based on a detailed network model view, given that a sufficient number of PMUs have been placed so that the network state can be completely calculated. For example:

- Loadability calculation using OPF or other optimization techniques [27]
- Topology detection and state calculation [24]

2.4 Communication

The main component of providing monitoring and control of the electric grids nowadays is the SCADA communication technology. It connects the substation to the control center, with a link capacity of thousands of bits per seconds and an updated rank every 2 to 4 seconds. This is considered a very slow rate of exchanging data comparing with modern communication networks. Due to this limited communication, the control of the power grid is held locally, i.e. on a substation basis. Therefore, making the relation between the WAMC applications and PMUs more accurate depends on the use of new technologies. For example, increasing the storage capacities in computers, deploying faster communication transportation, and on software level making it more flexible. These three factors, together with the Internet's already existing communication infrastructure, make us look forward to a real time monitoring and control of the electric power system. To realize this in an IT point of view, the hybrid network should be used. Figure 10 shows the communication network architecture for electric power system. The hybrid network is divided into two parts [28]:

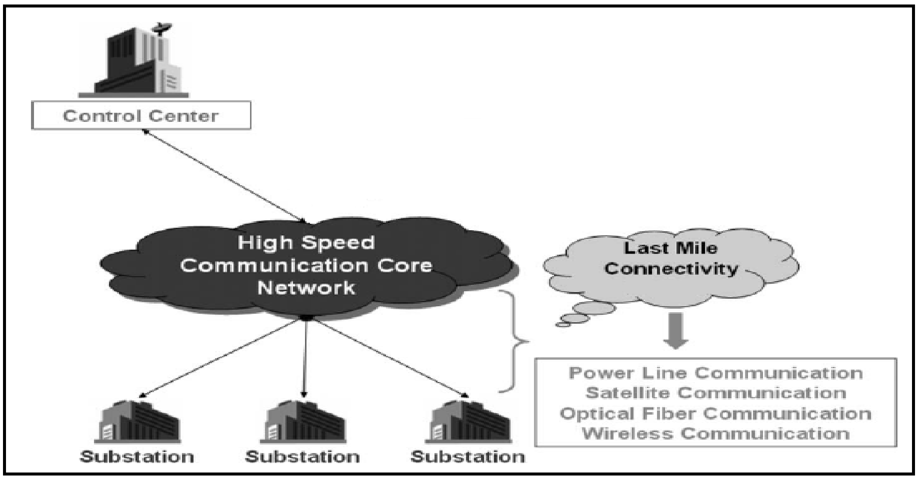


Figure 10: Communication network architecture for electric system automation [28]

• High speed communication core network: Depending on industrial needs, it can be a private network or public network. For example, Internet based Virtual Private Network (VPN) can be considered as a cost-effective high speed communication core network for electric system automation. A detailed explanation of VPN performance can be found in [28].

- Last mile connectivity: It includes the communication media between the substations and the high-speed communication core network. The most competent communication media for last mile connectivity are I-Power line communication, II-Satellite communication, III-Optical fiber communication and IV-Wireless communication. In the following subsections, the advantages and disadvantages of each media are introduced [28].

I-Power Line Communication: Within PLC, there is no need to construct communication infrastructure since the theory of this communication is to transfer data, with a rate of 4Mbps and electricity of medium 15/50 kV, simultaneously. PLC can also be deployed in low voltage power line 110/220 V. This provides the users with a wide coverage and reduced installation cost since there is no need to build communication infrastructure with the power lines already existing. On the other hand, a wide range of drawbacks are also present in PLC, ranging from low security, small capacity, limited energy and frequencies employment, open circuit problem signal attenuation and distortion, to high noise sources over power lines which result in high bit error rates during the communication [29].

II-Satellite communication: Satellite communication also has the advantage of not having to install wired network. A substation can profit from a high-speed service and global coverage provided by satellite communication, once the necessary technical equipments are in place. As for drawbacks, firstly, they are represented on the long delay basis in the round trip time; second, the weather plays a role in the characteristic of the communication; and last, the satellite communication has a high usage cost compared with other communications [29].

III-Optical fiber communication: In electric system automation, the optical fiber is one of the technically attractive communication infrastructures, because of the high performance provided by its extremely high bandwidth capacity. Whereas a single wavelength offers transmission rate up to 10Gbps; multiple wavelength, known as wavelength division multiplexing (WDM), offers from 40Gpbs to 1600Gbps transmission rate. In addition, compared with other wired infrastructures, where a repeater is present every 100 to 1000 Km, optical fiber communication systems require a smaller number of repeaters [30]. More advantages in optical fiber communication systems, compared with other communication infrastructures, are related to their low bit error rates (BER = 10 ^-15) as well as their immunity characteristics against electromagnetic interference (EMI) and radio frequency interference (RFI). This makes optical fiber communication an ideal communication medium for high voltage operating environment in substations [31]. The disadvantage of the current media is characterized by its expensive installation cost. However, as a result of its high performance and capabilities, once this infrastructure is found, it can be shared among a number of users and networks. This in turn opens a discussion of whether the cost is a disadvantage.

IV-Wireless Communication: In wireless communication two choices can be deployed; first, by using an existing communication infrastructure of a public network, e.g., cellular network. Recently, Short Message service (SMS) has been applied to remote control and monitor substations [32]; second, by installing a private wireless network which allows electric utilities to have more control over their communication networks. The relatively low cost and rapid installation are considered the advantages of wireless communication; while the disadvantages are present in three factors: limited coverage, capacity and security [28].

2.5 Network Protocol

Transport Control Protocol/Internet protocol (TCP/IP) is known as low level protocol, and is used mainly on Ethernet. TCP/IP is used to transport data, because it provides a highly reliable connection, using checksums, congestion control and automatic resending of bad or missing data. TCP/IP can have a problem with streaming continuous data, because an error will cause the data stream to be backed up for a period of time while TCP/IP protocol attempts retransmission of the missed data [36]. A detailed explanation of TCP/IP packet structure, connection establishment, and its layers can be found in [37].

2.6 Reference Architecture

Enhanced Performance Architecture (EPA) describes a method in which only the application, data link and physical layer are used for data communication. EPA is used when devices are equipped with identical or very similar operating systems, and data coding is either nonexistent or very simple [40]. EPA is designed to provide faster message response times by skipping the upper layers, and connecting the application directly to the data link layer in an effort to streamline critical communications [39].

2.7 Routing Protocol

The routing protocol identifies the way routers communicate with each other. Open Short Path First (OSPF) is a routing protocol that was developed by Internet Engineering Task Force (IETF). OSPF is a link state, hierarchical routing protocol. It is capable of doing neighbor discovery on different types of networks with minimal need for configuration. OSPF simplest interface type is a point to point interface. Point to point interface is the case when there is only one neighbor on the other side of the link [41].

2.8 OPNET

OPNET modeler is a very large and powerful software specialized for network research and development. OPNET offers the possibility to design and study communication networks, devices, protocols, and applications with great flexibility. OPNET contains a huge library of accurate models of commercially available fixed network hardware and protocol, it hierarchical structure modeling is divided into three main domains which are illustrated in Figure 11.

- Network model (highest level): entire network, sub-networks, network topologies, geographical coordinates.
- Node model: single network node, e.g. routers workstations, switches, servers and mobile devices.
- Process model: Single modules and source code inside networks nodes, e.g. data traffic source model, MAC, IP, and TCP.

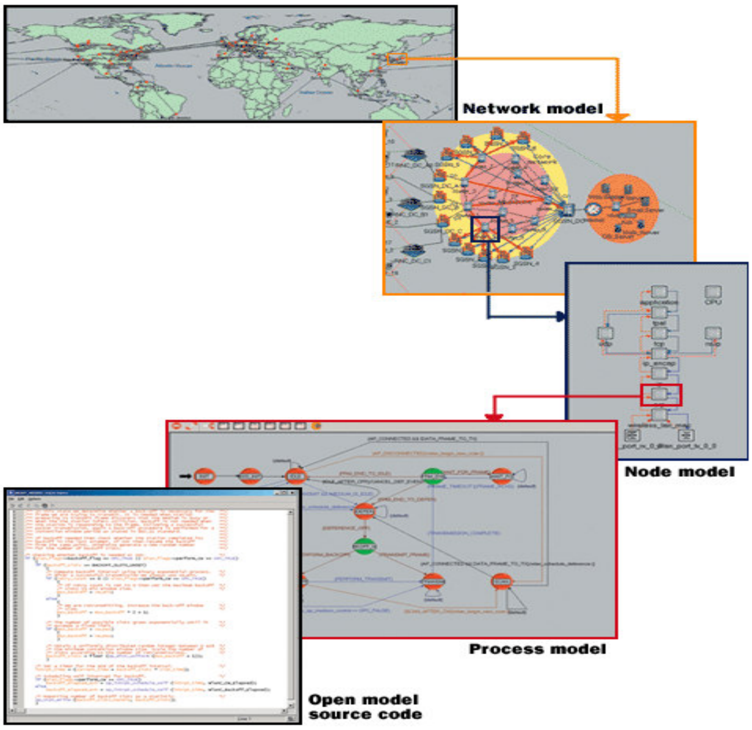


Figure 11: OPNET hierarchical structure

OPNET will never provide the best degree of accuracy, as simplifying assumptions are required in order to implement and simulate a network in a reasonable amount of time. More reading about OPNET can be found in [42].

2.9 North American SynchroPhasor Initiative (NASPI)

Throughout the study, research related to WAMC systems were examined. Valuable knowledge was obtained from online and published resources provided by NASPI [33]. The resources describe all guides and test results concerning PMU installation procedures, as well as application developments in wide area monitoring, analysis, control and protection.

NASPI is an extension of the Eastern Interconnect Phasor Project (EIPP) of North America. The vision was to improve power system reliability through wide-area measurement, monitoring and control. The organization is divided into tasks and teams from the Western Electricity Coordinating Council (WECC). The NASPI tasks titles are business management, data & network management, equipment placement, operations implementation, performances and standards, planning implementation and research initiatives. The listed titles are accessible on the organization’s website [33] where a number of documents about each task and reports describing their practices within the field are available.

2.9.1. Phasor network experience

The first monitor developed to display phasor measurements was presented in the mid 1980s, and it was funded by the Department of Energy (DOE). Moreover, after launching several projects to enhance the system, the researchers in 1996 were able to record real-time measurements of the power system breakups and blackouts that occurred in the western U.S with a wide area monitoring system based on GPS synchronized measurements.

Currently, more than twenty North American utilities have PMUs installed in their substations, but their level of experiences are not the same. The Eastern Interconnection utilities are still in the initial stage of implementing and networking PMUs, while the utilities in the Western Interconnection, motivated by the wide area monitoring project, have already developed a wide area phasor network in combination with monitoring and post-disturbance tools. Moreover, plans are established to identify and set out prototypes for wide area real time control and protection systems using phasor technology infrastructures [22]. Figure 12 shows a generic architecture of Wide Area Monitoring, Control and Protection (WAMCP) system.

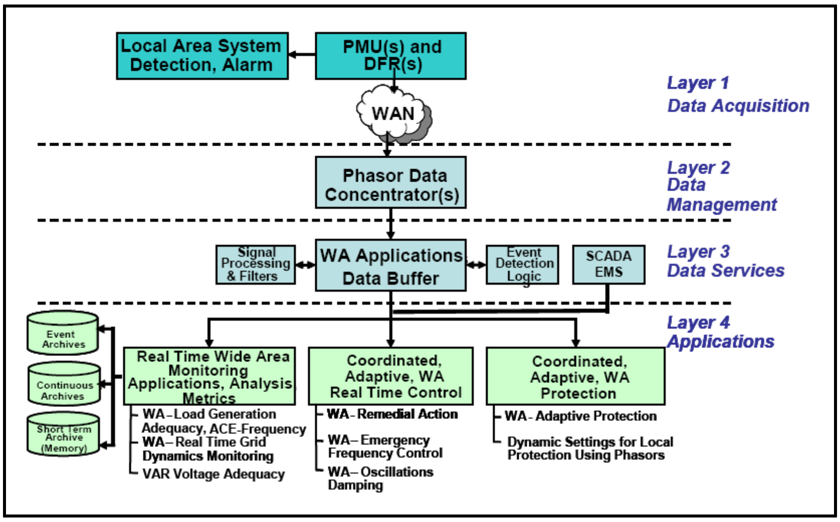


Figure 12: Generic architecture of a wide area monitoring, control and protection system [22]

- **Layer 1, Phasor Data Acquisition** – Presents the PMUs and Digital Fault Recorders (DFRs) that are located in substations to measure voltage, current and frequency.

- **Layer 2, Phasor Data Management** – Where the PDC collects the data sent from PMUs and other PDCs and correlates them into a single data set. It is then streamed to applications via the applications data buffer.

- **Layer 3, Data Services** – Data are served to different applications. Some of the services include supplying the data in the proper format required for applications and fast execution to leave sufficient time for running the applications within the sampling period. Moreover, system management occurs in data services layer by monitoring all the input data for loss, errors and synchronization.

- **Layer 4, Applications** – Phasor data applications are divided into three parts [22]:

    1. **Monitoring and Analysis** – Real time wide-area load generation balance, ACE-Frequency, wide area real time grid dynamics monitoring.
    2. **Real Time Control** – Wide area remedial action, emergency frequency control, oscillation damping

3. **Adaptive Protection** – Coordinated adaptive protection, dynamic settings for local protection using phasor measurements

2.9.2. Phasor network response time estimates

After presenting the generic architecture of the WAMCP system, it can be seen that communication infrastructures and delays from different hardware/software platforms play a crucial role in the response time of a phasor network. This is because a significant protection depends on the speed at which the control center can identify and analyze an emergency, in addition to the time needed before a control action takes effect. It has been researched and documented in [20] that the total process of obtaining a consistent system involves the 6 following activities with some time estimates for each:

1. Sensor Processing Time – 5 ms
2. Transmission Time of Information – 10 ms
3. Processing Incoming Message Queue – 10 ms
4. Computing Time for Decision – 100 ms
5. Transmission of Control Signal – 10 ms
6. Operating Time of Local Device – 50 ms

TOTAL Time – 185 ms [20]

Sensor processing time represents the time taken for a signal to be captured, digitized and ready to be transferred in the IEEE 1344 or C37.118 packet. This activity is hardware dependent and processing time differs according to the PMU manufacturers.

Transmission time of information represents the delay time from when data are transferred by PMUs until they are received by the PDC. This activity is network dependent and transmission time differs according to network communication media, communication protocols and network usages.

Processing incoming message queue represents the time that the PDC needs to sort the received data and be ready to transfer them again. This activity is hardware dependent and processing time also differs according to the developer of the PDC.

The computing time for decision activity is also software dependent. Known as the WAMC system, it is either bought or developed in-house. Computing time for decision is different for most applications, and depends also on the workstation speed.

Transmission of control signal represents the delay time from when a monitoring and control system sends a command through the network to when the command is received by a device in the substation. This activity is network dependent and transmission of the control signal differs according to network communication media, communication protocols and network usages.

Operating time of local device represents the time needed for a device to take action when it receives a command. This activity is hardware dependent and the operating time is different for each device.

The presented time estimations are based on the assumption that the utilities have a complete fiber optic network with dedicated channels, which is necessary for high priority communication and control signals [20].

In the OPNET implemented models, it was possible to investigate the time that was network dependent. However, the time that depended on software and hardware was hard to attain because of the time limitation of this work. The network dependent time captured from the simulations was used to replace the estimated time listed in the transmission time of information activity as well as in the transmission of control signal activity in order to estimate the designed models consistency.

3. Methodology

In this chapter, the method of working is presented.

Figure 13 shows the phases followed to achieve the desired goals. These phases are described in detail in the following sections.

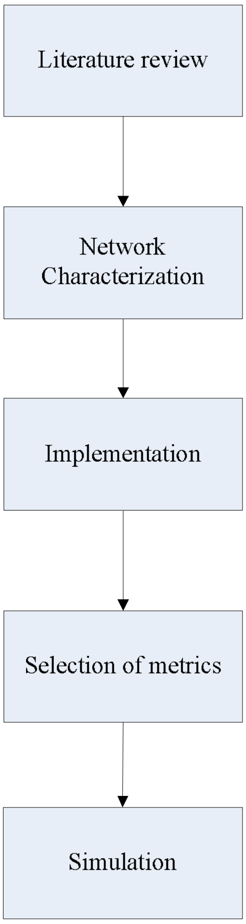


Figure 13: Phases of work

3.1 Literature review

The review was first carried out to understand the architecture and components of electric power systems as well as its behavior, most of the material is included in chapter 2 as background material. The resources for the literature review were collected from internet through published technical papers, and experiences related to such systems, especially by NASPI [33].

3.2 Network Characterization

After the literature review the draft communication network models were formulated. The models were then verified by contacting Svenska Kraftnät (SvK) for understanding the general configuration of a utility communication network, such as traffic levels, communication capacities, geographical distances etc. This was an important phase since it led to more specific insight on the architecture of typical utility networks which could then be generalized into simulation models.

3.3 Implementation

In the implementation phase, the simulation models were implemented in OPNET and the network characterizations collected from the previous phase were applied on the models as well as general information from reviewed literature.

The implementation phase was iterative. Enhancements and expansion of the models was done gradually. The iterative sub phases are illustrated in Figure 14.

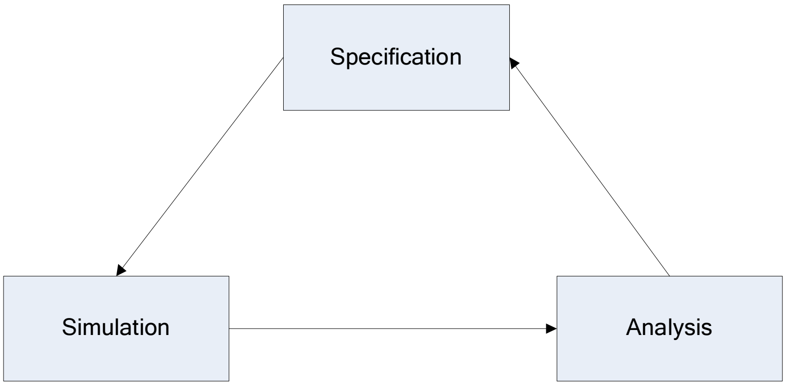


Figure 14: Iterative form sequence

The first part of the implementation was to implement a prototype with initial specifications. This was followed by simulating the prototype and analyzing the collected data. A re-specification of the prototype was then done by adding more advanced characteristics to the models, followed by the simulation and analysis part.

3.4 Selection of metrics

The selection of metrics for this work included:

- **End to End Delay**
  Delay measures the time difference in the transmission of information across a system [38]. End to End (ETE) delay is the time taken for a packet to reach its destination. This metric was collected separately for each source and destination pair.
- **Throughput**
  The throughput is the rate of the average number of delivered data. This metric is a good sign for the efficiency of size data operation [39].
- **Utilization**
  The utilization is the consumption in percentage of a link capacity.

3.5 Simulation

There are several techniques to evaluate the performance of network architecture such as statistical analysis, network monitoring or simulation. In this work, computer simulation was chosen as the evaluation tool since it has the great advantage of being less expensive than building up a network and performing the monitoring evaluation on it. Different simulators are available, such as ns2/ns3, NetSim, OPNET and QualNet. It is usually up to the designer to choose the modeler that best fulfills his/her specific needs. In this thesis, OPNET modeler version 14.5 was used as simulator for the following reasons. Firstly, OPNET is a very user-friendly tool with a library that contains wide choices of components. This can help in making the implementation phase easier for the designer. Secondly, with OPNET, different simulations can be run at the same time, which makes the analysis of the results more comparable and easier to understand.

The simulation was needed because of the following reasons:

- PMUs have not been installed on sites yet, so there was a need to investigate their behavior in a shared environment. In addition, it was important to observe the consumption of PMUs data in a dedicated environment.
- The simulation helped in understanding networking and modeling.

4. Implementation

This chapter presents the implementation of the networks. Two network models were implemented, a dedicated model and a shared model. The implementation followed the iterative sequence listed in the methodology chapter section 3.3.

To have a considerable architecture for the network models and to fulfill the objectives of the thesis, requirements of the PMU were collected from literature reviews. They included the PMU transfer rate, connection to the network and packet size. Whereas for topologies, protocols and communications between the PMUs and the control center, the requirements were obtained from both network characterization and literature reviews. The former was performed to check the states of the problems faced by existing networks, while the literature review was done to compare new technologies with the already existing ones used in electric system networks to conclude if the new technologies add any enhancement to the networks.

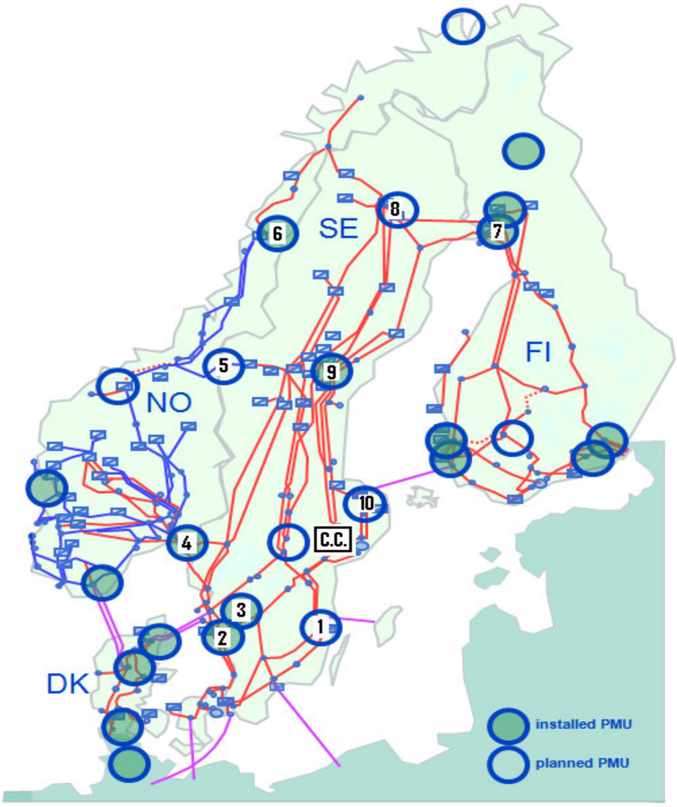


Figure 15: PMUs location chosen for implementation [35]

Figure 15 shows the locations of installed and planned to be installed PMUs in the Nordic region [35]. In this work ten PMUs locations were chosen for the implementation. The choosing criterion was the geographical locations of the PMUs. In a way, they covered all electric transmission paths between Sweden and the neighboring countries. These locations were implemented using distance based delay option in OPNET which calculates the delay based on the geographical distance between two nodes. Regarding the control center the location was chosen to be in Stockholm.

Two network models were implemented, with the first one using shared communication link and the second using dedicated communication channels. In the shared model, two different percentages of background traffic were introduced. In the dedicated model two different communication channels capacities were presented. The transfer rate of the PMUs was set to 30 samples/second, which was chosen because it was found during the literature review that the maximum rate needed for wide area monitoring functions was 30 samples/second. The OSPF routing protocol was used for the two implemented models, with the static routing tables used in the dedicated model and the dynamic routing tables used in the shared model. The TCP/IP protocol was chosen following the idea that switched Ethernet using TCP/IP protocol could fulfill the real time requirement of the implemented applications. Another analysis proving that switched Ethernet using TCP/IP is able to fulfill the real time requirement needed in electric power systems can be found in [34]. In some implementations, the parameters were simplified or modified. The simplification was due to time limitation while the modification was done to examine the differences when implementing different network configurations.

4.1 Data flow

The data flow section refers for getting, or collecting data of the implemented models using OPNET. The data was generated from computer components named as PMU. These computers were configured to generate samples rate similar to a real PMU, including the same packet size. Created data was transferred to a substation switch, and then to the substation router that in turn transferred the received data to the regional router. From regional router, the data were transferred to the core network. From core network, the data were transferred to the PDC. The PDC was located in the control center subnet. The implemented models had a sampling rate of 30 samples per second transferred from each PMU with a packet size of 76 bytes. The 76 bytes represented the size of C37.118 packet, containing the data of 10 phasor measurements, six analogue measurements and one digital measurement. The PDC was implemented as a computer component and was configured to generate the same rate as a PMU, 30 samples per second with a packet size equal to 760 bytes containing the measurements taken from 10 PMUs. The PDC transferred the data towards the WAMC. The WAMC was implemented as a computer component and was configured to send control commands to three different PMUs at three different times. The WAMC configuration was done to make it possible to capture the time taken for a control command to be received by a substation.

4.2 Common architecture for the dedicated and shared models

This section lists the common architecture that was implemented for the dedicated and shared models. It included the network model, subnets and core subnets implementations.

4.2.1. Network model

The geographical locations of the PMUs and routers inside the subnets, the subnets themselves, the core subnets and the control center subnet were common for both the dedicated and the shared models. Figure 16 shows the OPNET implemented locations of the subnets, core subnets and control center subnet. The contents of the subnets are described in the subsection 4.2.2. The dedicated and shared models shared the same locations and distances for the communication links connecting the subnets. The link capacity, however, was different and is described in details in sections 4.3 and 4.4.

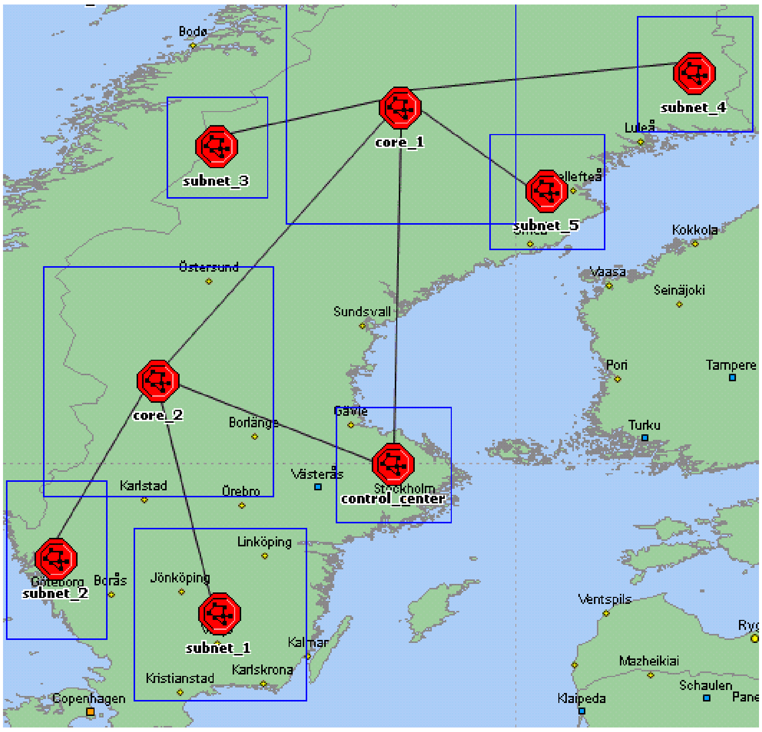


Figure 16: Network model used in both designs

4.2.2. Subnets

The location of the PMUs was chosen from Figure 15. This figure listed the already installed PMUs and the PMUs planned-to-be-installed in the near future. Ten PMU locations were chosen to be implemented for the dedicated and shared models. The PMU was connected to a substation switch which was then connected to a substation router. The substation router was connected to a regional router. Figure 17 shows the internal representation of subnet_1. All subnets were implemented in the same form except subnet_5 which was implemented with one PMU, one substation switch and one substation router. The link between the PMUs and the substation switch, as well as the link between the substation switch and the substation router was through a 100baseT link. The 100baseT link was used in both the dedicated and the shared models. Whereas the link between the substation router and the regional router was unique for each model and is described in details in sections 4.3 and 4.4. The link between the substation router and the regional router has been mentioned in the common architecture section because the locations and distances between those two components were similar for both models.

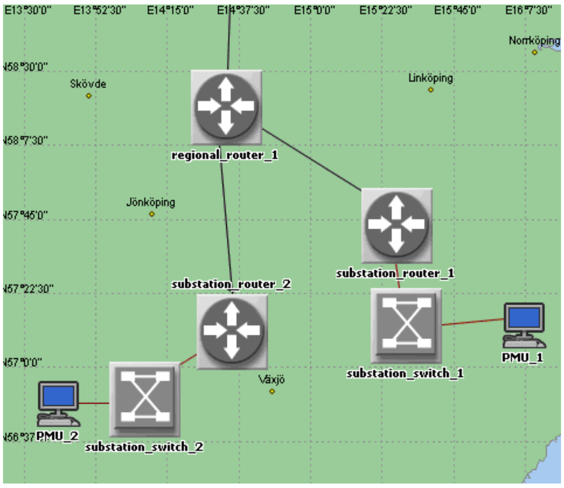


Figure 17: Internal representation of subnet_1

4.2.3. Core subnets

An additional common design that was implemented for the dedicated and shared models was the core subnets. Figure 18 shows the architecture of the core models implemented in OPNET. They were considered as a small model compared to a real core network model, with the latter composed of hundreds of routers. This was one of the limitations of this thesis work due to time limitation. The core models were designed in order to use mesh topology. The core_2 subnet was shown in Figure 18. The core_2 subnet was composed of routers and communication links. Routers were common for the dedicated and shared models while the links were unique according to each model's specifications.

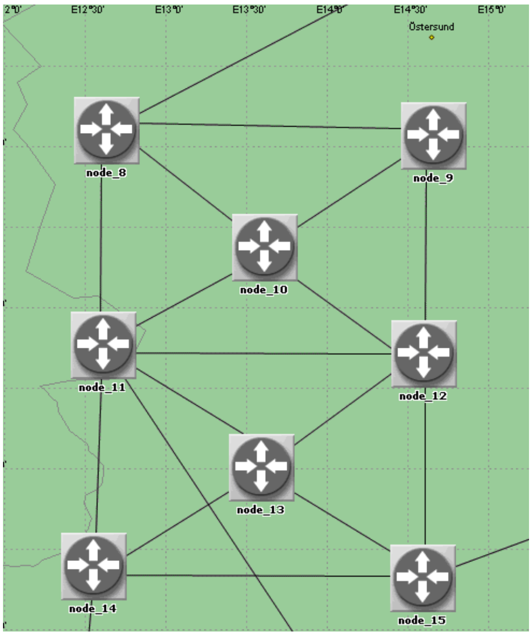
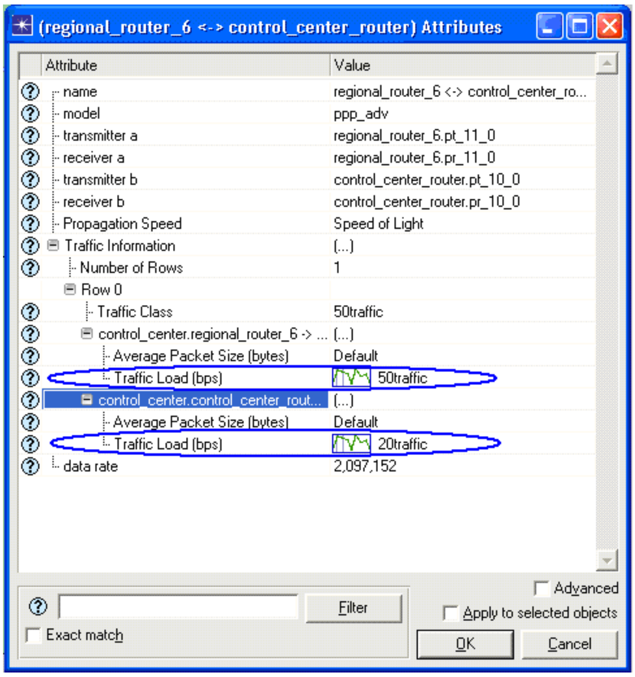


Figure 18: Core_2 internal components

4.3 Shared model implementation

The goal behind implementing the shared model in OPNET was attempting to create a scenario of a real network, where existing traffic characteristics were modeled to share the possible traffics introduced by a phasor network. To fulfill the goal, the background traffic was introduced in the communication links. This background traffic represented the existing traffic of a network, and it was configured within the attributes of the communication link as shown in Figure 19. The background traffic flow was present from the substation switch of each PMU toward the control center switch. The shared model was compiled in two different scenarios. In the first scenario, the percentage of the background traffic was 50%, which was chosen to check how the model would behave in moderate traffic; in the second scenario, 70% background traffic was chosen, to check the accuracy of the system when the network was heavily used.



(regional_router_6 <-> control_center_router) Attributes

Attribute	Value
name	regional_router_6 <-> control_center_ro...
model	ppp_adv
transmitter a	regional_router_6.pt_11_0
receiver a	regional_router_6.pr_11_0
transmitter b	control_center_router.pt_10_0
receiver b	control_center_router.pr_10_0
Propagation Speed	Speed of Light
Traffic Information	(...)
Number of Rows	1
Row 0	
Traffic Class	50traffic
control_center.regional_router_6 -> ...	(...)
Average Packet Size (bytes)	Default
Traffic Load (bps)	50traffic
control_center.control_center_rout...	(...)
Average Packet Size (bytes)	Default
Traffic Load (bps)	20traffic
data rate	2,097,152

Figure 19: Background traffic configuration between regional router 6 and control center router

As for the background traffic flow from the control center toward the substations switch, the background traffic was 20% in both scenarios. This was because it was assumed that the traffic sent from the control center would be much less than the traffic the control center received from the remote devices and components.

Shared model implementation using OPNET was done according to the following. A 2Mb communication media was used as the link between subnets, core subnets and the control center. The 2Mb capacity was chosen, because in fiber optical networks using standards such as Synchronous Digital Hierarchy (SDH), the fiber optic link can sometimes be “channelized” into multiple fixed rate channels, and 2Mb channel capacity is a frequent size.

Figure 20 shows the 2Mb link capacity between all subnets implemented in OPNET.

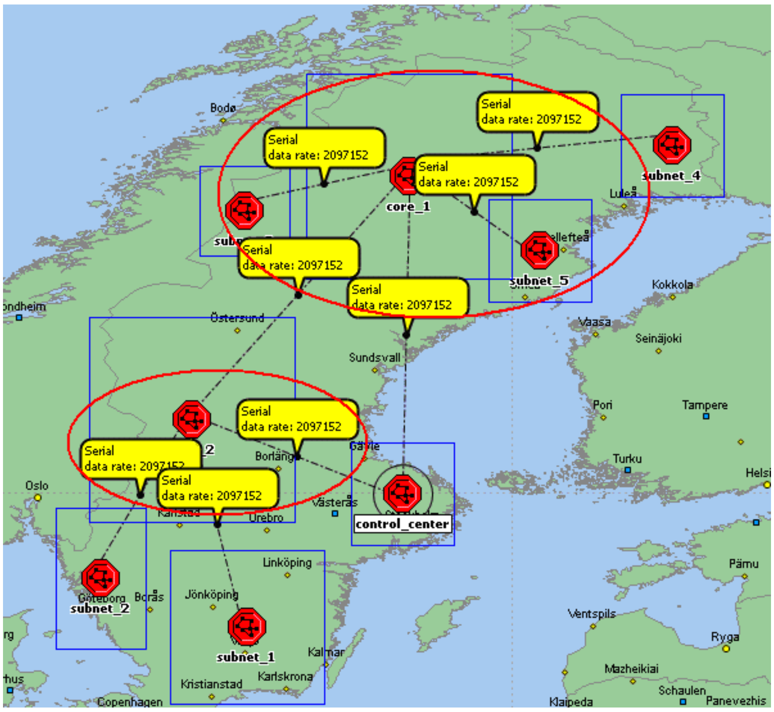


Figure 20: Shared network link capacity

For the communication protocol configuration of the shared model, TCP/IP was used. The TCP/IP detailed configuration was beyond the focus of this thesis, so the default configuration was left. The adoption of TCP/IP was to detect if the flow of data through TCP layers would affect the ETE delay.

Once the PMU packet is created, it will be transferred according to the TCP/IP protocol, as shown in the node model in Figure 21. The blue line shows the path of the created packets which are created in the application module and transferred from ip_tx_0_0.

For routing protocol, the OSPF was used in the shared model.

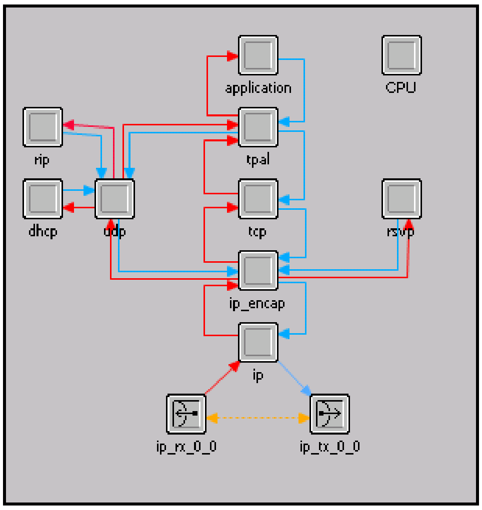


Figure 21: PMU node model

The transfer rate of the PMUs was 30 packets/second. In the application definition, the transfer rate, the destination address and the packet size (assumed to be 76 bytes in this thesis) were configured. Each packet was encapsulated in a TCP packet. If the packet size of the PMU exceeded the size of the data field of a TCP packet, the PMU data would be divided into two or multiple TCP packets. Figure 22 shows the data rates of the packets leaving the TCP module node in PMU_1. The same rate was used for the ten PMUs.

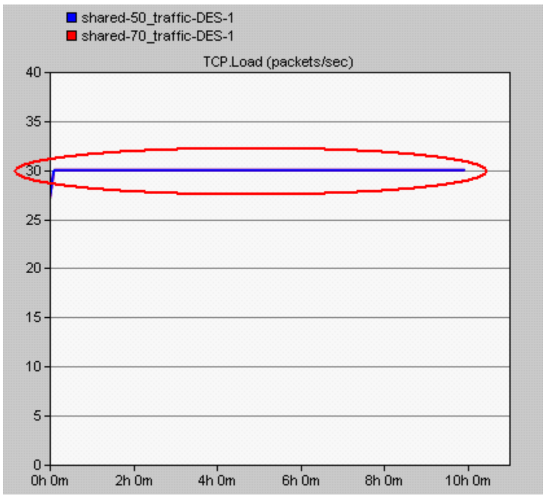


Figure 22 PMU_1 traffic loaded from TCP layer

Arriving at the IP module node, the number of packets was increased to 34 packets/second as shown in Figure 23. This increase in the number of packets was because of the fragmentation in the IP layer. An IP packet data field size was not enough to encapsulate a TCP packet, so the IP fragmented the 30 TCP packets into 34 IP packets.

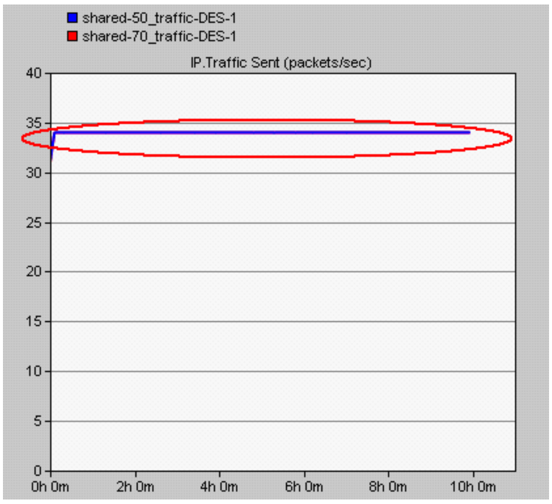
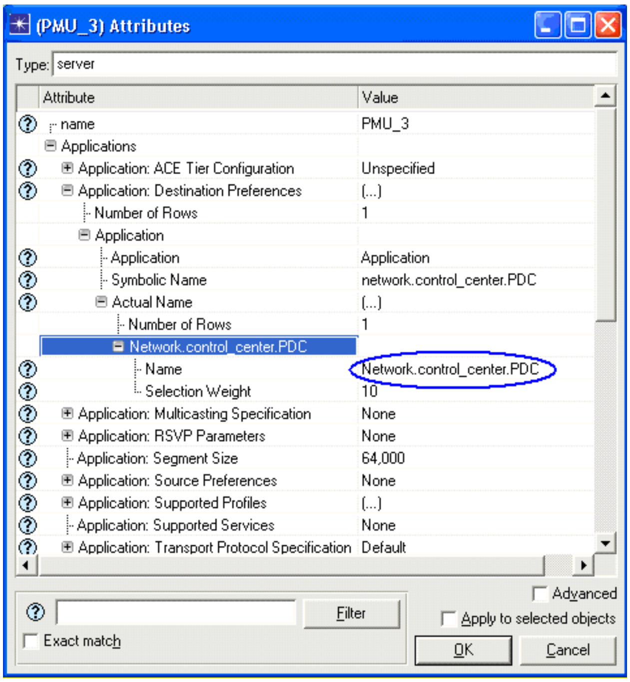


Figure 23 PMU_1 traffic sent from the IP layer

The destination address of all PMUs was the PDC. The PDC was located in the control center subnet. The destination address was configured within the PMU attributes as shown in Figure 24. The symbolic name shown in the figure can be exchanged by the PDC IP address.


(PMU_3) Attributes

Type: server

Attribute	Value
name	PMU_3
Applications	
Application: ACE Tier Configuration	Unspecified
Application: Destination Preferences	(...)
Number of Rows	1
Application	
Application	Application
Symbolic Name	network.control_center.PDC
Actual Name	(...)
Number of Rows	1
Network.control_center.PDC	
Name	Network.control_center.PDC
Selection Weight	10
Application: Multicasting Specification	None
Application: RSVP Parameters	None
Application: Segment Size	64,000
Application: Source Preferences	None
Application: Supported Profiles	(...)
Application: Supported Services	None
Application: Transport Protocol Specification	Default

Figure 24: Configuring the destination address of the transferred data

The PDC had the same configuration as the PMUs, but in the PDC the transfer packet size was ten times larger than the PMU. The destination address of data transferred from PDC was the WAMC located in control center subnet.

Three control commands were configured in the application called “profile control” used by the WAMC component. The WAMC communication protocol was similar to the PMU and PDC. It received packets from the PDC; and in turn, sends a defined packet rate to different applications. In a real network, the WAMC is supposed to send commands to the substations whenever there is a disturbance in the electric system.

The WAMC was configured to send 10 packets at three different times, each time to a different PMU. The first 10 packets were sent to substation switch 3, the second 10 to substation switch 6 and the third 10 to substation switch 8. The implementation of the commands was done to be able to measure the time taken for the data to reach a substation to deliver a command. The control command packet size was 10 bytes.

Switches and routers in the shared model were kept with default configurations. The dynamic routing tables were used for the routers.

4.4 Dedicated model implementations

Two scenarios were implemented for the dedicated model. The first scenario was carried out by setting the transmission capacity of the communication link implemented in the network to a multiple of 64Kb channels; while in the second scenario the communication link was the multiple of 128Kb channels. The two scenarios were implemented in order to compare the ETE delay with different transmission capacities and to observe the link utilizations. No background traffic was introduced in the dedicated model for both scenarios.

The implementation in OPNET was done as follows: a dedicated channel was assigned between each PMU and PDC. The dedicated channels were implemented in the core network level. On substation level where the 100BaseT was used, the PMUs had for both models (dedicated and shared) a personal link connecting them to the substation routers. Comparing the dedicated model with the shared model, it could be seen that the 2Mb link capacity between the substation router and the control center router in the shared model was exchanged to a multiple of 64Kb or 128Kb in the dedicated model.

Figure 25 shows the link capacity between the subnets and the core subnets of the dedicated model, for a channel capacity equaling to 64Kb. The data rate shown in Figure 25 is in bytes, but throughout the explanations it is referred to as Kilobytes for simplification. The differences in link capacities explain how many PMUs data were passing through the communication link. The link capacity between subnet_5 and core_1 was equal to 64Kb, which mean that only one PMU data was passing through this link. While for the link capacity between core_1 and the control center, it was equal to 192Kb, which mean that three PMUs data were passing through the link. The link capacity between core_2 and the control center was equal to 384Kb, which mean six PMUs data were passing through the link.

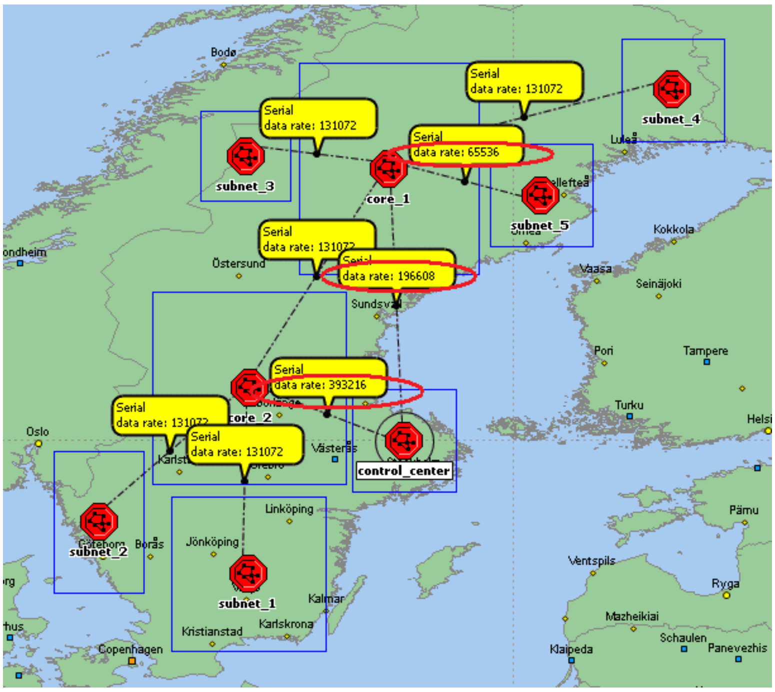


Figure 25: Link capacities of the dedicated model 64Kb scenario

Here is a general description of the dedicated model: when two or more PMUs data meet at a specific path, the transmission capacity of the link in that path would be the multiple of the number of PMUs, until the data arrived at the PDC in one path with capacity equaling to 10*(64Kb or 128Kb). The 10 represented the number of implemented PMUs.

The routing protocol used in the dedicated model was OSPF routing. The stack used in the dedicated network implementation was EPA which was mostly used in industrial networks [39].

The implementation of the PMU transfer rate and packet size was done in the traffic generator node model. Once a packet left the traffic generator, it went to the IP encapsulation module where it would be encapsulated in an IP packet and sent out to the network. The blue arrows in Figure 26 shows the passage that the data follow when they are transferred from the PMUs.

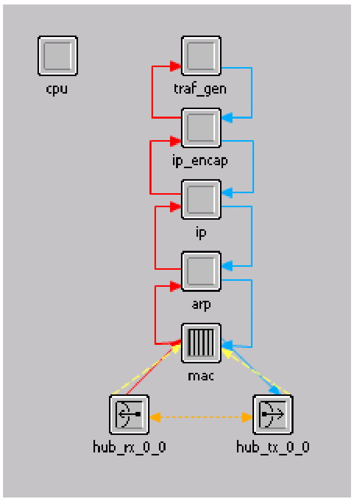


Figure 26: PMU node model

The packet size was set to 76 bytes in order to represent a C37.118 [21] packet containing the measurements of 10 phasors. The transfer rate was 30 samples/second, as this rate was considered enough for most of the already developed applications, which has been mentioned in section 2.3.

Since the size of the PMU packet was less than the maximum size of the data field of the IP packet, the number of packets leaving the IP layer was 30 packets/second, as shown in Figure 27

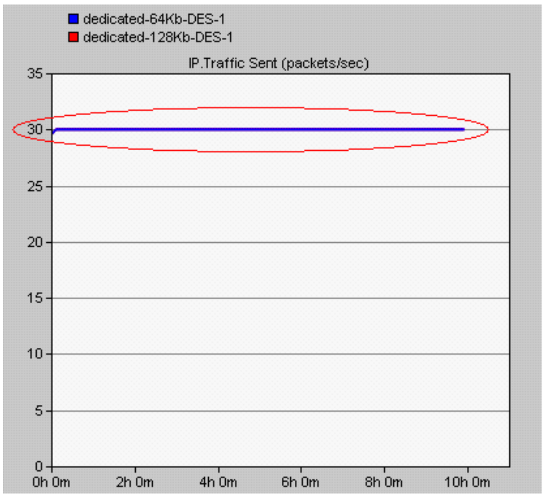


Figure 27 traffic sent from PMU_1 IP layer

The PDC and the WAMC nodes were implemented the same way as a PMU in the dedicated model. PDC received the data from the PMUs, and then transferred them towards the WAMC. The PDC transfer rate was 30 packets/second.

Figure 28 shows the link capacity between regional router 6 and the control center router. The data rate showed in the figure is in bytes, representing 10*128 Kb. In this path, all the links channels gather towards the PDC.

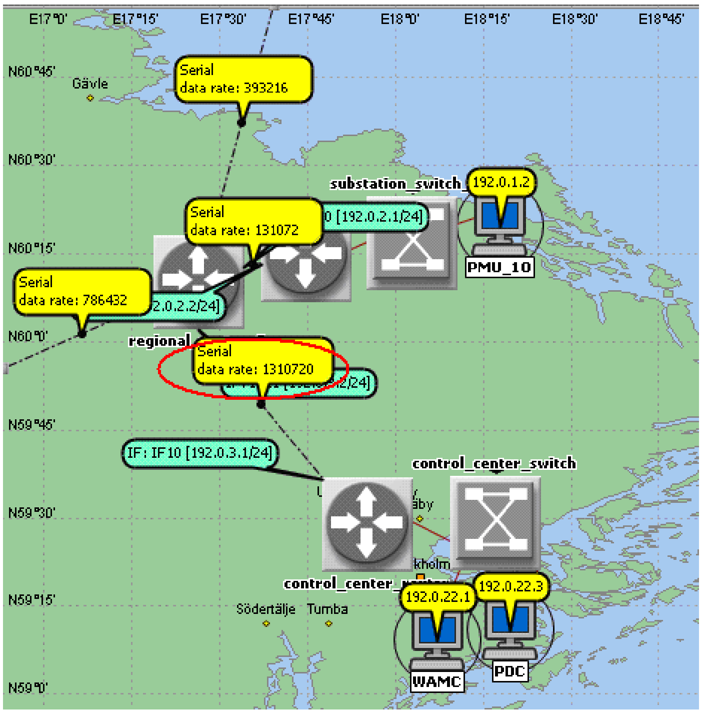


Figure 28 control center subnet configuration in the 128Kb scenarios

The role of the WAMC in the dedicated model was similar to its role in the shared model. Three control commands, each composed of 10 packets, were sent to three PMUs at three different times. The configuration of the WAMC packet size and sample rate was done in the process model of the traffic generator. While the passage that the data should follow towards the substations switch was defined in the static routing tables of each router, the commands were sent to substation switch 3, substation switch 6 and substation switch 8 in the dedicated model.

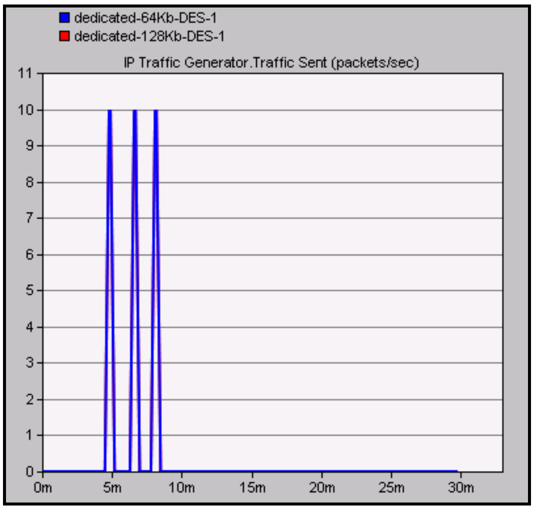


Figure 29 control commands sent from WAMC toward substations switch

Figure 29 shows the three control commands sent from the WAMC. The first command is sent towards substation switch 3, the second towards substation switch 6 and the third towards substation switch 8. Each control command was composed of 10 packets. Figure 30 shows the control command received by substation switch 6.

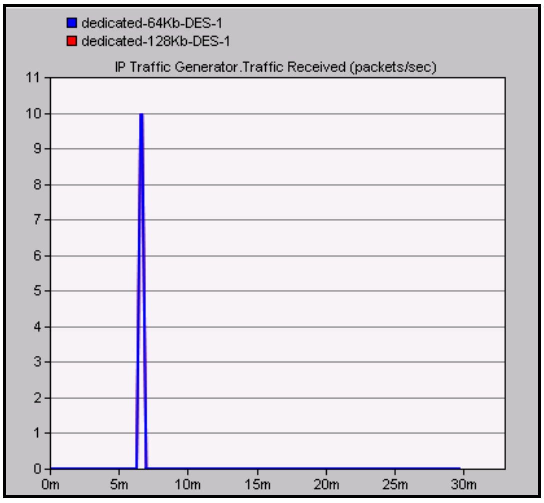


Figure 30 Control command received by substation switch 6

Default configuration was kept for switches in the dedicated model, while the routing tables in the routers were configured manually, which is known as static routing. Static routing was used in order to control the data flow from the PMUs toward the PDC. When the data flow was known, it became capable to increment the link capacity when more than one PMU data meets on the same path.

5. Simulation results

A summary of the main points of the models implementation and configuration have been presented in the implementation chapter. In this chapter the results of the simulations for the shared and dedicated models are presented and discussed. The collected results were ETE delays, link throughput and utilization. The simulations were compiled for ten hours' duration.

5.1 End to End delays

The ETE delay represents the time (in seconds) taken for a packet to reach its destination. In other words, it is the difference between the time a packet arrives at its destination and the time when the packet is created. The statistics were collected separately for each source and destination pair. Each simulated scenario had fourteen ETE delays. Among them, ten were captured from the links from PMUs to PDC; one was captured from the link from PDC to WAMC; and three were captured from the control commands.

5.1.1. End to End delays from PMUs to PDC in shared model

The shared model ETE delay results were collected from two scenario simulations. In the first scenario, 50% background traffic was introduced in the path from PMU to PDC; and in the second scenario, the background traffic was increased to 70%. The path from PDC to PMU had 20% background traffic for both simulations. During the simulations, all PMUs were generating constant traffic. In addition, constant background traffic was added to the network, so that differences between the delays could be related to the distances between PMUs and PDC. Here the usage of constant background traffic was a way to observe the effects of distances in causing delays. In a real network, PMUs generate constant traffic in all cases, but the background traffic may vary.

Table 1: ETE delays from PMUs to PDC in the shared model

ETE delays from PMUs to PDC (sec)	50% Background traffic	70% Background traffic
PMU_1	0.016	0.028
PMU_2	0.016	0.028
PMU_3	0.012	0.021
PMU_4	0.012	0.021
PMU_5	0.019	0.033
PMU_6	0.019	0.033
PMU_7	0.018	0.031
PMU_8	0.017	0.029
PMU_9	0.013	0.023
PMU_10	0.005	0.011

Table 1 shows the ETE delays collected from the PMUs to PDC links for the 50% and 70% scenarios. The most important measurement from the ETE delay measurements between PMUs to PDC was the highest delay measurement in each scenario. It was important because of the PDC aggregation of data, as mentioned in section 2.2.4. In the 50% scenario, the highest delay was identified in PMU_5 and PMU_6 with ETE delays equaling to 19ms; and in the 70% scenario, the highest delay was identified also in PMU_5 and PMU_6, but with ETE delays equaling to 33ms.

5.1.2. End to End delays from PMUs to PDC in dedicated model

The dedicated model ETE delay results were collected from two scenarios simulations. In the first scenario, 64Kb channel capacity was established between each PMU to PDC path; and in the second scenario, the channel capacity was 128Kb.

Ten PMUs were generating the same packet rate and size for the 64Kb and 128KB scenarios. Table 2 shows the collected ETE delays from PMUs to PDC in the 64Kb and 128Kb scenarios. The differences between ETE delays in the same scenario were related to geographical distances between PMUs and PDC. Whereas when comparing the ETE delays collected in the 64Kb and the 128 Kb scenarios, the delays were reduced by half. In other words, when the channel capacity was doubled, the ETE delay was reduced by half.

Table 2: ETE delays from PMUs to PDC in the dedicated model

ETE delays from PMUs to PDC (Sec)	Channel capacity 64Kb	Channel capacity 128Kb
PMU_1	0.041	0.021
PMU_2	0.045	0.024
PMU_3	0.037	0.020
PMU_4	0.031	0.016
PMU_5	0.065	0.035
PMU_6	0.072	0.039
PMU_7	0.042	0.022
PMU_8	0.046	0.025
PMU_9	0.039	0.020
PMU_10	0.015	0.008

In both scenarios, the highest delay, which was also the most important one, was identified between PMU_6 and PDC. The highest delay represented the PDC's waiting time until the ten PMUs transferred packets reached PDC. The PDC method of working was explained in section 2.2.4. In the first scenario, the highest delay is equal to 72ms; and in the second scenario, the highest delay is equal to 39ms.

5.1.3. End to End delays from PDC to WAMC for dedicated and shared models

The purpose of presenting the PDC to WAMC link was to observe the impact of throughput capacity on the result of delays. Since the PDC to WAMC link was implemented with the same communication media and distance for the dedicated and shared models, the only difference between the two models was that for the shared model, the transfer of PMUs data was through TCP/IP; while for the dedicated model, the transfer of PMUs data was according to EPA. The ETE delay in this path was affected neither by the background traffic added in the shared model, nor by the dedicated channel capacities used in the dedicated model.

Table 3: ETE delay from PDC to WAMC for the shared model

ETE delays from PDC to WAMC (sec)	50% Background traffic	70% Background traffic
WAMC	0.00056	0.00056

Table 3 shows the ETE delay from PDC to WAMC for the shared model simulations. The ETE delay was equal for the 50% and 70% scenarios, which can be explained by the absence of background traffic on this link. PDC and WAMC were located in the control center subnet and were connected to the same LAN. The limit of the background traffic was the control center switch, because after the switch each data leave for its destination. The ETE is equal to 0.56ms as it is shown in Figure 31. The link capacity was 100baseT, and it only contained PDC data going towards WAMC at a rate of 30 samples/sec.

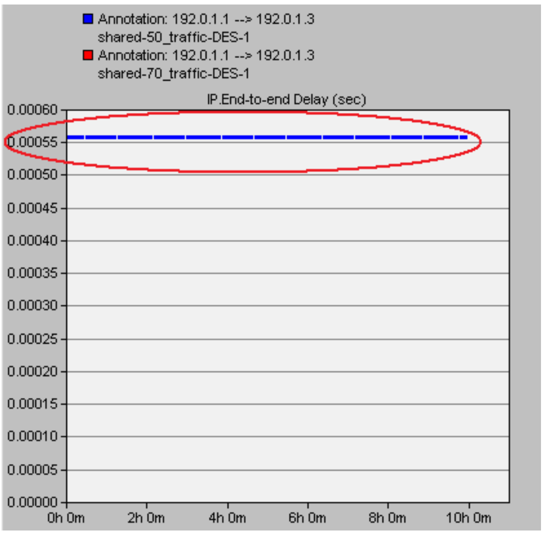


Figure 31: ETE delay from PDC to WAMC for the shared model in the 50% and 70% scenarios.

Table 4 shows the ETE delays from PDC to WAMC for the dedicated model simulations. The ETE delays for the 64Kb and the 128Kb scenarios are equal to 54ms. Once again, the reason behind this equality was because the PDC and WAMC shared the same LAN in the control center subnet. The LAN capacity was 100baseT, and was not affected by the dedicated channels which were used to connect substations routers to control center router.

Table 4: ETE delay from PDC to WAMC for the dedicated model

ETE delays from PDC to WAMC (Sec)	Channel capacity 64Kb	Channel capacity 128Kb
WAMC	0.00054	0.00054

In the dedicated and shared models, the same communication media and geographical locations were used for the PDC to WAMC link. The difference between the dedicated and shared models delays was related to the stack used in each model. The stack in the shared model used more time to transfer and receive data between different components than the stack used in the dedicated model did.

5.1.4. End to End delays from WAMC to substation switch 3, substation switch 6 and substation switch 8

The control commands of the ETE delays for the dedicated and shared models are presented in this section. Three substations switches (substation switch 3, substation switch 6 and substation switch 8) were configured to receive commands from the WAMC. The control commands were composed of ten packets each and were sent from the WAMC at three different times during the simulations.

In shared model

For the simulations of the 50% and 70% scenarios, 20% background traffic was introduced in the direction from the control center to the substations. The background traffic was introduced in the 2Mb link, and in the 100bateT link located between the substations routers and switches.

Table 5 shows the ETE delays of the control commands for the 50% and 70% scenarios, the collected data was shown in one row, because the configurations and results were the same in the two scenarios. The ETE delay of WAMC to substation switch 3 is equal to 7.1ms, to substation switch 6 is equal to 10.7ms and to substation switch 8 is equal to 9.3ms.

Table 5: ETE delays of the control commands for the 50% and 70% scenarios

ETE delay (sec)	substation switch 3	substation switch 6	substation switch 8
WAMC 50% & 70%	0.0071	0.0107	0.0093

Transferring the same amount of data through the same communication links, together with introducing same constant background traffic, could relate the differences between the delays to the geographical distances between the WAMC and the substation switches.

In dedicated model

For the simulations of 64Kb and 128Kb scenarios, the path from WAMC to substation switches was using the opposite side of the links connecting the PMUs to the PDC. The control commands paths were implemented using static routing tables. The communication link used from substation switches to substation routers, and from WAMC to the control center router was 100BaseT for both scenarios.

Table 6 shows the ETE delay of the control commands for the 64Kb and 128Kb scenarios. The ETE delay in the 64kb scenario is equal to 42ms for the path from WAMC to substation switch 3, 43ms for the path from WAMC to substation switch 6 and 42ms for the path from WAMC to substation switch 8. Whereas in the 128kb scenario the ETE delay is 21ms for the path from WAMC to substation switch 3, 22ms for the path from WAMC to substation switch 6 and 22ms for the path from WAMC to substation switch 8.

Table 6: ETE delays of the control commands for the 64Kb and 128Kb scenarios

ETE delay (sec)	Substation switch 3	substation switch 6	substation switch 8
64Kb	0.42	0.43	0.42
128Kb	0.21	0.22	0.21

Distances separating the substation switches from WAMC did not affect the ETE delays belonging to the same scenario, because only a small amount of data was transferred through the links. When increasing the channel capacity to 128Kb, the ETE delays were reduced by half compared with the 64Kb scenarios.

5.2 Link throughput and utilization

Throughout the following section the throughput and utilization of the communication links used in the dedicated and shared models are presented. The throughput represented the number of packets which were transmitted or received through a link. The unit used was sample per second. Utilization represented the percentage of consumption of a link. The statistics were collected separately for each scenario. In the figures in this section, the blue line represents the 50% scenario of the shared model, while the red line represents the 70% scenario of the shared model. Whereas for the dedicated model, the blue line represents the 64Kb scenario, and the red line represents the 128Kb scenario. When a result figure shows only a blue line, it means that the two scenarios of a model were equal. Since the ten PMUs were generating the same amount of data, and PMUs configuration and links were the same, it was enough to show the measurement of one path from PMU to PDC for simplicity.

5.2.1. Shared model

The shared model throughput and utilization presented in this section were taken from four locations wherever there was a change in the communication link capacity when changing from 100BaseT to 2Mb, or vice versa. The locations were between substation switch and substation router, substation router and regional router, regional router 6 and control center router and between regional router 6 and substations router. The last location was taken to measure the throughput and utilization of control commands.

The connection between PMU and regional router was composed of two communication links. The First link was 100baseT and it was from PMU to the substation switch and from the substation switch to the substation router. The second link was 2Mb, and it was located between substations router and regional router 6.

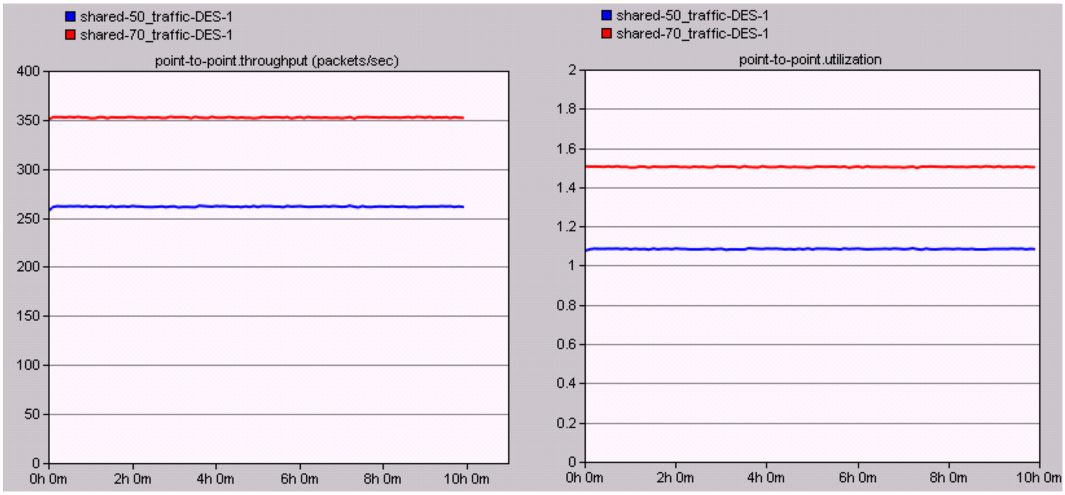


Figure 32: Link throughput and utilization between substation switch to substation router

Figure 32 shows the throughput and utilization between the substation switch and the substation router. The throughput shown on the left hand side of the figure is equal to 265 packet/sec for the 50% scenario, and 355 packets/sec for the 70% scenario. The throughput capacity was the summation of the two traffic sources. The transfer rate of a PMU was equal to 34 packets/sec, as discussed earlier in the implementation chapter section 4.3. The rest of the packets corresponded to the background traffic. The background traffic added to the network represented 50% and 70% of the 2Mb network. The right side of Figure 32 shows the utilzation in a 100BaseT link between the substation switch and the substation router. The utilization is equal to 1.1% in the 50% scenario, and 1.5% in the 70% scenario.

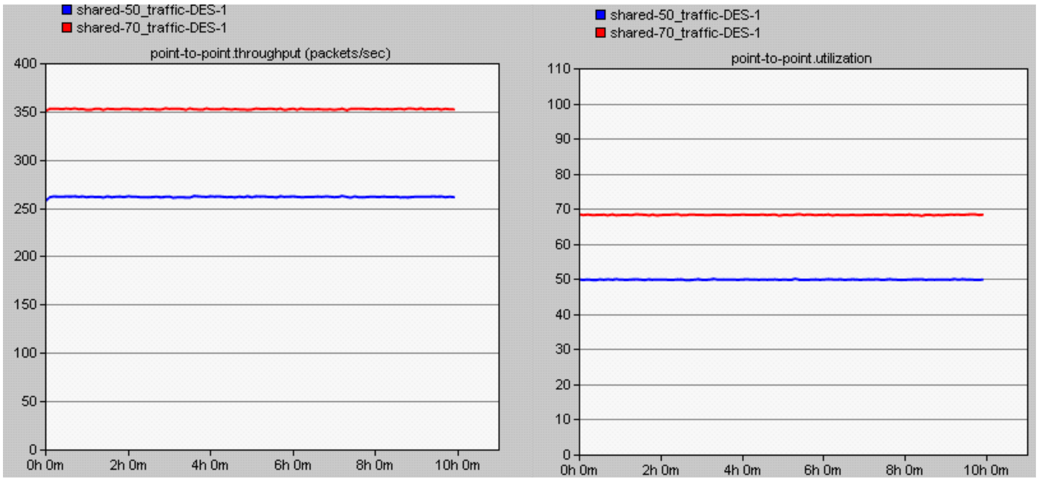


Figure 33: Link throughput and utilization between the substation router and the regional router

Figure 33 shows the throughput and utilization between the substation router and the regional router. The left side of the figure shows the throughput which was equal to the throughput shown in Figure 32. The utilization shown on the right hand side of Figure 33 is equal to 50% in the 50% scenario, and 69% in the 70% scenario. The utilization was measured on the 2Mb link.

The throughput was increased each time an additional PMU data joined the flow of data towards the PDC, which resulted in increasing the utilization of the link. On the 2Mb link between regional router 6 and the control center router, shown on the left hand side of Figure 34, the throughput capacity is 571 packets/sec for the 50% scenario and 661 packets/sec for the 70% scenario. These numbers symbolized the introduced background traffic and 10 PMUs data. The utilization between regional router 6 and the control center router is shown on the right hand side of Figure 34 is equal to 64% in the 50% scenario, and 84% in the 70% scenario.

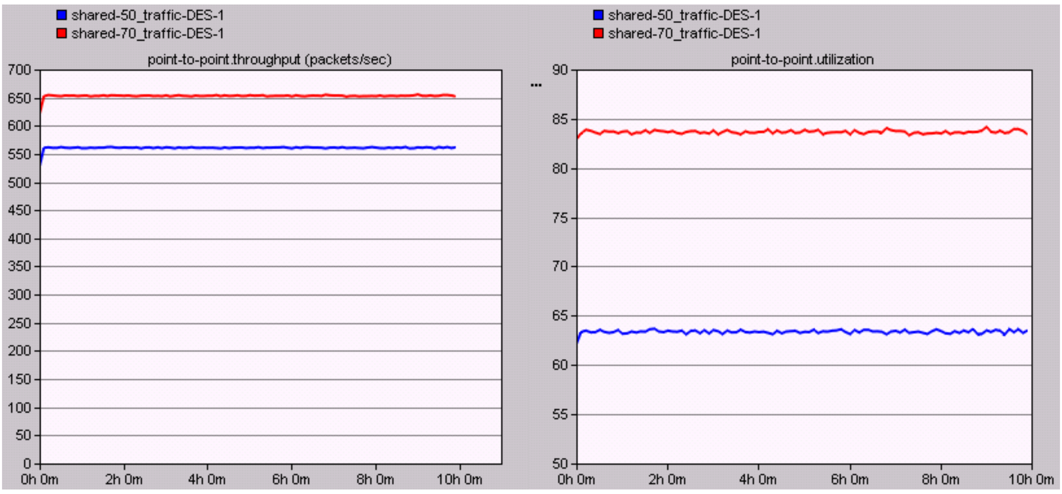


Figure 34: Link throughput and utilization between regional router 6 and the control center router

340 packets/sec was the traffic added by 10 PMUs to the network. This addition was equal to 14% of a 2Mb Link. PMUs can share up to 86% of the background traffic in a 2Mb link, but sharing a high percentage of background traffic would result in increasing the ETE delay, as shown in Table 1 (the ETE delay increased when the background traffic was increased from 50% to 70%). An increase in the ETE delay would lead to an increase in the processing time of the PDC. Increasing the processing time would result in increasing the response time of the control commands, which was something not esteemed, because it would be too late for applications to act in urgent situations.

For the throughput and utilization for the path between WAMC and the substation switches, 20% background traffic of a 2Mb was presented during the whole simulation time, while 10 packets representing control commands were sent in three different times. The importance of this path was that the data sent on this path was critical and had to arrive within minimum time to take action in an emergency. In real networks, control commands data were not encouraged to share network traffic because of its high sensitivity and security requirements.

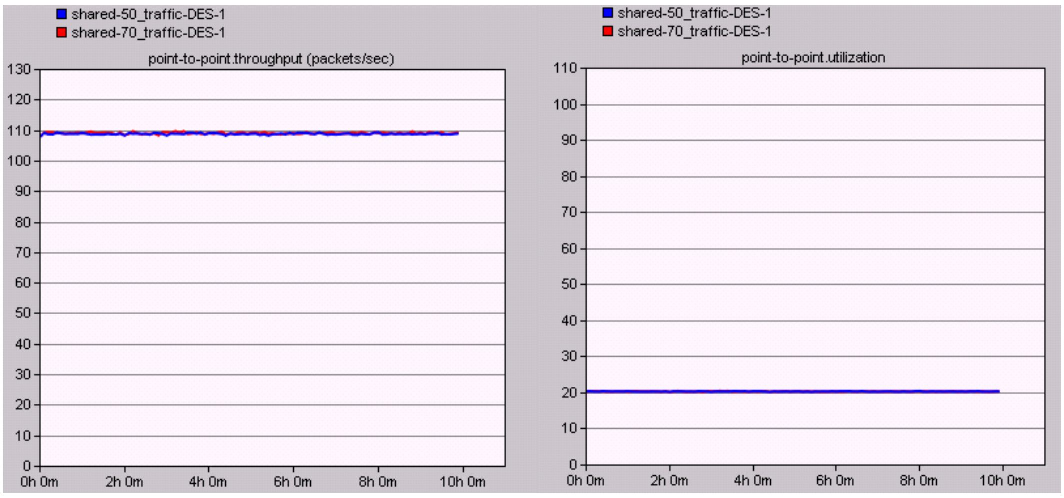


Figure 35: Link throughput and utilization between regional router and substation router 3

Figure 35 shows the throughput and utilization between the regional router and substation router 3. The throughput is shown on the left hand side of Figure 35, and represented 20% background traffic. In addition to the 10 packets/sec of a control command, this resulted in a total of 110 packets/sec for the 50% and 70% scenarios. The utilization shown on the right hand side of Figure 35 is 20% of 2Mb link.

5.2.2. Dedicated model

The dedicated model throughput and utilization presented in this section were taken from six locations wherever there was a change in the communication link capacity when changing from 100BaseT to 2Mb link, or vice versa. The locations were between the substation switch and the substation router, the substation router and the regional router, the regional router and the core subnet, the regional router 6 and the control center router, and between the control center router and the control center switch.

The connection from PMU to the regional router was composed of two communication links. The First link was 100baseT, and it was from PMU to the substation switch and from the substation switch to the substation router. The second link was 64kb in the first scenario and 128 Kb in the second scenario.

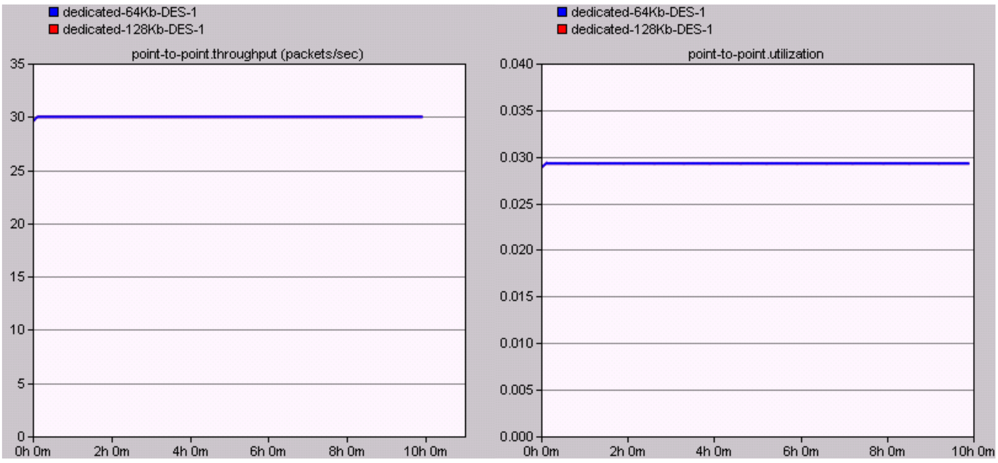


Figure 36: Link throughput and utilization between the substation switch and the substation router

Figure 36 shows the throughput and utilization between the substation switch and the substation router. The throughput capacity shown on the left hand side of Figure 36 is equal to 30 packets/sec for the 64Kb and 128Kb scenarios. The transfer rate of PMU was equal to 30 packets/sec as discussed earlier in the implementation chapter section 4.4. The utilization shown on the right hand side of Figure 36 shows the utilization of one PMU data in the 64Kb and the 128Kb scenarios, and the utilization is equal to 0.029% in 100BaseT link.

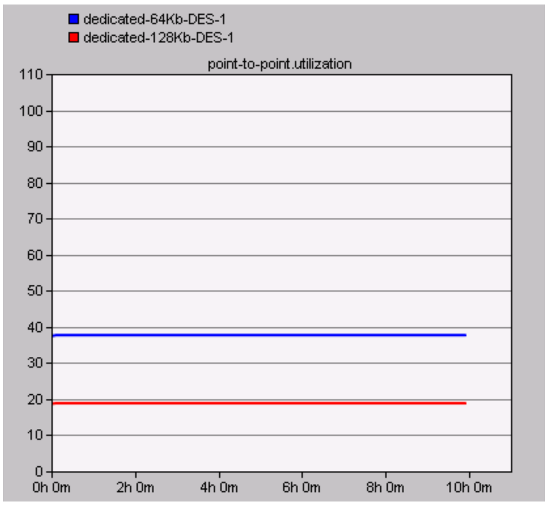


Figure 37: Link utilization between the substation router and the regional router

Figure 37 shows the utilization between the substation router and the regional router. The throughput between them was equal to 30 packets/sec. The utilization shown in Figure 37 is equal to 38% for the 64Kb scenario, and 19% for the 128Kb scenario.

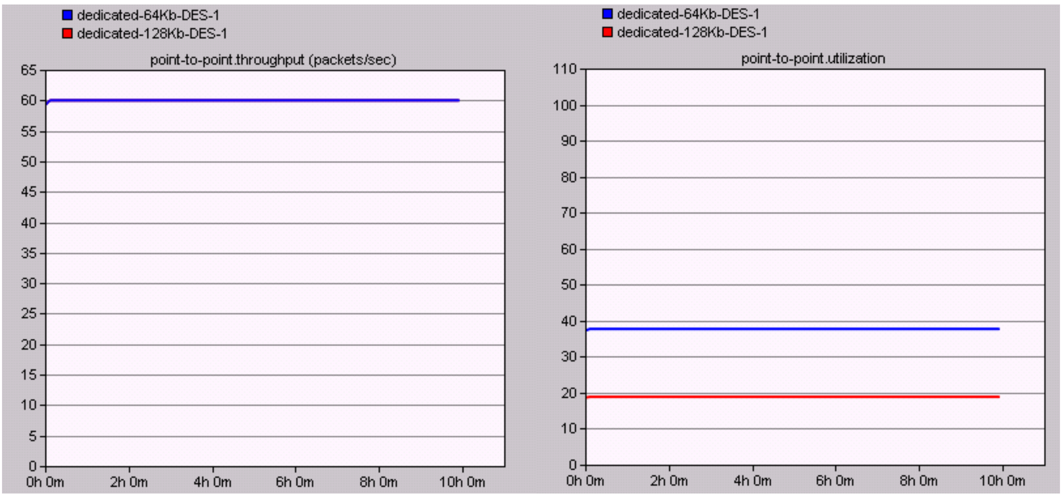


Figure 38: Link throughput and utilization between the regional router and the core subnet

Figure 38 shows the throughput and utilization between the regional router and the core subnet. On the left hand side of Figure 38, the throughput is 60 packets/sec, because two PMUs data were passing through this link. On the right hand side of Figure 38, the utilization is 38% for the 64Kb scenarios, and 19% for the 128Kb scenario. The throughput of the links was increased each time an additional PMU data joined the flow toward the PDC. While the utilization of the links was kept the same, because the link capacity was increased each time a PMU data was added, as explained in the implementation chapter section 4.4.

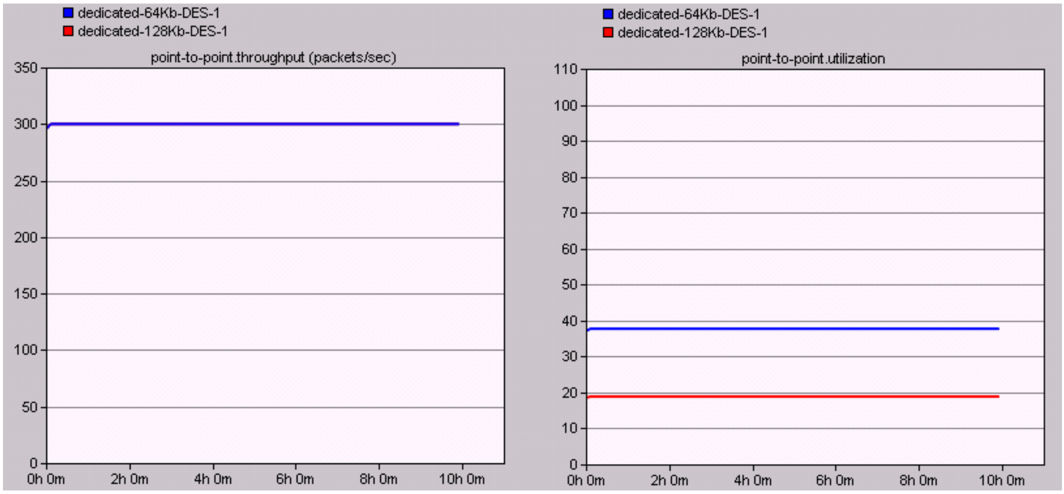


Figure 39: Link throughput and utilization between regional_router_6 and the control center router

Figure 39 shows the throughput and utilization between regional router 6 and the control center router. The throughput capacity was shown on the left hand side of Figure 39. It is equal to 300 packets/sec which represented the traffic of 10 PMUs. The utilization was shown on the right hand side of Figure 39, the utilization is equal to 38% for the 64Kb scenario, and 19% for the 128Kb scenario. The link capacity between regional router 6 and the control center router was equal to 640Kb for the 64Kb scenario, and 1280Kb for the 128Kb scenarios.

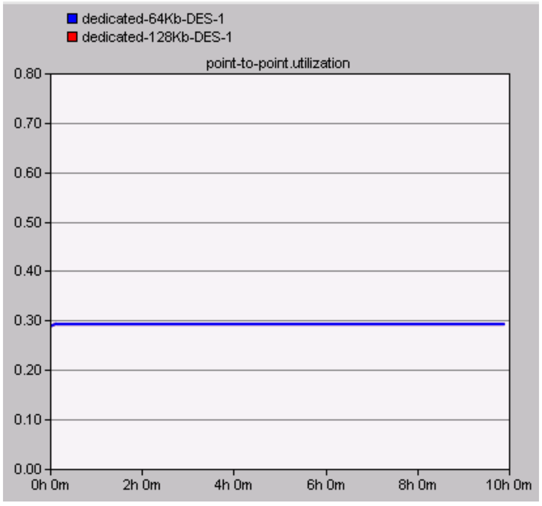


Figure 40: Link utilization between the control center router and the control center switch

Figure 40 shows the utilization between the control center router and the control center switch. The utilization is equal to 0.29% of a 100BaseT. The throughput between control center router to control center switch is equal to the throughput shown on the left hand side of Figure 39.

5.3 Response time of the designed models

Communication infrastructures and delays presented by different hardware/software platforms play a crucial role in the whole response time of a network, because a significant protection depends on the speed at which the control center could identify and analyse an emergency. As mentioned in section 2.9 the total process of making a consistent system involves six activities. Through the ETE delays captured in our simulations, we were able to collect results related to two of those activities. The first activity was transmission time of information and the second activity was transmission of control signal. For the transmission time of information activity, the largest ETE delay found from PMUs to PDC was used. For the transmission of control signal, the ETE delay collected from WAMC toward substation switch 3, substation switch 6 and substation switch 8 was used. For the other activities the times estimates stated in section 2.9.1 were used, because these activities were machine and middleware related.

5.3.1. In shared environment

This section lists the response time of a phasor network implemented in a shared environment. Table 7 shows the response time of the network in 50% background traffic scenario, and Table 8 shows the response time of the network in 70% background traffic scenario. Since the control commands ETE delays were the same for the 50% and 70% scenarios, as was shown in section 5.1.4, the transmission of control signal activity had the same values in Table 7 and Table 8, with the transmission of control signals toward substation switch 3 equaling to 7.1ms, towards substation switch 6 being 10.7ms and towards substation switch 8 being 9.3ms.

The transmission time of information activity shown in Table 7 was the time of the largest ETE delay found between PMUs to PDC in the 50% scenario. This delay was equal to 19ms.

Table 7: Response time of the shared model in 50% scenario

For 50% background traffic (ms)	Substation_3	Substation_6	Substation_8
Sensor processing time	5	5	5
Transmission time of information	19	19	19
Processing incoming message queue	10	10	10
Computing time for decision	100	100	100
Transmission of control signal	7.1	10.7	9.3
Operating time of local device	50	50	50
Total	191.1	194.7	193.3

The response time for a phasor network composed of ten PMUs with a transfer rate of 30 packets/sec and in the presence of 50% background traffic is equal to 191.1ms for substation 3, 194.7ms for substation 6 and 193.3ms for substation 8.

For the 70% background traffic scenario, the largest ETE delay found from PMUs to PDC was equal to 33ms, this delay was used in the transmission time of information activity shown in Table 8.

Table 8: Response time of the shared model in 70% scenario

For 70% background traffic (ms)	Substation_3	Substation_6	Substation_8
Sensor processing time	5	5	5
Transmission time of information	33	33	33
Processing incoming message queue	10	10	10
Computing time for decision	100	100	100
Transmission of control signal	7.1	10.7	9.3
Operating time of local device	50	50	50
Total	205.1	208.7	207.3

The response time for a phasor network composed of ten PMUs and sharing 70% background traffic is equal to 205.1ms for substation 3, 208.7ms for substation 6 and 207.3ms for substation 8.

5.3.2. In dedicated environment

This section lists the response time of a phasor network implemented in a dedicated environment. Table 9 shows the response time of the network with 64Kb dedicated channels, and Table 10 shows the response time of the network with 128Kb dedicated channels.

The transmission time of information activity shown in Table 9 was equal to the largest ETE delay (72ms) found from PMUs to PDC in the 64Kb scenario. For the transmission of control signal activity shown in Table 9, the ETE delays from WAMC to substation switches found in the 64Kb scenario were used. These ETE delays were equal to 42ms towards substation switch 3, 43ms towards substation switch 6 and 42ms towards substation switch 8.

Table 9: Response time of the dedicated model in 64Kb scenario

For 64Kb channel (ms)	Substation_3	Substation_6	Substation_8
Sensor processing time	5	5	5
Transmission time of information	72	72	72
Processing incoming message queue	10	10	10
Computing time for decision	100	100	100
Transmission of control signal	42	43	42
Operating time of local device	50	50	50
Total	279	280	279

The response time for a phasor network composed of 10 PMUs with a transfer rate of 30 packets/sec and using 64Kb dedicated channels is equal to 279ms for substation 3, 280ms for substation 6, and 279ms for substation 8.

For the transmission time of information and transmission of control signal shown in Table 10. The transmission time of information activity was equal to 39ms which represents the largest ETE delay found from PMUs to PDC in the 128Kb scenario. The transmission of control signal activity was equal to the ETE delays from WAMC to substation switches in the 128Kb scenario. These ETE delays were equal to 21ms towards substation switch 3, 22ms towards substation switch 6 and 21ms towards substation switch 8.

Table 10: Response time of the dedicated model in 128Kb scenario

For 128Kb channel (ms)	Substation_3	Substation_6	Substation_8
Sensor processing time	5	5	5
Transmission time of information	39	39	39
Processing incoming message queue	10	10	10
Computing time for decision	100	100	100
Transmission of control signal	21	22	21
Operating time of local device	50	50	50
Total	225	226	225

The total response time for a phasor network composed of 10 PMUs with a transfer rate of 30 packets/sec and using 128Kb dedicated channel is equal to 225ms for substation 3, 226ms for substation 6 and 225ms for substation 8.

6. Conclusion and future work

This work is a contribution to the ongoing project of installing PMUs in the electric power system industry for wide area monitoring and control purpose. The results obtained from the simulations have contributed to a preliminary understanding of the performance and requirements of the PMU in a shared and dedicated environment.

A large fraction of the project was dedicated to the studies of PMUs in wide area monitoring and control systems. The relevant factor was the PMU transfer rate that is enough to fulfill the necessities for the majority of the wide area monitoring and control applications. The transfer rate was 30 packets/sec.

The results shown in chapter 5 showed the performance of PMUs data in shared and dedicated network environments. In the shared model simulations the effect of the background traffic on the ETE delays was illustrated. While, in the dedicated model simulations the effect of the channel capacity on the ETE delays was illustrated. Whereas for the estimations of the response time of the total process, the designed models simulations showed that an action towards unbalanced system can be initiated in a matter of milliseconds.

As a conclusion, we can affirm that the simulations showed satisfactory results, even though the implementation was faced by some simplified assumptions as mentioned in chapter 4 due to the theoretical composition of the thesis and time limitation. Hence, the author is totally aware of the fact that this is only a one case simulation of a complex reality.

From the hardware aspect, the models were simplified by using already built workstations provided by OPNET, and they were configured according to the need of the models. Concerning the configurations, the models were simplified by using the default configurations of the TCP/IP protocol and the OSPF routing protocol.

The simulation running time was 10 hours. According to the configurations and chosen metrics, no supplementary behaviors can be shown with additional simulation time.

Consequently, further research can be conducted by studying the Quality of Service (QoS) mechanism, which controls the real-time stack processing time.

This thesis work can also be extended through implementations of the TCP/IP and the OSPF protocols with advanced configurations.

Another interesting aspect concerning further research is to re-estimate the response time of the total process, due to the dynamic development process of communication networks for wide area monitoring and control systems.

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Appendix

SvK's Network characteristics

The data listed in this appendix represents a summary of the relevant characteristics of SvK's networks; this data was provided by the IT department in order to implement a realistic network.

- The PMU measurements are expected to be transferred through the following networks: the Ethernet LAN inside the substation, through coaxial cables in the WAN, and throughout optical fiber in the SDH. The longest distance from a PMU to the control center is 1000 Km to 1200 Km.
- The topology used in the WAN and SDH is meshed topology.
- Network protocols for the Ethernet network
    - Transport, internet, network layer: IP , OSPF
    - Data layer: PPP
    - Physical layer: 100BaseT
- Network protocols for Wide Area Network
    - Transport, internet, network layer: IP , OSPF
    - Data layer: PPP
    - Physical layer: Coaxial cable
- Network protocols for SDH
    - STM-1, STM-4
    - Dual node architecture , multiple rings
    - The SDH node is considered as a repeater
- All components in a substation are connected to a switch and then to a router.
- Response time for a control function already deployed in the system is 2 seconds
- Critical traffic in shared network is prioritized through QoS, but the ideal case is to have a dedicated network.