WIDE AREA MONITORING AND CONTROL SYSTEMS - APPLICATION COMMUNICATION REQUIREMENTS AND SIMULATION

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ABSTRACT

Today's electrical transmission & distribution systems, are facing a number of challenges related to changing environmental, technical and business factors. Among these factors are, increased environmental restrictions leading to higher share of production from renewable and uncontrollable sources as well as local environmental concerns regarding construction of new transmission and distribution lines. The re-regulation of the electricity market has created a dynamic environment in which multiple organizations have to coordinate and cooperate in the operation and control of the power system. Finally, the high rate of development within the ICT field is creating many new opportunities for power system operation and control, thanks to introduction of new technologies for measurement, communication and automation.

As a result of these factors, Wide Area Monitoring and Control (WAMC) systems have been proposed. WAMC systems utilize new ICT based technologies to offer more accurate and timely data on the state of the power system. WAMC systems utilize Phasor Measurement Units (PMUs) that have higher data rates and are time synchronised using, GPS satellites. This allows synchronized observation of the dynamics of the power system, making it possible to manage the system at a more efficient and responsive level and apply wide area control and protection schemes. The success WAMC systems, on the other hand, are largely dependent on the performance of the Information and Communication Technology (ICT) infrastructure that would support them.

This thesis investigates the requirements on, and suitability of the ICT systems that support WAMC systems. This was done by identifying WAMC applications and the elicitation of their requirements. Furthermore, a set of simulation projects were carried out to determine the communication system characteristics such as delay and the impact of this delay on the WAMC system.

This thesis has several contributions. First, it provides summary and analysis of WAMC application priorities and requirements in the Nordic region. Secondly it provides simulation based comparison and evaluation of communication paradigms for WAMC systems. The research documented in this thesis addresses these paradigms by providing a comparison and evaluation through simulation. Thirdly, the thesis provides insight to the possible sources of delay in WAMC architecture and the impact of these delays on data quality specifically data incompleteness. This provides insight on what applications are important to practitioners and what is the expected performance of these applications, as seen from the power system control and operation point of view.

Key words: Wide Area Monitoring and Control systems, Phasor Measurements Units, Power System Communication, SCADA systems.

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List of Papers in the Thesis

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Paper B: Chenine, M., Nordström, L., "Modeling and Simulation of Wide Area Monitoring and Control Systems in IP-Based Networks", In Proceedings of IEEE Power Engineering Society General Meeting, Calgary, Canada, July 26-30, 2009.

Paper C: Chenine, M., Nordström, L., "Investigation of Communication Delays and Data Incompleteness in Multi-PMU Wide Area Monitoring and Control Systems", In Proceedings of the conference on Electrical Power and Energy Conversion Systems, Sharjah, U.A.E, November 9-12, 2009.

Paper D: Chenine, M., Nordström, L., "Modeling and Simulation of Wide Area Communication for Centralized PMU-based Applications", Submitted to IEEE Transactions on Power Delivery, September 2009.

LIST OF PAPERS NOT INCLUDED IN THE THESIS

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Publication III: Lagerström, R., Chenine, M., Johnson, P., Franke, U., "Probabilistic Metamodel Merging", *Proceeding of the* 20^{th} *International Conference on Advanced Information Systems Engineering, Montpellier, France, 18-20 June, 2008.*

Publication IV: Närman, P., Schönherr, M., Johnson, P., Ekstedt, M., Chenine, M., "Using Enterprise Architecture Models for System Quality Analysis", *Proceedings of the IEEE Enterprise Distributed Object Computing Conference, Munich, Germany, September 15-19 2008.*

Publication V: Chenine, M., Nordström, L., Johnson, P., "Factors in Assessing Performance of Wide Area Communication Networks for Distributed Control of Power Systems", In Proceedings of IEEE Power Tech 2007, Lausanne , Switzerland, July 1-5, 2007.

Publication VI: Chenine, M., Zhu, K., "PMU-based Applications Requirements: A Survey in the Nordic Region", Technical Report TRITA-EE 2008:064, Royal Institute of Technology, Stockholm Sweden, 2008

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CHAPTER 1

INTRODUCTION

This chapter provides a brief introduction to the research topic and the objectives of the research presented in this thesis. The chapter then provides a summary of the results of the research and states the contribution. Finally the chapter provides an outline of the thesis.

BACKGROUND

The electrical power network is a critical infrastructure in modern society. The dependence and demand on electricity is continuously rising, while at the same time, this rising demand for electricity has been met with strains in terms of production and expansion of transmission capacity. This is, among other factors, due to tighter environmental policies and increasing costs. Furthermore, the re-regulation of the electrical market and the connection of national grids with neighboring nations have resulted in a more complex and dynamic environment, in which multiple organizations coordinate and cooperate in the operation and control of the power system.

Power system operation and control has for decades been performed with systems built in a centralized architecture, with a SCADA and Energy Management System (EMS) located in a control centre. In the control centre, operators have been provided with analogue measurements and digital indications from the power system via the SCADA system. This has allowed them to monitor and control the power system on a near real-time basis [1]. With the advent of new communication and computing technologies, numerous visions for future distributed control systems for power system operation and control have been created [2], [3], [4], [5]. In these future architectures, the functionality needed for control and protection of the power system can be located at any computing platform within a distributed control system. One strong drive towards distribution of functionality comes from the separation of the entities operating the power system caused by the re-regulation of the power industry. Additional drivers, also an effect of the re-regulation, are the need to operate the power system more efficiently and closer to stability margins to support market development and introduction of new energy sources. This in turn requires tighter real-time control of the power system not possible in the traditional hierarchical system architectures. A third, indirect driver, is the appearance of new technologies from other industries that enables the distribution of functionality, and also allows utilization of lower cost de-facto standards.

There is global interest and implementation drive, in both academia and industry, on the prospects of Phasor Measurement Unit (PMU) based monitoring and control technology [6], [7], [8]. These systems promise to offer more accurate and timely data on the state of the power system increasing the possibilities to manage the system at a more efficient and responsive level and apply wide area control and protection schemes. Generally, most of the effort internationally e.g. [7], [8], [9], [10], [11], has been on developing monitoring and assessment applications based on PMU measurements, in addition to platforms that would support these applications, e.g. the Gridstat project [12]. Monitoring and assessment applications are known as Wide Area Monitoring Systems (WAMS), these new application were previously not possible with SCADA measurements due to its generally low data sampling rate quality, and lack of exact time synchronization. There has been generally less work on developing protection systems for PMU based monitoring and assessment application, and even less so for wide area control applications. This second group of systems which not only monitor the power system states are referred to as Wide Area Monitoring and Control Systems (WAMC).

RESEARCH OBJECTIVES

WAMC systems are a promising solution that could facilitate real time operation and control of the power system. This would allow greater utilization of transmission capacity in existing infrastructure and a fast corrective response in abnormal transient situations in the power system. As is stated in [9] the performance of the WAMC systems is largely dependent on the performance of the Information and Communication Technology (ICT) infrastructure that supports these systems. If the ICT infrastructure is unsuitable for the requirements for the applications in WAMC systems, then these systems will not be as useful as intended.

The objectives of this research are:

- Investigate and document the communication requirements that core applications that would be used in WAMC systems have.
- Analyze the fulfillment of these communication requirements in various contemporary Wide Area Network architectures
- Identify the impact of the architecture on data quality specifically, the currency and completeness of the data.

RESEARCH RESULTS

The results of the research documented in thesis fall into three categories, requirements elicitation for WAMC applications as well as prioritization of these applications from a power system control and operation perspective. Secondly, Simulation of network level delays using two network communication paradigms. And finally the simulation of the impact of network levels delays as well as certain characteristics of WAMC systems on the overall application level. The rest of this section provides a summary these results.

In terms of WAMC application requirements, a survey has been conducted among researchers and practitioners in the Nordic region. The survey queried the participants on the current stage of development and implementation of WAMC systems. The survey also collected prioritizations for WAMC applications from the participants. These prioritizations represent the degree of importance the participants attached to the applications, given the characteristics of their respective power systems. For example, the voltage stability application function was the highest priority when the power system had a large number of wind generation units, which could lead for fluctuating voltage stability margins.

The most important outcome of the survey was however a set of ICT requirements for WAMC applications. The requirements deal with aspects of the applications such as the data resolution or network delay tolerable for the measurements form the remote PMUs to reach the control center (specifically to be accessed by the application). An example of the requirements collected is depicted in Figure 1 below. The figure shows the requirements for the oscillation detection application. These requirements represent the opinion of participants that would apply these applications in an industrial setting. The survey and its findings are the topic of Paper A and are also documented in greater detail in [13].

Interviewees	Expected Latency	Expected Resolution	Expected Time Window for Response	Format/ Protocol	Time Delay for Current/Tested Control Schema	Expected Execution Time for Control Schema
TSO 1		10 Hz	Less than 0.3 seconds	IEEE 1344 /updating to C37.118	To be determined	
TSO 2	Less than 2 seconds	10 Hz	Fractions of seconds	C37.118	Not applicable	Fractions of seconds
TSO 3						
TSO 4	0.25-2 or 3 seconds	10/50 Hz for online/offline applications		C37.118	0.25 seconds	0.25 seconds
Research Institute 1	Seconds		Seconds/Minutes for automatic/manual control			Seconds
Research Institute 2	Fractions of seconds	Above 10 Hz	Less than 1/10 of the cycle time of studied oscillation	C37.118		
Research Institute 3	1 second	50 Hz	Less than 0.2/5 seconds for POD/SPS		Less than 1 second	
NASPI	1-5 seconds	10 Hz	Seconds	PDC Stream/ C37.118		

Figure 1: Oscillation Detection Application Function

Using information from the survey as an input, a model of possible communication networks for PMU communication was built. This model is documented in paper B and deals with PMU and WAMC communication networks. The model had two scenarios modeling different PMU communication paradigms. In the first scenario, the PMU and WAMC communication occurs on a "dedicated network", where every single PMU had a dedicated channel to the control centre, this paradigm is advocated by researchers, for example in [14], [15] .This is due to the concern that other data traffic would introduce delays on the measurements. Low measurement delay is a critical feature that is necessary to ensure timely response to fast developing dynamic disturbances in the power system. The second scenario models, PMU and WAMC communication in a "shared communication network". The network in this case would carry other power system instrumentation data from RTUs to the control center or other utility related data such as Voice over IP (VoIP). Furthermore the shared network would employ the standard TCP/IP protocol suite, which is the de facto communication protocol of the internet. The contribution of the paper was two-fold. First, that it would be possible to use the shared communication paradigm if proper precautions were made, specifically adequate bandwidth provisioning and planning in the network. This would result in even lower delays in respect to dedicated networks with fixed bandwidth. Second is that the amount of data generated by the PMUs exceeds the proposed dedicated link capacities of 64 Kbps and 128 Kbps.

Using the delay results from paper B, and abstracting the WAMC system and the communication network, enabled the general specification of delays experienced in WAMC systems. This was done by studying the impact of these delays in the Phasor Data Concentrator (PDC), specifically in terms of the waiting time limits and data loss that may occur if these limits were introduced. The waiting time limits at the PDC determine the maximum delay that can occur on the network and is a direct result of the delay variations in the communication network, between the remote PMUs and the control centre. Paper C discusses these aspects, and simulates various waiting times and associated data loss rates, an example of these results are given in Figure 2. The figure illustrate the delay and data incompleteness of a WAMC system with 8 PMUs for normal or "Base" delay and delays that are above normal level, labeled "Extended" in the figure.

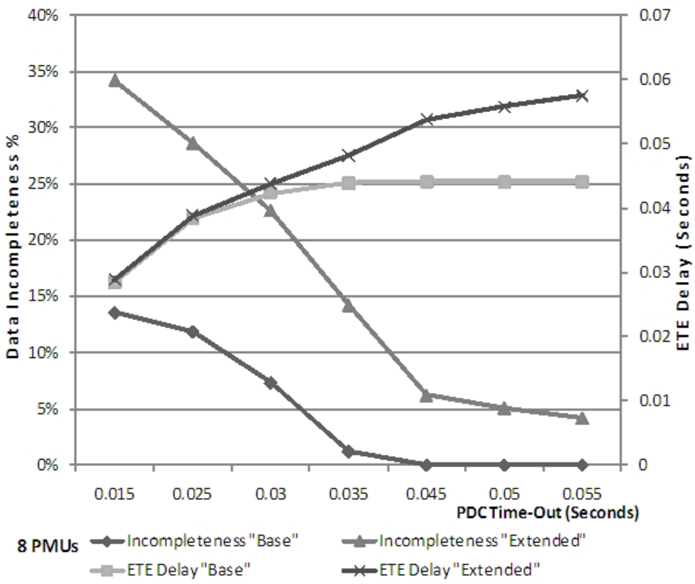

Figure 2: ETE Delay and Data Incompleteness in a WAMC system with 8 PMUs

These results are a step forward at understanding WAMC systems possibilities and limitations. WAMC systems intended for centralized applications such as Situational Awareness require data from several separate locations within the power system. The simulations presented in this paper indicate that the geographic distances, background traffic and architecture of the WAMC system will have an impact on the delay and/or completeness of the PMU data provided to the applications at the central location. Depending on configuration of the Phasor Data Concentrator (PDC) and the characteristics of the network in terms of delay, some central applications may not receive data of a sufficient quality to provide useful support in transient situations.

The results point out that the communication links between the PMU and the PDC is not the only bottleneck in the architecture of these systems, the PDC settings and performance must also be taken into consideration. The actual use of the PDC model in the study is an important distinction from previous works in the field where the PDC was not taken into account or assumed to be an insignificant part.

CONTRIBUTION

The contribution of this thesis work can therefore be summarized in the following points

- A summary and analysis of WAMC application priorities and requirements in the Nordic region. This provides insight on what application are important to practitioners and what is the expected performance of these applications, as seen from the power system control and operation point of view.
- Simulation based comparison and evaluation of communication paradigms for WAMC systems. The research documented in this thesis addresses these paradigms by providing a comparison and evaluation through simulation.
- Impact of the communication delays and components on the overall data quality in WAMC systems. This research provides insight to the possible source of delay in WAMC architecture and the impact of these delays on data quality specifically data currency (end to end delay of the phasor measurements) and data incompleteness i.e. (the percentage of phasor lost in the communication).

THESIS OUTLINE

The rest of this thesis is structured as follows; Chapter 2 gives an overview of the research area in more detail, describing contemporary control system architectures based on SCAD and EMS systems and giving an overview of PMU application and related systems. Chapter 3 is a brief description of the methodology that was used to implement the research described in this thesis. Chapter 3 also describes related simulation work and approaches.

Chapter 4 provides a summary of the papers that make up the thesis. The papers A, B, C and D are included towards the end of the thesis. Finally the appendix at the end of the thesis provides some source code extracts of the simulations conducted in this research.

CHAPTER 2

RESEARCH BACKGROUND

This chapter provides a background to the topic of wide area monitoring and control systems. Specifically, the chapter provides overview of SCADA and EMS functions as well as WAMC systems, their components and application functions.

SCADA SYSTEMS

Power system control has since the early years utilized some sort of automation system in order to monitor and control the power system. The earliest power control systems were based on electromechanical systems that were used for a small number of simple monitoring and control points [2][16]. With the advent of computer systems, it became possible to collect large amounts of measurements and indications and present these at the control center. The collected information would be used by operators to evaluate the state of the power system. it would also be used in applications for further contingency analysis based on the judgments by the operators or results of the by the application, command may be send out to remote actuators to change the state of the process. These control systems are known as Supervisory Control and Data Acquisition (SCADA) Systems [1], [2], [16], [17].

The main functions of a simple SCADA system are:

- Data Acquisition: This functionality deals with collecting data from remote/local devices to a central location, e.g. a central online database [18].
- Monitoring: This function monitors the incoming/stored data and compares them to previously received data or to limits set by the operators. The monitoring function also raises alarms to operators that certain limits have been reached or certain values have changed. For example, a change in the voltage level beyond a pre set threshold would generate an alarm to inform the operator. In some cases the monitoring function may raise an alarm and automatically call on control functions to be executed [18].
- Control: The system also has the functionality to execute control functions. These control function change the state of the process by changing the state of remote devices. Opening or closing breakers or switches is an example of a control function [18].

As SCADA is employed in diverse industrial processes, these systems have specific functionality related to the industry onto which they are applied; in the case of power systems this extra set of functionality is called Energy Management Systems (EMS) [19].

EMS FUNCTIONS

While SCADA system performs the routine collection of data, and sending of control signals, the actual functionality that is used to operate the power system is provided by Energy Management (EMS) systems. These systems, actually suites of applications run on top of the SCADA functionality in order to process and compute relevant information from the data that is collected. This information aids in safe and reliable operation of the power system, as it provides the operator with filtered processed information from the power system. The foundation of the EMS applications is power system state estimation.

In power systems state estimation, the current state of the power system is determined. The state is based on the measurements (e.g. voltage and power flow) and set point (e.g. breaker status) collected by the SCADA system. In some cases, these data may not be available from several parts of the power system or may be distorted or erroneous. The state estimator calculates estimates of all states, normally voltages and phase angles, at all buses using the data provided by for the SCADA system [19]. Building on this power system state information are other EMS applications. An example of such applications is Optimal Power Flow (OPF). In OPF several hypothetical scenarios are calculated by varying the system parameters. This is usually done for particular criteria, for example cost of generation or transmission line losses. This allows the operators to analyze the best scenario that meets the load conditions [20] and at the same time minimize losses.

For a more in depth discussion on SCADA/EMS evolution, architecture and functionality see [1], [2],[17], [18], [19].

PHASOR MEASUREMENT UNITS

Phasor Measurement Units (PMUs) are designed to measure the analog AC waveforms of the positive sequence voltage and current phasors at a very high measurement rates, up to 60 measurements per second. In relation conventional RTU/IED measurements are sampled every 10 -60 seconds depending on system configuration. Accordingly, this advancement makes PMU a suitable tool to capture power system dynamics. Besides the phasors, PMU is also capable to measure the system frequency. The GPS signal is used to provide a time stamp for each measurement using coordinated universal time as the reference. For analogue to digital conversion, discrete Fourier transform is commonly applied to estimate fundamental frequency components of the measured analog signal given samples taken at appropriate intervals [21][22]. Figure 3 illustrates the modules that make up the PMU.

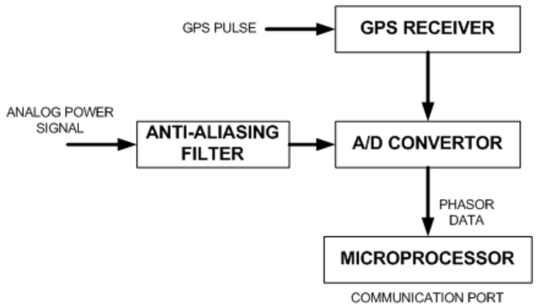

Figure 3: Phasor Measurement Unit block diagram [14]

WIDE AREA MONITORING AND CONTROL SYSTEMS

A complete PMU based monitoring and control system is a system in which PMU measurements are collected from various locations in the electrical grid, the measurements are communicated to a central location where they are used by an assessment or monitoring application that would raise alarms or calculate results. The alarms raised and results calculated by these monitoring systems are in turn used to provide corrective actions or control on the power grid. Such a complete PMU based system is known as a WAMC. Alternative architectures, such as using a few remote PMU signals in a local system for a specific protection application is also possible, but is outside the scope of this study.

WAMC system includes four basic components: A PMU, a PDC, the PMU-based application and finally the communication network [23]. Logically, there are three layers in a WAMC which in essence are very similar to more traditional SCADA systems. Figure 4 illustrates the logical architecture of WAMC systems. Layer 1 where the WAMC system interfaces with the power system on substation busbars and power lines is called the Data Acquisition layer. In this layer the PMUs are located. Layer 2 is known as the Data Management layer and it is where the PMU measurements are collected and sorted into a single time synchronized dataset. Finally Layer 3 is the Application Layer that represents the real time PMU based application functions that process the time synchronized PMU measurements provided by the Layer 2.

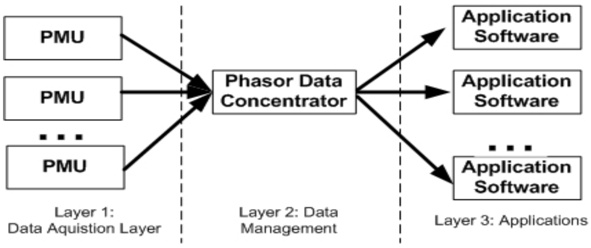

Figure 4: Layers and components of WAMC system

An in depth discussion of various architecture and communication systems for WAMC systems can be found in [12], [14], [15], [23], [24] ,[25], [26].

NORTH AMERICAN SYNCHROPHASOR INITIATIVE

There have been many research and industrial initiatives regarding different aspects of WAMC systems. The North American Synchrophasor Initiative (NASPI) is one such example. NASPI is a consortium of governmental, academic, research and industrial organizations that aim at expediting the deployment of WAMC and PMU based system in North America. NASPI is made up of several task teams that focus of various aspects of developing and deploying PMU measurement technology [27]. Examples of such task teams are the Operations Implementation Task Team (OITT) and the Data and Network Management Task Team (DMTT).

OITT focuses on applications that utilize PMU measurements for real time monitoring and control, this includes deployment and training for these tools as well as development if these tools were none are commercially available. OITT has developed a phasors application taxonomy, in which a set of applications that utilize phasor measurements to improve power system monitoring and operation [28] are identified. The phasors application taxonomy also details requirements for these applications. These requirements address issues such as, phasor data resolution needed, or protocol required [29]. Paper A of this thesis reports on a similar study on requirements for a set of applications in the Nordic region and compares these studies to the findings of NASPI's OITT.

The DMTT is responsible for the specification of hardware and software related to WAMC systems in NASPI. This includes the elicitation of requirements for the PMU communication network (in the USA), the specification of hardware and software requirements that would support the WAMC system [28]. The US Department of Energy has assigned the DMTTT, the responsibility of the specification of NASPInet. NASPInet is based on the Gridstat project [12], and is the main communication infrastructure for sharing PMU measurements between different power system operators and stakeholders. NASPInet is based on a distributed publish-subscribe architecture that includes Quality of Service (QOS) and security mechanism functionality, among others [28].

PMU-BASED APPLICATIONS

The ability to compute synchronized phasors distinguishes the PMUs from the other power system measuring devices. The possibility of direct measurement of the power system states tends to trigger a paradigm shift several monitoring and control applications. For example the conventional state estimation process can be substituted by a state measurement stage acknowledging that power system bus angles can be directly metered by PMUs.

Additionally, the traditional SCADA/EMS systems are based on steady state power flow analysis whose measurement data resolution are in order of seconds, and consequently are insufficient to capture the fast power system dynamics. PMUs can provide time synchronized measurements from dispersed locations in order of sub-second, typically, 20, 50 or 60 samples per second. System wide installed PMU systems are capable to provide a snapshot of the system dynamic, which opens up new promising ways to maintain power system stability in an active manner.

The involvement of phasor measurement from PMUs can benefit many potential applications for power system monitoring and control. In this section six application functions are briefly summarized. The first five application functions described in [9] were used in the survey to collect communication and data requirements. These are Oscillation detection, Voltage stability assessment of transmission corridors, Voltage stability assessment of mesh networks, Frequency instability assessment, and Line temperature monitoring. An additional application that can benefit from phasor measurements is state estimation, in this section a brief overview of hybrid state estimation that uses a combination of SCADA and PMU measurements is discussed.

POWER SYSTEM OSCILLATION DETECTION AND CONTROL

For large interconnected power grids, the increase in grid scale and loadability inevitably pushes the system to operate at its limit. Usually the low frequency oscillation in the range from 0.05 Hz to 2 Hz characterizes the power system stability and decides the power exchange capacities between the regions [8]. Conventionally, the control in power systems is in most cases performed based on local information, which is an approach that is heavily dependent on a mathematical model of the system. The introduction of the PMU system brings in the possibility to use remote information for control and accordingly the dependency of the system model can be significantly reduced [30]. The damping information relating to these modes can be tracked online through the PMU system and these signals can be applied to tune the controllers, like the Automatic Voltage Regulator (AVR) or Power System Stabilizer (PSS) to suppress oscillations. The awareness of accurate and real time the damping values tend to contribute to a larger operation security margin for the system.

FREQUENCY INSTABILITY ASSESSMENT

Power system frequency is commonly used as an indication of the real power balance in the grid. Commonly, unpredicted and large generation loss can lead to frequency instability [8]. A frequency reduction beyond a certain threshold may lead to system collapse, for example, the power generating system cannot withstand too low frequency operation. Under frequency load shedding is the most widely applied protection against frequency instability [31]. Given on line synchronized phasors, frequency stability control actions can be performed based on the real time information instead of the conservative offline assumptions used in the conventional frequency maintaining functions [9].

VOLTAGE STABILITY ASSESSMENT

Voltage stability refers to the ability of power system to maintain steady voltages at the entire grid scale after being subjected to a disturbance from a given initial operating condition. Voltage instability normally occurs in heavily stressed systems in the form of a progressive and uncontrollable fall in voltage. Depending on the time scale, the voltage stability problems can be cataloged as short-term (a few seconds) or long-term (up to minutes). PMUs placed at the appropriate buses are capable of providing real time information, through which, a more accurate bus loadability assessment can be performed [32][9].

TRANSMISSION LINE TEMPERATURE MONITORING

Disregarding constrains concerning stability, the maximum power flow on a line is limited by its heating capacity which is commonly predefined as in the situation without wind and at high ambient temperature. Consequently, it is usually a conservative guess, since this assumed situation rarely happens. In [9], an on-line transmission corridor temperature monitoring method is presented given real time voltage and current phasors measured at the end of the supervised lines and the properties of the line conductor.

HYBRID STATE ESTIMATION

The state estimator determines a best estimate of the current power system states, usually including the voltage phasors, transformer tap positions and circuit breaker status, given the stream of telemetry that has been seen from the system's sensors so far, current network model and information from other data sources. The core idea of state estimation is to estimates the states that are not directly measurable from available data sets and enhance the accuracy of the other observable states given measurement redundancy. Some pioneer experiments have already shown that the introduction of PMU measurements can improve the estimate accuracy [33], improve the system observability [34] and aid bad data detection [35].

CHAPTER 3

RESEARCH DESIGN

This chapter discusses the research process and methods used in the research presented in this thesis. The chapter begins with a section on data collection methods used, starting with an overview of the research process and then discusses the methods for data collection, such as literature review, survey and expert input and validation. The next section discusses the analysis methods available. Simulation was the main analysis method that was selected, but other methods are discussed. The simulation process section describes how these simulations were built. Related simulation works in the field are also presented in this chapter. The chapter is concluded with a summary discussing the potential future use of the simulation platform.

DATA COLLECTION

The research in this thesis, utilized two methods to accumulate data and to analyze results. First data collection was executed through literature review, followed by a survey of a specific focus group. The results of the literature review and the survey was then applied as input for building the simulation models. The amount of data collection was highly concentrated at start of the research and gradually decreased as the models and simulations were built the following figure depicts the research process and how the Paper A, B, C and D fit in.

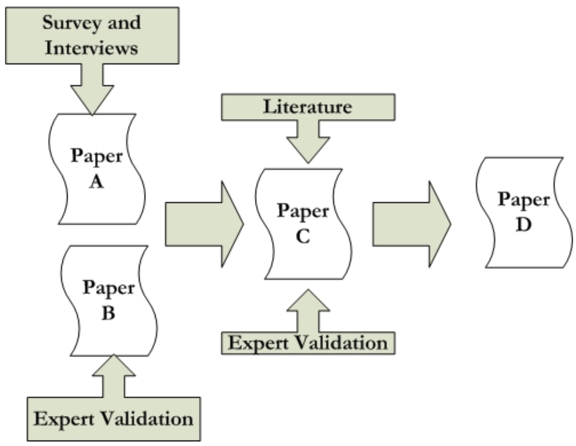

Figure 5: Research output and related input from methods

The following table illustrates how the various data collection and simulation methods apply to the papers that are included in this thesis

Table 1: Papers included and the thesis and the application of data collection and simulation methods

	Paper A	Paper B	Paper C	Paper D
Survey	Yes			Yes
Interviews	Yes	Yes		Yes
Expert Input or Validation		Yes	Yes	Yes
Simulation		Yes	Yes	Yes

LITERATURE REVIEW

As mentioned in the related works section of Chapter 2, there has been similar work in the field by other researchers and organization. A review of their work formed a basis for direction. The literature review was important in the sense that it led to a survey and to the selection of the focus group for the survey.

THE SURVEY

The early stages of the research in this thesis had certain elements that were based on a survey conducted regarding ICT requirements for WAMC applications. The survey was conducted using interviews and questionnaires. The questionnaire was made up of thirteen questions sent out to TSOs and researchers involved in or planning to be involved in PMU project implementations. The survey was conducted both online, by use of emails, as well as using face to face interviews conducted on the TSOs/researchers' premises.

The questionnaires were semi-structured in a manner so as to guide the participants through the relevant topic areas, but flexible enough to allow the participants to provide insight into their opinions. Interviews were also conducted with participants, in which case the contents of the questionnaire were used as the main agenda of the interview.

EXPERT INPUT/VALIDATION

Data was also collected from experts as input to simulation models or for the verification of simulation models. For example, data from the survey was used in Paper B to build a preliminary communication network based on PMU locations, the actual characteristics and properties of the final network model were verified with experts who were not survey participants. In the case of Paper C, the algorithm for the PDC, described in the paper was derived from literature, but then validated with an expert developing PDCs.

ANALYSIS

In this research simulation was the main analysis technique used. There are two basic categories of methods for ICT system evaluation. These are (1) measurements of existing systems and (2) predictions based on models that abstract existing or upcoming systems [37]. These models can then be further divided into analytical models and simulation based models.

DIRECT MEASUREMENT

Measurements of existing systems is the most accurate technique, since we can measure all aspects of interest without imposing abstractions or assumptions. The drawback of this method is of course that it is specific to the system being measured and it is difficult and sometimes impossible to measure variations in the performance characteristics as the systems parameters change [38]. Doing so would mean changing an existing system which could mean taking the system offline and out of operation.

ANALYTICAL MODELING

Analytical modeling involves defining a model of the system that expresses the relation between the performance characteristics and other system parameters. Analytical modeling usually involves a number of assumptions regarding the system and its environment [38]. Two prominent techniques within analytical modeling are network calculus and queuing theory.

Network calculus is targeted at communication network performance, specifically towards service guarantees and deterministic traffic [39]. Queuing theory on the other hand has been applied for both communication [40] and computer systems [38] where systems are modeled in terms of service times and queue lengths of nodes and traffic is represented in varying arrival patterns. Queuing theory is probability based and gives a statistical estimation of the parameter and characteristics of interest.

The general drawback of analytical methods is that as the system gets more complex the methods also gets less feasible since the models of the system grow in complexity. To be manageable, analytical models focus on a limited set of parameters while ignoring the effect of other system parameters or properties which may also affect the performance of the system.

SIMULATION

Simulation is applied in many fields ranging from the business domain to that of the military. A simple definition of simulation, found in [36], states that:

"Simulation is the imitation of the operation of the real-world process or system over time".

Simulations duplicate real life phenomenon through the use of mathematical models. Simulations are therefore, models of a real life phenomenon that can be executed and observed on a computer system. Simulation models can be classified as follows

- Discrete Simulation Models

- Continuous Simulation Models
- Combined Discrete Continuous Models

Discrete simulation is characterized by the fact that its variables change only at discrete points or events, for example when a bank customer shows up at the teller, the teller will respond. A continuous simulation's variables are always a subject to time, a queue of bank customers at the teller, how long will it take to serve the queue. Combined discrete-continuous simulations, as the name suggests, is a combination of both, the simulations parameters are subject to time, but they also change according or discrete events that may happen during the course of the simulation. Simulations are used for product design, testing and training among others, and applied in such fields as manufacturing, automobile industry, healthcare, military, etc [36].

Generally speaking, the parameters can be more varied than those involved in analytical analysis. Example of a general purpose simulation package is OPNET [41] which can model many characteristics of communication networks. Especially targeting Power System Control, a set of simulators has been combined into a platform, EPOCH. In [42] the EPOCH simulator is used to model different protection and control schemes including power system as well as communication system characteristics. Yet simulation still cannot model every single detail of the system and involves assumptions and simplifications in order to implement the program and to execute it in a reasonable amount of time [38].

SIMULATION PROCESS

The simulation models implemented in this research is based on discrete event simulations. The OPNET Modeler [41], a flexible communication and applications simulator, was used to build the simulation models. The simulation models in Paper B used, built in and reusable, models from OPNETs library. In Paper C, most of the models where built on top of basic OPNET components using the simulator's propriety "C/C++-like" language called, proto-C.

The steps in the method used for building the models in Paper B and C are illustrated in Figure 6. These steps are based on recommendations from [43].

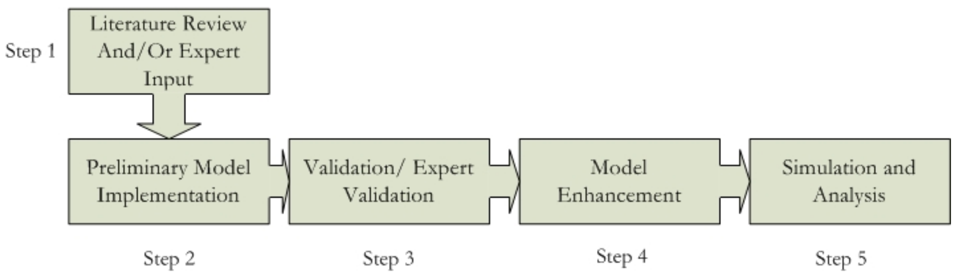

Figure 6: Simulation steps performed in simulation projects.

The first step, establishes the need for building a simulation project, by identifying a set of questions that a model should answer, this is question may arise from literature review or from the results of previous research. The specification of the model in terms of characteristics, properties and behavior is could also come from literature review or from experts familiar with the characteristics and behavior of the physical or concept that is being modeled. In the case of the research in this project, the model was intended to answer questions related to end to end delays and other data quality issues for wide area networks for WAMCs. This information is the basis for step 2, the building of a preliminary model, that is not necessarily detailed but enough to capture all properties of the real world concept being modeled, but detailed enough to represent the question or goal laid out in step 1.

The preliminary model is then or validated in step 3 in order to establish its compliance with the input from literature, experts and/or the goal or question that was set at the start of the project. The validation may establish new aspects to correct or to add to the model. In Step 4 the model is enhanced to meet the recommendations and findings from step 3. Finally step 5 involves running the simulation, collecting results as statistics and analyzing the results.

RELATED APPROACHES AND SIMULATION WORK

There exists related work employing simulations for the evaluation of power system related ICT infrastructure or components, for example in [42], [44],[45]. This section discusses simulation projects that are similar to the simulation models built in this thesis.

Simulation modeling of ICT components, specifically using the OPNET simulator has been applied in the substation automation domain, specifically for the performance evaluation of substation communication networks. In [46] OPNET was used to model switched industrial Ethernet communications in a substation utilizing IP communication. The authors examined the End to End (ETE) delay and jitter characteristics of such networks. This work was based on OPNET's built-in model library but also had customizations of these models for specific purposes. In Paper B of this thesis, models from OPNET built-in model library were also used and customized according to the scenarios implemented. While the authors in [46] looked at substation architectures using TCP/UDP/IP and Ethernet protocols customized for their specific scenarios. Paper B, on the other hand, dealt with Wide Area Networks and used simplified substation networks, represented by a link between the PMU and the switch. Furthermore, Paper B, utilized the TCP and IP protocol and did not use UDP or customize the Ethernet protocol settings.

In [47] and [48] OPNET was used to implement reusable IEC 61850-based Intelligent Electronic Devices (IED) models. These models were customized implementations and were not from OPNET's model library. The IED models were then reused to build several substation networks with scenarios utilizing quality of service, where data is prioritized, and scenarios with no quality of service applied. ETE delays were collected for different kinds of messages such as raw data and interbay trip messages. In Paper C a customized model of a PDC was implemented, but the focus was on wide area communication and the functionality of the PDC.

In [49] data flows of NASPI's NASPInet network were simulated to determine communication bandwidth requirements, impact of security mechanisms on the bandwidth and the ETE delays. The data flows come from the PMUs and are sent to a PDC. The PDC forwards the data to a Phasor Data Gateway (PDG) that acts as a publisher of PMU data, sharing and distributing PMU data to authorized subscribers. This model is implemented in the Network Simulator 2 (NS2)[50]. The scenarios implemented represented NASPInet as the main communication network for the Western Interconnect grid in the USA. The concept used in the NASPInet simulation has similarities to both Paper B and Paper C, that is, the determination of the bandwidth requirements and the analyses of ETE delays.

On the other hand, there are notable differences. In the case of Paper B the following differences exist. Firstly, a fictitious communication network for possible PMU locations in one power system (Sweden) was built. The distance based delay was calculated automatically by the OPNET simulator and was not configured on the link as in the NASPInet simulations. Secondly, Paper B modeled dedicated and shared communication networks with different communication capacities, background traffic and protocols. This was not the case with NASPInet were the links were point-to-point and the UDP/IP protocol suite used in the scenarios, but the variation between the scenarios was mainly whether Quality of Service (QoS) or security mechanisms were configured in the data flows. Thirdly the simulations in paper B included ETE delays measurements for control signals. This was not modeled in the NASPInet simulations.

In relation to Paper C, there are two main differences. Firstly, the PDC model in paper C is more elaborate and is described in detail in the paper, it included configurable parameters such as time-out configurations and phasor set size. It is not clear how the PDC model in the NASPInet simulations time-aligns the phasor sets received. Secondly, the impact of PDC's time-out parameter and the delay in the wide area network on the data loss or phasor set incompleteness was studied. This was not the case in the NASPInet simulations, but the authors claim that it could be possible to reconfigure the simulation framework to measure such data loss.

SUMMARY

The research in this thesis utilized a variety of data collection methods in order to build and validate models. Simulation was also used as the main analysis techniques for these models. The advantage of using simulation is the reusability and extensibility of the models, even though the models described in Paper B are focused on a specific region they could easily be adjusted to meet evolving architectures and protocols. Similarly the models in Paper C could also be easily modified and extended to capture more advanced architectures and statistics.

CHAPTER 4

SUMMARY OF INCLUDED PAPERS

The previous chapters have stated the objective and contribution of the research presented in this thesis, as well as background to the topic area. Furthermore chapter 3 outlines how this research was planned and executed. This final chapter provides a summary of the papers in which the research was published and on which this thesis is based..

The first paper, Paper A, presents the results of a survey conducted with researchers and TSOs that are involved in, or are planning to be involved in, projects related to PMU deployment or PMU-based application function development.

Paper B addresses the transmission time of phasor measurements and feedback control signals, by analyzing these detailed level qualities a base is established on which PMU based systems could be analyzed on a higher level, specifically, the applications level.

The next paper, Paper C, studies the impact of delays and other parameters on the incompleteness of the data sent from the PMUs to the Phasor Data Concentrator (PDC). Paper D, ties together the research presented in earlier papers, and draws an overall conclusion on the findings presented earlier.

Paper A – Survey on Priorities and Communication Requirements for PMU-based Application in the Nordic Region

This paper presents the results of a survey conducted with researchers and TSOs that are involved in, or are planning to be involved in, projects related to PMU deployment or PMU-based application function development. The survey also documents the current stage of development the participants are in and collects priorities and requirements on possible application functions.

First, general WAMC architecture and communication requirements are presented. An overview of the WAMC components is presented along with a short description of the functionality. A major section in this part is the communication network, where the concept of dedicated and shared communication networks for WAMC systems is briefly presented and discussed. The advantages and disadvantages of using dedicated or shared communication in WAMC systems, is also included in the discussion, as well as, delay estimates from related research.

The paper also presents current PMU deployments and application in the Nordic region, this part of the paper is divided in to three parts, the first part discusses the PMU deployments, presenting figures on the number of deployed PMUs and PDCs in the region and discusses network protocols and capacity, the paper also presents a figure on future planned deployments of PMU among the TSOs in the region. The next part discusses current PMU based application being developed or deployed. Finally the section closes with a short discussion on vision for PMU measurement information exchange architectures.

The paper is concluded with a presentation of the results of the survey in terms of application prioritization and requirements. The first part discusses the prioritization of PMU-based application functions as seen by TSO. The paper then moves on to discusses the requirements for the five PMU-based application function presented to the TSOs and researchers. Finally, there is a short analysis section which discusses and compares the requirements to similar requirement prepared by the North American Synchrophasor Initiative (NASPI). The requirements are organized in tabular form in the appendix, at the end of the paper, each application function requirement in captured in a single table.

PAPER B – MODELING AND SIMULATION OF WIDE AREA MONITORING AND CONTROL SYSTEMS IN IP-BASED NETWORKS

The purpose of this paper is to illustrate the use of common simulation tools to verify and study PMU based networks and applications. this paper addresses the transmission time of phasor measurement and feedback control signals, by analyzing the these detailed level qualities a base is established on which PMU based systems could be analyzed on a higher level, specifically, the applications level. The paper begins with an overview of WAMC components, and moves on to describe communication infrastructure for WAMC systems. Specifically, describing the dedicated and shared communication paradigms and briefly commented on advantage of each. This background section also contains common WAMC delay requirements estimated by researchers in the field. The paper moves on to describes the simulation model that was built to study PMU communication. The simulation model was based on PMU locations in Sweden, but it does not represent the actual communication network of the Swedish TSO. The simulation model had four scenarios representing dedicated and shared communication with different configuration. In the case of the dedicated scenarios the main parameter that was altered was the bandwidth. The bandwidth of the first scenario was 64 kilobits/seconds while the other dedicated scenario had a bandwidth double that, at 128 kilobits/second.

For the shared communication scenario, it was assumed that other devices (e.g. RTUs) utilized the same network as the PMUs. Therefore the main parameter that varied between the scenarios was the background traffic that represented traffic from other devices. In the first shared communication scenario, the background traffic was 50% of the communication link. In the second shared communication scenario this was increase to 70% of the communication link. The bandwidth of the communication links in both scenarios was 2 megabits/second. The specifications of the scenarios, such as the topology, bandwidth and background traffic for both dedicated and shared communication was validated by experts at the Swedish TSO. Once the simulation models had be described, the paper then, presents the results collected from the simulation scenarios. End to End (ETE) delays between the PMUs and PDC at the control center were collected from all four scenarios. Furthermore, ETE delay statistics from the WAMC system to the a set of substations were the PMUs would be located was also collected, this delay was collected to provide an estimate for delay on control commands from the WAMC applications at the control center to actuators in substations.

The paper ends with a discussion on the results of the simulation comparing them to previous estimates made by researchers. The discussion also includes a comparison between the results from the dedicated communication scenario and those of the shared communication scenarios.

PAPER C – INVESTIGATION OF COMMUNICATION DELAYS AND DATA INCOMPLETENESS IN MULTI-PMU WIDE AREA MONITORING AND CONTROL SYSTEMS

The purpose of this paper is twofold. First to specify the delays experienced in wide area monitoring and control systems, and second to study the impact of delays and parameters on the incompleteness of the data sent from the PDC to the WAMC applications. The paper also includes a simulation model implemented to model the ICT infrastructure and its behavior is used to verify and illustrate the delay and incompleteness attributes of data in WAMC systems.

A very brief overview of WAMC components and the related communication infrastructure is first presented. A simplified model to represent the communication infrastructure and the WAMC systems, is then introduced. This simplified model includes the basic WAMC components such as the PMU, WAN, PDC and application functions. Based on this simplified model the delays transmission delays are specified.

The PDC functionality is discussed and the delays relating to the functionality of the PDC are specified. Previous simulations of PMU communication have rarely taken into account the behavior of the PDC and its impact on the overall delay and data quality, the section discusses this aspect. The impact of the PDC is therefore taken into account in the specification of delay in WAMC systems.

The next part of the paper describes the simulation model that was built to illustrate and verify these delays and observe the impact on the data completeness given variation of certain PDC parameters, such as the PDC waiting time. The paper also describes the PDC model that was implemented and the possible combination of parameters. A total of forty-two scenarios were built by varying parameters such as PDC waiting time, network delay, and the number of PMUs on the network.

The final part of the paper, presents the results of simulations, and compares the data collected from the different scenarios implemented. Based on the results of the simulations, the paper closes with a discussion on the impact of delay in the communication network and waiting time, on the total end-to-end delay and on the data incompleteness, pointing out future work that can be done in this field.

PAPER D – MODELING AND SIMULATION OF WIDE AREA COMMUNICATION FOR CENTRALIZED PMU-BASED APPLICATIONS

This paper ties together the research presented in earlier papers, and draws overall conclusions on the findings presented earlier. The paper begins with an overall introduction, stating the scope of the paper and provides an overview of WAMC components.

The first part of the paper summarizes the results of the Paper A, the Nordic PMU application requirements and priorities survey, giving an overview of the priorities and communication requirements, this part establishes the role of the survey in the research. Next, the paper presents a overview of the PMU communication simulation model presented in Paper B, discussing the purpose of the building the simulation model and relating the project to the results of the survey.

The survey was an important source of input to building the PMU communication simulation model, since the information on the possible number of PMUs, location of PMUs, communication network capacity, number of PMU samples to be sent to the control center per second, as well as other characteristics were taken from the results of the survey.

The third part of the paper describes the simulation model and results from the project on time delay and its relation to data incompleteness. This project is the subject of Paper C, and is, in this paper, related to the results of the PMU communication simulation model from Paper B.

The paper is concluded with a discussion on the bottlenecks that may arise in WAMC system and possible future works that would be possible in this field

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A

Paper A

Survey On Priorities and Communication Requirements for PMU-based Applications in the Nordic Region

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Abstract

Phasor based Wide Area Monitoring and Control Systems (WAMC) promise to offer more accurate and timely data on the state of the power system, thus, increasing the possibilities to manage the system at a more efficient and responsive level and apply wide area control and protection schemes. This paper presents results of a survey on communications and technical requirements for applications based on Phasor Measurement Units (PMU). The survey was carried out in the Nordic Region with participants from Transmission System Operators (TSOs) and researchers. The survey focused on documenting the stage of research and development among TSOs and researchers in the Nordic Region, as well as, their plans and visions for the future. This includes planned PMU deployments and prioritization of PMU based applications. Furthermore, a significant part of the survey was an elicitation of communication requirements for applications based on PMU data. In the paper, an examination of the time requirements for these applications in terms of delays and samples per second and comparison similar published specifications is provided.

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Keywords: *Phasor Measurement Unit. Wide Area Monitoring and Control (WAMC), WAMC applications communication requirements.*

I. INTRODUCTION

Electrical power networks are a critical infrastructure in modern society. Our dependence and demand on electricity has risen sharply while recently this rising demand for electricity has been met with a serious strain in terms of production and expansion of transmission capacity. This is due to increasing environmental policies and costs among other factors.

There is an international interest and implementation drive, in both academia and industry, on the prospects of Phasor based monitoring and control technology [1][2]. These systems promise to offer more accurate and timely data on the state of the power system increasing the possibilities to manage the system at a more efficient and responsive level and apply wide area control and protection schemes [3].

Such systems are needed in the modern electrical power system, where transmission expansion is limited by monetary and environmental regulations. Furthermore, the re-regulation of the electrical market and the connection of national grids with neighbouring nations have resulted in a more complex and dynamic environment, in which multiple organizations coordinate and cooperate in the operation and control of the power network.

There have been various research and industrial initiatives by universities and Transmission System Operators (TSOs) in the Nordic region for the implementation and study of PMUs. The Nordic Region in this case constitutes Sweden, Norway, Finland, Iceland and Denmark. These countries have a common connected transmission grid known as NORDEL (Iceland is in the NORDEL organization but its grid is not physically connected to any of the other members) [4]. This report summarizes a survey carried out in the Nordic region (with the exception of Iceland) to study the current practices and future plans of researchers and TSOs for the implementation of PMU based Monitoring and Control Systems.

A. PURPOSE

The purpose of this survey is to examine and document the stage of research and development among TSOs and researchers in the Nordic Region. Specifically, this is done by examining the current state of PMU deployments and application development and specific communication and data requirements on five commonly concerned PMU-based applications requirements. The five application functions are: Oscillation detection, Voltage stability assessment of transmission corridors, Voltage stability assessment of meshed networks, Frequency instability assessment, and Line temperature monitoring [8]. Finally the requirements collected from these applications would be compared with existing documented requirements from the North American Synchrophasor Initiative (NASPI) [5].

OUTLINE

The paper begins with a summarization of WAMC architectures as well as general communication network requirements in section II. These requirements are the basis to building such systems. Section III goes on to discuss the current PMU deployments and application in the Nordic region. Furthermore, the requirements for PMU based application as seen by TSO and researchers are presented in Section IV, followed by a general comparison with NASPI requirements are outlined in section V. The paper is concluded in section VI. Finally an appendix containing tables summarizing the requirements for the PMU application functions mentioned earlier is provided in Section VIII at the end of the paper.

II. GENERAL WAMC COMMUNICATION REQUIREMENTS

Generally, most of the effort internationally [1][2][5][8] has been on developing monitoring and assessment application based on PMU measurements, in addition to platforms that would support these applications, e.g. the Gridstat project [6]. Monitoring and assessment applications are known as Wide Area Monitoring Systems (WAMS), these new application were previously not possible with SCADA measurements due to its generally low data sampling rate and quality, as well as time synchronization. There has been generally less work on developing control systems for PMU based monitoring and assessment application.

A complete PMU based Monitoring and Control Systems is a system by which PMU measurements are collected from various locations on the electrical grid in a nation or region. The measurements are then used by an assessment or monitoring application which would raise alarms or calculate results. The alarms raised and results calculated by these monitoring systems are in turn used to provide corrective actions or control on the power grid. Such a complete PMU based system is known as a Wide Area Monitoring and Control System (WAMC).

A. WAMC COMPONENTS

WAMC system includes four basic components: A PMU, a Phasor Data Concentrator (PDC), the PMU application system and finally the communication network [9].

Logically, there are three layers in a WAMC which in essence is very similar to more traditional SCADA systems. Figure 1 illustrates the logical architecture of WAMC systems. Layer 1 where the WAMC system interfaces with the power system on substation bars and power lines is called the Data Acquisition layer this is where the PMUs are placed. Layer 2 is known as the Data Management layer and that is where the PMU measurements are collected and sorted into a single time synchronized dataset. Finally Layer 3 is the Application Layer that represents the real time PMU based application functions that process the time synchronized PMU measurements provided by the Layer 2.

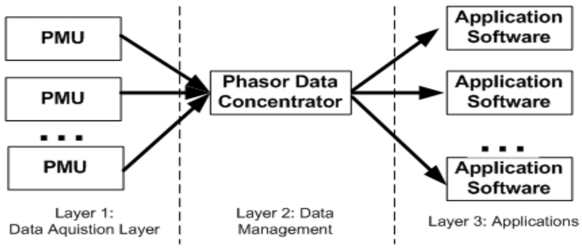

Figure 1: Layers and components of WAMC system.

B. COMMUNICATION NETWORK

The communication infrastructure is an important component in the architecture of WAMC. This is because PMU devices would be distributed on a wide area, covering various locations within a nation's boundaries. The PMU devices are then connected to a central control center or several control centers over the communication network. Therefore the communication network is a possible bottleneck in the architecture of these systems, since, the delays and data quality of the remote data from PMUs would depend on the communication infrastructure' capabilities and architecture.

Several research and experiences have suggested the use of fiber optic as the main communication media for PMU communication networks [8][11]. This generally resembles the architecture depicted in Figure 2. The network architecture would be composed of a main optical fiber backbone connected to the substation router. In turn the PMU can be connected to the substation router. The PMUs would be connected with the substation router through the standard substation Local Area Network (LAN). The measured phase angles from the PMUs are then transferred to a PDC which sorts and synchronizes the phasors according to the time stamps. The PDC also performs error checking and other functionalities such as data archiving.

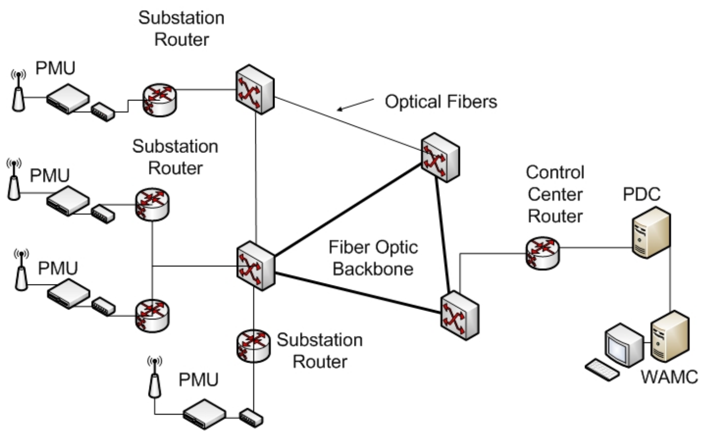

Figure 2: PMUs on a dedicated optical fiber network.

The main argument for using point to point optical fibers is for minimizing the effects of delay. Delay is an important measure to the success of PMU based application. Power system phenomenon could then be observed directly in real time rather than from post disturbance analysis.

On the other hand, a wide area shared network based on TCP/IP protocol suite, rather than a dedicated optical fiber network can be used. In such a network, illustrated in Figure 3, the traffic from PMU devices would be accompanied by traffic from substations RTUs as well as other network uses such as utility Voice-over-IP.

The media of network infrastructure in this case may, be optical fibers, but may also include other communication technologies used by modern utilities such as microwave and radio. The main concern that arises in this case is the reliability of these media as well as to the reliability of the TCP/IP protocol suite as the main communication protocol for critical power system communication. The diverse media may introduce a higher degree of delay due to their inherent physical properties

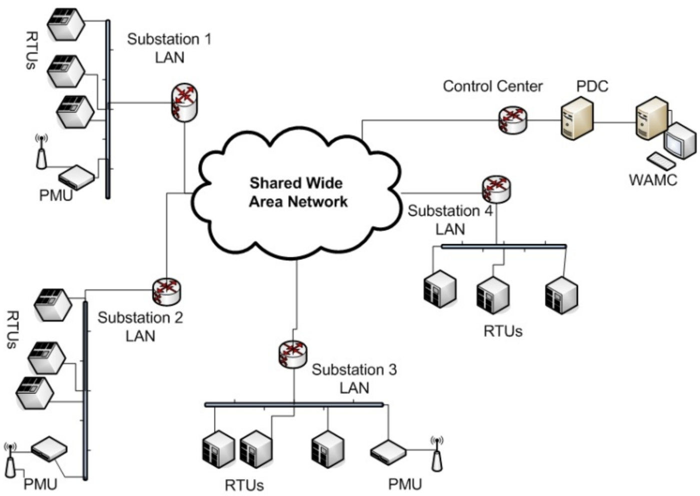

Figure 3: PMUs on a shared Wide Area Network

Real time wide area monitoring and control systems require stringent time requirements in order indentify, analyze and respond to emergency phenomenon in the power system, according to [8] and [9]. Table 1 presents estimations on the total time delay assuming that the system responds automatically to the emergency phenomenon (i.e. in the case of wide area protection scheme):

Activity	Time
Sensor Processing Time	**5 ms**
Transmission Time of Information	**10 ms**
Processing Incoming message queue	**10 ms**
Computing time for decision	**100 ms**
Transmission of control signal	**10 ms**
Operating time of local device	**50 ms**
Total Time	**185 ms**

Table 1 : Time estimates for steps in wide area protection [8]

This estimation depends on the assumption that the optical fibers are used as the main medium of the network and that the nodes and applications are optimized [14].

III. CURRENT PMU DEPLOYMENT AND APPLICATIONS

The survey was made up of thirteen semi-structured questions that were sent out to TSOs and researchers involved or are planning to be involved in PMU project implementations. The survey was sent out in the form of emails, as well as face to face interviews conducted on the TSOs/researchers' premises.

Part of the survey was aimed at collecting information on current activities, deployments and applications being executed or developed by researchers and TSOs in the Nordic region. In this section these results are presented. Specifically, information on current and planned PMU deployments by TSOs is presented as well as offline and online applications being developed and used. Finally a discussion on communication and information insights is summarized.

A. CURRENT AND PLANNED DEPLOYMENTS

In general the participants in the Nordic survey are still in the early phases of WAMC application functions development and deployment with the main focus being mostly on deploying PMUs and developing WAMS applications. Statnett (Norway) and Fingrid (Finland) are in the most advanced stage in WAMS applications, in comparison to other TSOs, with the development of prototype Oscillation monitoring system. Norway will begin testing control applications using Static Var Compensators (SVC) in cooperation with ABB. Both Statnett and Fingrid have deployed PMUs in substations and have a functioning PDC, a prototype online application function and exchanging PMU measurements Figure 4 illustrates the current number of PMU and PDC installations in the Nordic region.

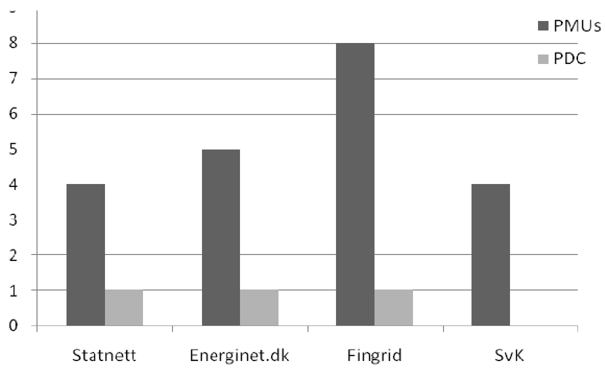

Figure 4: Current PMU and PDC deployments in the Nordic Region

Statnett has four installed and operational PMU connected to one PDC. There is one PMU in the east Norway on the on the main interconnections to Sweden, another PMU is located in the south near HVDC connection to Denmark. The other two PMUs are located in the northern and western part of the Norwegian power system. The PMUs installed in Norway use the IEEE 1344 protocol [19]. Statnett is also upgrading Digital Fault Recorders (DFR) to PMUs.

Fingrid has eight PMUs installed and operational, of which three are in the north and five in the south of Finland. All PMUs in Fingrid are connected to one PDC. Furthermore, Statnett and Fingrid exchange PMU measurement from their respective PMU over the Electronic Exchange Highway, which is a communication link for Nordic utilities with a capacity of 2 MBits/s.

Svenska Kraftnät (SvK), Sweden, has made four PMU installations. These PMUs are currently not online or operational. SvK has taken a policy of PMU installation as they refurbish their substations. Engerginet.dk (Denmark) has five installed and operational PMUs, four in Denmark and one in Germany, all PMUs stream using IEEE C37.118 [20] over TCP/IP.The following Figure 5 illustrates future plans in terms of PMU and PDC installations for Statnett, Fingrid, SvK and Energinet.dk

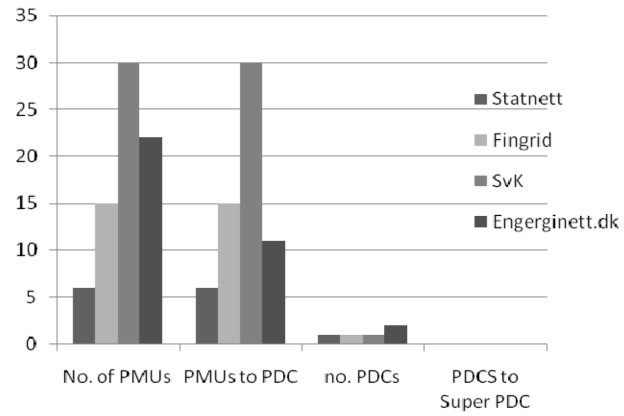

Figure 5: planned PMU installations and PMU to PDC connections

In addition, there are research deployments in Sweden and Finland being studied by the several universities. Four PMUs are deployed in Sweden at universities and one in Tampere, Finland.

B. CURRENT APPLICATIONS

Generally most of the application developed or purchased by TSOs in the Nordic regions has been for offline studies and analysis of phase angles from PMUs. But they are some online monitoring and analysis software being developed.

Statnett's offline applications are generally for surveying historical data in respect to trends in voltages, frequency and power oscillations. PMU measurements are also used for fault analysis if the disturbance occurred in the vicinity of an installed PMU. In addition, the tools for analyzing PMU measurements are also used to analyze data from fault recorders. Statnett as well use the MATLAB based "Morten Tool" [2] for offline or post disturbance analysis. Likewise Fingrid also has tools for analysis and studies, specifically, disturbance analysis and grid model verification and use mostly ABB's PSGuard for this. Energinet.dk has basic software for collecting and archiving PMU measurements for future studies.

As mentioned earlier SvK has deployed PMUs but they are not operational, so they do not yet have any offline (or online applications), but they have initiated some projects, notably phasor measurement integration into state estimation, and specifically in accuracy improvement for estimates. Two implementations combining PMU signals with SCADA measurements were tested in a MATLAB based power grid model. And also one optimum PMU placement with the objective to enhance estimation accuracy is studied as well.

In terms of online applications Statnett is developing LABVIEW based analysis and visualization software. In which they can view all variables measured by the PMUs and observing active and reactive power flows on incoming and outgoing lines. In addition, both Statnett and Fingrid are developing Oscillation Monitoring applications in cooperation with

ABB. Energinet.dk also been developing a MATLAB based application for online visualization of measurements from PMUs.

C. INFORMATION EXCHANGE ARCHITECTURE

Since the stage of WAMC systems is still in development in the Nordic region, the communication architecture has been given basic considerations. Most TSOs in the region are satisfied with their current set up. Nearly all TSOs are using shared network, except Sweden that would have dedicated channels for their PMUs when they become operational.

In General All TSOs will adapt C37.118 as the main protocol for PMU data, Statnett still uses IEEE 1344 but has installed some protocol translators and will upgrade to C37.118. The TSOs seemed to that currently shared using TCP/IP is sufficient for development.

Fingrid and Statnett exchange PMU measurements through the Nordic Electronic Highway (EH) information exchange network. Fingrid has reported some delays on the EH, but that is sufficient for now. In that architecture the measurements coming from the PDC in Norway are treated as an ordinary PMU in Fingrid's PDC, and vice versa. Figure 6 illustrates this architecture.

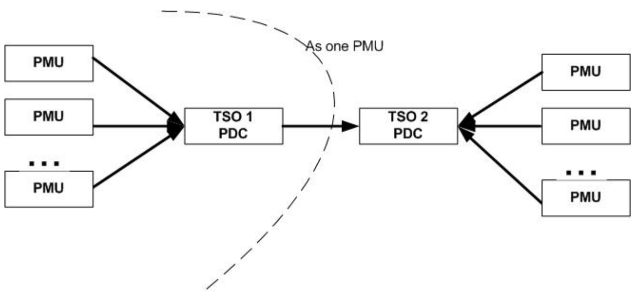

Figure 6: TSO 1 PDC acts as a PMU to PDC at TSO 2

While there are some packet loss and delays on the EH between Statnett and Fingrid, according to Fingrid, most TSOs have commented that this will be the architecture they will choose and that they would not want one single central Super PDC. This results in a meshed architecture of PDC in which from any given TSO the other PDCs are treated as standard PMU measurements. Figure 7 illustrates how a meshed architecture would like. So far due to the development stages in all participants the exact PMU architecture and components that would result and the integration with current SCADA systems are still unclear.

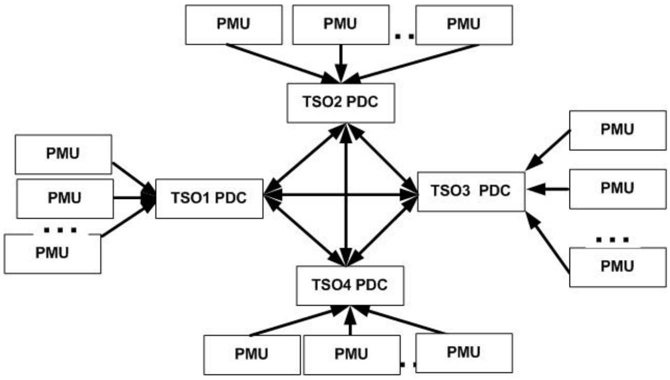

Figure 7: Nordic Phasor Measurements Exchange Architecture

IV. WAMC APPLICATIONS REQUIREMENTS IN NORDEL

This section discusses communication requirements for the PMU-based applications. The participants were presented with the same 13 questions for each application function. The purpose of the questions was to collect requirements on such issues as time to complete assessment, time window for response to phenomenon, PMU sample rate requirements and protocols as well as possible control functions that could be based on these applications. The answers were then compared with NASPI's application classification and requirements.

The appendix at the end of this paper contains the requirements summarized in the tables for each application function. The column headings are requirements that were collected for each application. Latency expected requirement is the amount of time it takes for the phasors to be sent from the PMU until they arrive at the application processing this information. Data resolution is the number of phasor samples required by the application.

Expected time window for response is the amount of time that the application needs for processing the incoming data and outputting the result either raising an alarm or initiating a corrective control scheme in the case of anomalies in the power system. Data source indicated whether other sources of input other than phase angles are needed for the application function, e.g. measurements from SCADA.

The participants also were asked about the format of the data i.e. which protocol would be used for the transmission of information from the PMU to the WAMC. The next column indicates the time required for the execution of currently implemented control schemes that used to remedy anomalies, e.g. current voltage instability control schemes. Finally, the last column indicates the time required for the execution of control schemes that would be based on the results of the PMUs based application.

In the discussion and in the tables the respondents have been made anonymous for sensitivity reasons. The TSO are referred to as TSO 1, 2, 3 and 4. while the researchers from research institutes are referred to as Research Institute 1, 2 and 3.

A. APPLICATION PRIORITIZATION IN NORDEL

Five PMU based application functions [8] were presented to TSOs and researchers in the Nordic region and they were asked to prioritize the importance of each application function in their opinion and in terms of their needs. The participants were then asked specific communication delays and response requirements for each application in addition to information on the required resolution and possible feedback control schemes.

Figure 8 presents the priorities of TSOs in the Nordic region. The figure illustrates the similarities in priorities. There is only a slight variation between the priorities and this can be due to the configuration of the power grid and to the presence of different generation portfolio. E.g. Denmark has a larger percentage of wind power generation than any other nation, which could explain why voltage stability applications is critical to them.

Statnett and Fingrid have identical priorities in terms of application functions, while SvK shares some similarities especially in terms of prioritization of Oscillation detection. Note, that most TSOs viewed voltage stability of transmission corridors and that of meshed networks as the same functionality and provided the same requirements (as discussed the later sections) in terms of response time and resolutions, but prioritized each application function differently, in tems of implementation, except Energinet.dk that prioritized them the same.

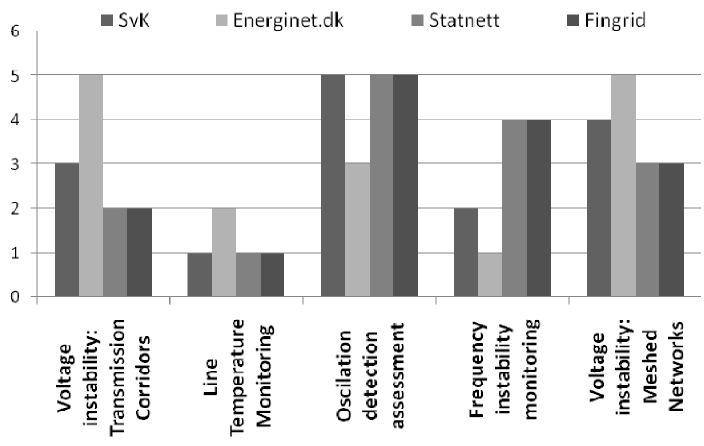

Figure 8: Applications Prioritizations in the Nordic Region

B. OSCILLATION MONITORING AND CONTROL

With the exception of TSO 3 which considers oscillation monitoring of medium importance among the applications included in the survey, all other TSOs in the Nordic countries listed oscillation monitoring with their highest priority.

Usually power systems are mostly influenced by the low frequency oscillation in the range of 0.05 Hz to 2 Hz [15] and the required latency for this application is considered to be dependent on the targeted oscillation frequency. TSO 1 aims at a refresh rate less than 2 second which is higher than that of their current SCADA/EMS. For TSO 3 the normal communication time, from 0.25 seconds to 2 or 3 seconds, is sufficient. The latency suggested by Researcher 1 and 3 together with TSO 2 is in seconds and by Researcher 2 is in fractions of seconds. Generally, suggested data resolution is in the range from 10 to 50 Hz for all the interviewees. Specifically, for online applications, TSO 4 believes 10 Hz is sufficient, and for offline applications, the sample rate should reach up to 50 Hz. The proposed time window is in fractions of seconds for TSO 1 and TSO 2. Research Institute 1 indicates that time window for the automatic control is more critical comparing to the control schemes executed manually. And Research Institute 2 believes this number should be below the 1/10 of the captured oscillation cycle and a fast response contributes a higher reliability and efficiency. All the participants believed that current SCADA is not sufficient for this application. And as for other applications, they preferred communication protocol is C37. 118.

TSO 1 has initialized a R&D project introducing "global" measurements from PMU to the PSS on SVC aiming to damp the critical oscillation modes. To improve the system damping, Research Institute 1 and 2 have scheduled tests of utilizing wide area measurements in the control of HVDC and FACTs components. Most of the TSOs have the ambition to have the control schemes executed in fractions of seconds. Table 2 in the appendix summarizes the participants' requirements on this application function.

C. VOLTAGE INSTABILITY ASSESSMENT

In the survey the users were queried for requirements on voltage instability assessment of transmission corridors and meshed networks as two separate application functions, but most respondents considered these two applications as being the same. However, some TSOs who have significant large percentage of meshed network choose different priorities for these applications, giving a higher priority for assessment of voltage instability in meshed networks. TSO 3 prioritized these two items equally, as the highest, since their grid network does not contain significant transmission corridors compared to the other three countries whose network spans larger geographical distance. Besides it, the large percentage of wind power in that nation's generation portfolio also contributes the voltage instability as TSO 3's critical concern.

In general the latency requirement depends on the time frame for voltage instability phenomenon. In Nordic countries, the long term voltage stability issue is more critical. According to TSO 4 and Research Institute 1, the accepted time delay is in the order of a few seconds. And to TSO 3 and Research Institute 3, time delay is of comparably low importance for this application, and their expected delay is 0.5 minutes and 1 minute respectively. Researchers TSO 3 and Research Institute 2 consider a low resolution to be sufficient for this application while Research Institute 3 suggested a high resolution as 50 samples per second. When it comes to the question of expected time window related to the application response, the Swedish researchers give answers in the range from seconds up to 1 minute.

Most researchers expected the data for the voltage stability assessment application function to come from a hybrid measurement set combined from SCADA and PMU information while the others claimed a fast and reliable SCADA is also accepted. The recommended communication protocol for PMU measurements is C37. 118.

TSO 4 has been using a state estimation based voltage collapse detection program, to assess voltage stability among several transmission bottlenecks for years [23]. Based on the obtained results, control schemes, like control of HVDC links for emergency power regulation, can be executed to maintain the voltage stability. And from their experience, the entire operation takes 2 or 3 seconds and current delay is from 0.2 to 1 second when the dedicated communication channels with redundancy are used. The requirements for this application function are summarized in table 3 in the appendix.

D. FREQUENCY INSTABILITY MONITORING

TSO 1 and TSO 2 have prioritized frequency instability assessment as second important, while TSO 3 and TSO 4 consider it of relatively low importance comparing to other applications involved in the survey.

TSO 2 and Research Institute 3 expect the latency of this application in order of few seconds and TSO 4 considers it to be in fractions of seconds. Research Institute 3 claimed the delay for this control function is mainly decided by the reaction time of the operators. The expectations for the data resolution lie in the range from 1 Hz up to 50 Hz. To most researchers, a response time window in seconds is sufficient. However, TSO 4 has a higher expectation as 0.15 seconds while Research Institute 2 considers that for this application time window for response is not important.

Currently, no synchronized phasor measurements have been involved in the frequency information based control function. The disturbance in Swedish power grid at September, 23, 2003 has proved that the current SCADA/EMS based under-frequency load shedding is too slow. And also similar experiences can be drawn from TSO 2 [23][1].

In the future, the remotely collected frequency information is proposed to be involved in generation and load control, power exchange monitoring, power system protections and

[1] This is reference should refer [24].

control of HVDC links. Most researchers preferred the data for frequency monitoring to come from a PMU measurement set in future while there is another that school believes that both SCADA and PMU measurements are acceptable. The recommended communication protocol is also C37. 118 for PMU data exchange.

Several measurements are needed in determination of power system frequency and the data processing takes about 0.05 seconds. TSO 4 has the ambition that the control function based on wide area frequency information should be executed and confirmed in 0.1 seconds while Research Institute 1 and TSO 2 are expecting this function to be completed in a few seconds. The requirements for frequency instability monitoring are listed in table 3[2].

E. LINE TEMPERATURE MONITORING

The line temperature monitoring application function is somewhat of a low priority function for TSOs in the Nordic region regarding the applications in the survey, and therefore the response on this application function was rather limited. All TSOs and researchers generally agree that this application function covers a slow developing phenomenon, especially in comparison to the other application functions discussed in this report. The monitoring, detection and the response to such a phenomenon, in terms of time and delay, are not critical.

Some TSOs, for example TSO 1 have commented that this application function is not applicable since their overhead lines go through very different landscapes. On the other hand, TSO 4 has commented that this maybe an interesting project in the future, especially in relation to wind power utilization. Specifically when maximum wind power is being produced at the same time as hydro production, this would result in heavy load on the transmission lines, especially when considering that the transmission lines in that nation were built to match the maximum capacity of their hydro production. Table 4 [3]summarizes the requirements for the line temperature monitoring application function according to the participants.

V. ANALYSIS

In general, the requirements collected from the TSOs and researchers dealing with PMU-based application are similar to specifications outline by NASPI. But there are some differences, for example, in terms of voltage instability monitoring, TSOs in Nordic countries generally have a higher ambition considering the response time window comparing to the NASPI classifications. The expectations for frequency instability monitoring from TSOs in NORDEL are fairly similar to NASPI classifications. While their requirement on response time window is again longer, comparing to the NASPI classifications.

[2] Errata: Should refer to Table 4 in the Appendix.

[3] Errata: Should refer to Table 5 in the Appendix.

In terms of line temperature monitoring the TSO and researchers in the Nordic region have a tighter requirement on response time of the application with is in the order of seconds while in comparison to NASPI's recommendation the response time is approximately 1 hour. Another difference is in the required phasor data resolution where in the Nordic region it is believed that a low data rate (without specifying exactly) is sufficient while NASPI suggestion 30 samples per second.

VI. CONCLUSION

The aim of this survey is document current stage of WAMC development and deployment in the NORDIC region and to collect application expectations and requirements from TSOs and researchers involved in the development and deployment and compare these results with requirements specified by previous experiences specifically with NASPI. By doing this information could be dissipated in the region and encourage cooperation.

The survey has shown that the aim and goals of participants is more or less similar. While Statnett and Fingrid have made significant progress, especially in application development, the other TSOs and researcher are also deploying PMUs and planning to employ these systems.

In terms of applications functions the prioritization of is more or less identical with minor exceptions. The similarity is also true for the communication requirements and data requirements. Finally, it was found that the development and requirements are also in line with previous experiences, specifically those from NASPI.

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VIII. APPENDIX

Interviewees	Expected Latency	Expected Resolution	Expected Time Window for Response	Format/ Protocol	Time Delay for Current/Tested Control Schema	Expected Execution Time for Control Schema
TSO 1		10 Hz	Less than 0.3 seconds	IEEE 1344 /updating to C37.118	To be determined	
TSO 2	Less than 2 seconds	10 Hz	Fractions of seconds	C37.118	Not applicable	Fractions of seconds
TSO 3						
TSO 4	0.25-2 or 3 seconds	10/50 Hz for online/offline applications		C37.118	0.25 seconds	0.25 seconds
Research Institute 1	Seconds		Seconds/Minutes for automatic/manual control			Seconds
Research Institute 2	Fractions of seconds	Above 10 Hz	Less than 1/10 of the cycle time of studied oscillation	C37.118		
Research Institute 3	1 second	50 Hz	Less than 0.2/5 seconds for POD/SPS		Less than 1 second	
NASPI	1-5 seconds	10 Hz	Seconds	PDC Stream/ C37.118		

Table 2: Oscillation Detection.

Interviewees	Expected Latency	Expected Resolution	Expected Time Window for Response	Format/ Protocol	Time Delay for Current/Tested Control Schema	Expected Execution Time for Control Schema
TSO 1						
TSO 2						
TSO 3		Depends on a PhD project output		C37.118		
TSO 4	1 to 2 seconds (Long term)	Low	Less than 1 minute	C37.118	From 200-300 ms to 1 second. (on a dedicated channel)	
Research Institute 1	Above seconds		Up to 1 minute			Several seconds
Research Institute 2	Up to 10 seconds (Long term)	1 to 10 Hz	Fractions of a second or longer	C37.118	A few seconds	
Research Institute 3	30 seconds	50 Hz	2-3 seconds			0-5 minutes
NASPI	Few seconds	30 Hz	Minutes/Seconds for long/Short term voltage stability	C37.118		

Table 3: Voltage instability

Interviewees	Expected Latency	Expected Resolution	Expected Time Window for Response	Format/ Protocol	Time Delay for Current/Tested Control Schema	Expected Execution Time for Control Schema
TSO 1		5-10 Hz				
TSO 2	Seconds		Seconds	C37.118	Not Applicable	Less than 5 seconds
TSO 3						
TSO 4	0.25-0.5 seconds	50 Hz	0.15 seconds	C37.118	Not Applicable	0.1 Seconds
Research Institute 1			Seconds		Under frequency load shedding was too slow on September 23 2003.	Seconds
Research Institute 2	1/10 of the operator reaction time	1-10 Hz	Not important		Fractions of a second.	
Research institute 3	1 second	10 Hz				1-2 seconds
NASPI	1-5 seconds	30 Hz	Few minutes	PDC Stream/ C37.118		

Table 4: Frequency Instability

Interviewees	Expected Latency	Expected Resolution	Expected Time Window for Response	Format/ Protocol	Time Delay for Current/Tested Control Schema	Expected Execution Time for Control Schema
TSO 1						
TSO 2	Minutes		Minutes			Minutes
TSO 3	Slow phenomena on, slow process	1 Hz	Less than 1 second	C37.118		
TSO 4	10 minutes	Low Data Resolution				
Research Institute 1	Seconds or minutes		Seconds to minutes			Minutes
Research Institute 2	Few minutes		Fractions of seconds	C37.118		
Research Institute 3	5 minutes	1 Hz				15 minutes
NASPI	Few seconds	30 Hz	1 hour	IEEE 1344 / C37.118		

Table 5: Line Temperature Monitoring

B

PAPER B

MODELING AND SIMULATION OF WIDE AREA MONITORING AND CONTROL SYSTEMS IN IP-BASED NETWORKS

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ABSTRACT

Phasor based Wide Area Monitoring and Control Systems (WAMC) is becoming a reality with increased international research and development. Many aspects of these systems are being addressed and researched. These systems depend largely on high performance communication architecture. This paper addresses the analysis of PMU systems and communication architectures by utilizing simulation tools to implement and analyze models. Specifically, focusing on the transmission of Phasor samples to the Phasor Data Concentrator (PDC) and control signals from the WAMC systems back to substations devices. This done by implementing shared and dedicated communication network scenarios to analyze delays. This is the first step to analyzing the performance and scalability of the IT infrastructure to support PMU-based Systems

Keyword: *PMU Communication, Wide Area Monitoring and Control, communication simulation, PMU communication delays.*

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I. INTRODUCTION

Electrical power networks are a part of the critical infrastructure in modern society. Our dependence and demand on electricity has risen sharply while recently this rising demand for electricity has been meet with a serious strain in terms of production and expansion of transmission capacity. This is, among other factors, due to increasing environmental policies and costs. Furthermore, the re-regulation of the electrical market and the connection of national grids with neighbouring nations have resulted in a more complex and dynamic environment, in which multiple organizations coordinate and cooperate in the operation and control of the power system.

There is an international interest and implementation drive, in both academia and industry, on the prospects of Phasor Measurement Unit (PMU) based monitoring and control technology [1], [2]. These systems promise to offer more accurate and timely data on the state of the power system increasing the possibilities to manage the system at a more efficient and responsive level and apply wide area control and protection schemes.

Generally, most of the effort internationally e.g. [1][2][3][4][5], has been on developing monitoring and assessment application based on PMU measurements, in addition to platforms that would support these applications, e.g. the Gridstat project [6]. Monitoring and assessment applications are known as Wide Area Monitoring Systems (WAMS), these new application were previously not possible with SCADA measurements due to its generally low data sampling rate quality, and lack of exact time synchronization. There has been generally less work on developing protection systems for PMU based monitoring and assessment application, and even less so for wide area control applications. This second group of systems which not only monitor the power system states are referred to as Wide Area Monitoring and Control Systems (WAMC).

A. PURPOSE

The purpose of this paper is to illustrate the use of common simulation tools to verify and study PMU based networks and applications. In this paper addresses the transmission time of phasor measurement and feedback control signals, by analyzing the these low level qualities a base is established on which PMU based systems could be analyzed on a higher level, specifically, the applications level. The simulations are promising and show good correlation with similar studies in other systems. This paper is also a continuation of previous work in analyzing factors of wide area network for distributed control of power systems [7] and PMU based application requirements [8].

B. OUTLINE

This paper is structured as follows; Section II provides necessary background information on PMU based WAMC components and architecture, points out the importance of the communication infrastructure and two basic communication paradigms. Section III explains the simulation model created and the different scenario implemented. Section IV describes results of the simulation and section V briefly discusses of the results of the different scenarios. Finally section VI concludes the paper and points out further work that is being done in this area.

II. GENERAL WAMC COMMUNICATION REQUIREMENTS

A complete PMU based Monitoring and Control Systems is a system in which PMU measurements are collected from various locations in the electrical grid in a nation or region. The measurements are then communicated to a central location where they are used by an assessment or monitoring application that would raise alarms or calculate results. The alarms raised and results calculated by these monitoring systems are in turn used to provide corrective actions or control on the power grid. Such a complete PMU based system is known as a Wide Area Monitoring and Control System (WAMC).

A. WAMC COMPONENTS

As depicted in Figure 1, WAMC system includes four basic components: A PMU, a Phasor Data Concentrator (PDC), The PMU application system and finally the communication network [9]. Logical, there are four layers, in a WAMC which in essence is very similar to more traditional SCADA systems. Figure 1 illustrates the logical architecture of WAMC systems. Layer 1 is where the WAMC system interfaces with the process on substation bars and power lines, is called the Data Acquisition layer and is where the PMUs are placed. Layer 2 is known as the Data Management layer and that is where the PMU measurements are collected and sorted into a single dataset which in turn is forwarded to the Data Services layer. Layer 3, the Data Services Layer, provides services to meet the requirements of different application software, such as error checking, and data format conversion. Finally Layer 4 is the Application Layer that represents the real time PMU based application functions.

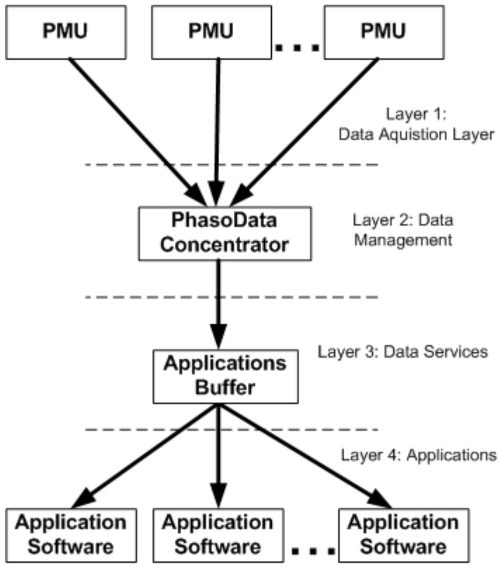

Figure 1: Layers and components of WAMC system

B. COMMUNICATION INFRASTRUCTURE

The communication infrastructure is an important component in the architecture of WAMC system. This is because PMU devices are distributed over a wide area, covering various locations within a power system's boundaries. The PMU devices are then connected to a central control center or several control centers over the communication network. Therefore the communication network is a possible bottleneck in the architecture of these systems, since, the delays and data quality of the remote data from PMUs would depend on the communication infrastructure's capabilities and architecture.

1) DEDICATED NETWORK SOLUTIONS

Several research and experiences have suggested the use of dedicated channels in fiber optic network as the main communication media for PMU communication networks [10] [11]. This generally resembles the architecture depicted in Figure 2. The network architecture would be composed of a main optical fiber backbone connected to the substation router. In turn the PMU can be connected to the substation router. The PMU would be connected with the substation router through the standard substation Local Area Network (LAN). The measured phase angles from the PMUs are then transferred to a PDC which sorts the phasors according to the GPS time stamps. The application buffer performs error and synchronization checking among other functionalities [9].

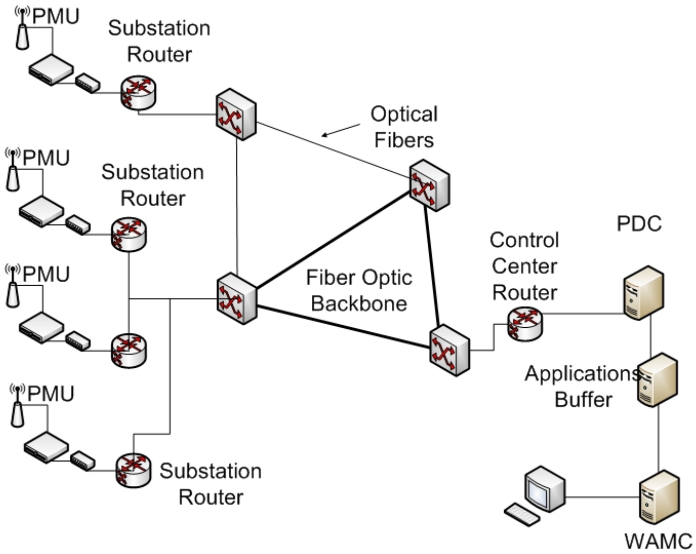

Figure 2: PMUs on a dedicated optical fiber network

The main argument for using dedicated channels is for minimizing the effects of delay and congestion. Delay is an important measure for the success of PMU based application, since the main advantage of such application over SCADA based applications is observability of transient phenomena in the power system. These phenomena could then be observed directly in real time and used for control and protection purposes rather than merely for post disturbance analysis.

2) SHARED NETWORKS SOLUTIONS

As alternative, a wide area network based on TCP/IP protocol suite rather than a dedicated optical fiber network can be used. In such a network, illustrated in Figure 3, the traffic from PMU devices would be accompanied by traffic from substations RTUs as well as other network uses such as utility Voice-over-IP. TCP/IP, the main protocol for the internet is an emerging protocol suite in utility networking, as it offers an open standard as well as wide adoption in industry. This means cheaper, more flexible, interoperable software and hardware [12].

The media of network infrastructure in this case may also be optical fibers but may also include other communication technologies used by modern utilities such as microwave, coaxial, and radio. The main concern that arises in this case is reliability of these media as well as to the reliability of the TCP/IP protocol suite as the main communication protocol for critical power system communication.

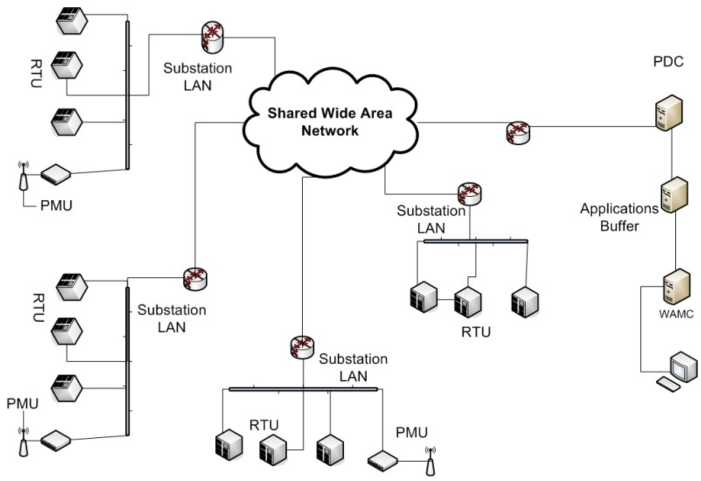

Figure 3: PMUs on a shared Wide Area Network

3) *WAMC TIME REQUIREMENTS*

As is described in to [8] and [9] the WAMC must fulfill stringent time requirements in order indentify, analyze and respond to emergency phenomenon in the power system. Table 1 presents estimations on the total time delay assuming that the system responds automatically to the emergency phenomenon (i.e. in the case of wide area protection scheme):

Table 1: Time estimates for steps in wide area protection [10]

Activity	Time
Sensor Processing Time	5 ms
Transmission Time of Information	10 ms
Processing Incoming message queue	10 ms
Computing time for decision	100 ms
Transmission of control signal	10 ms
Operating time of local device	50 ms
Total Time	185 ms

This estimation depends on the assumption that the optical fibers are used as the main medium of the network and that the nodes and applications are optimized [10].

III. IMPLEMENTING A PMU COMMUNICATION MODEL IN OPNET

To get a better estimation of the delays and utilization in PMU communication a model representing such communication was implemented in OPNET Modeler [14] a communication network simulator. This model was based on possible locations of PMUs in Sweden. The model contains different scenarios corresponding to both dedicated and shared network paradigms discussed in Section II It is important to note that the communication model built is not the actual communication networks used by the Swedish TSO. Geographical placement in the simulation model is important since the model utilizes OPNET's distance based delay, where the delay due to distance is a component of the total delay between to network devices. The rest of this section describes the model and the different scenarios implemented as well as the assumptions made.

A. THE PMU COMMUNICATION NETWORK MODEL

The PMU Communication network model has 4 scenarios representing different configurations, two support the dedicated and two the shared communication paradigms discussed in section II. The following figure 4 gives a high level view of topology and illustrates geographical scope of the models.

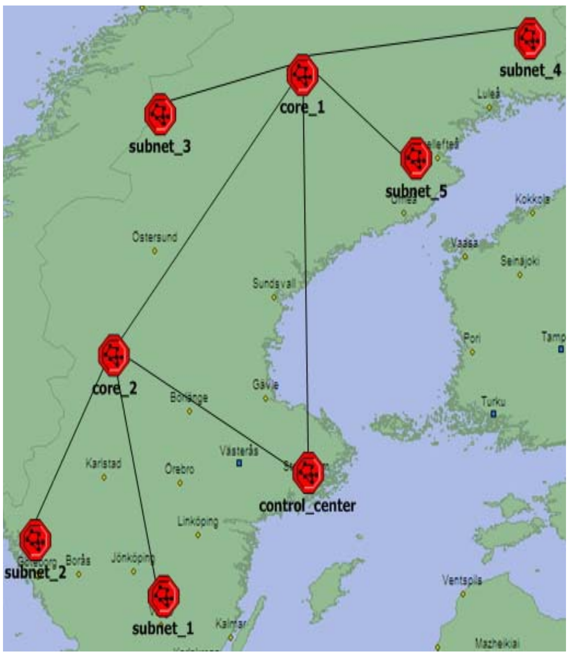

Figure 4: The fictitious PMU Communication Network

The octagons on the map represent subnets. Subnets are a logical grouping of communication networks. There are two core subnets, core_1 and core_2. The core subnets represent a network or meshed router (or Synchronous Digital Hierarchy (SDH) switches in the case of the dedicated communications scenario). This was done to represent the complexity and meshed topology that exits in real world networks. Figure 5 illustrates 8 meshed routers in the core2 subnet.

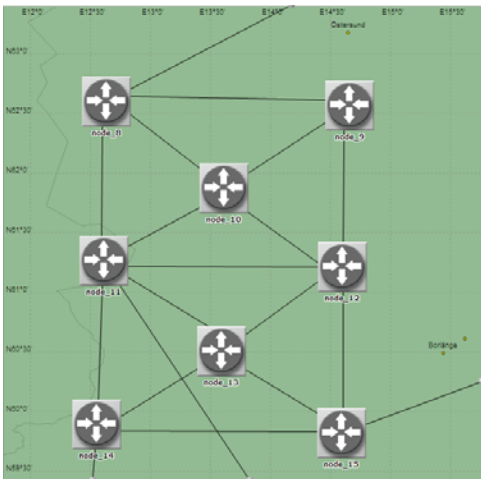

Figure 5: the core2 subnet made up of 8 meshed routers

The control center subnet (control_center) represents the control center, where the main measurements and status from the power system process are sent and from where the main commands are sent back to the devices regulating the electrical process. The control_center subnet contains two Ethernet networks on it, one representing a substation in the vicinity of the control centre and the other the control center LAN.

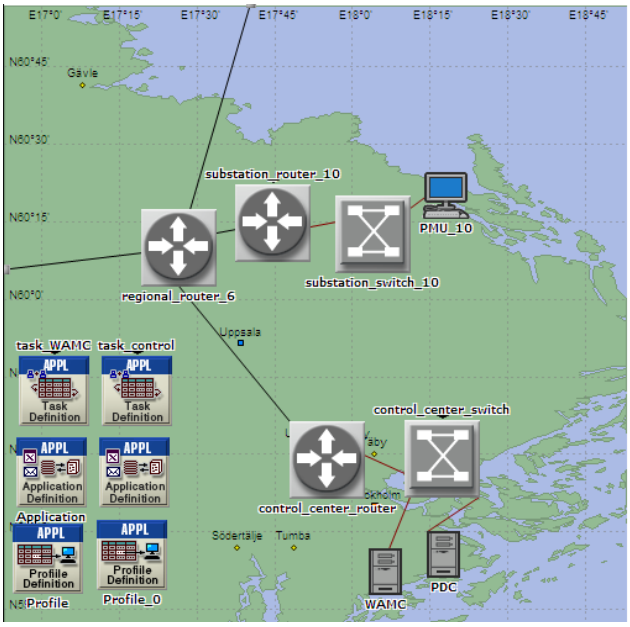

Figure 6: The control_center subnet

The rest of the subnets in the model represent substations, most subnets contain two substations, except subnet_4 which has only one substation. The following table lists the PMUs by Subnet.

Table 2: Contents of subnets in the simulation model

Subnet	No. of PMUs	Relevant Nodes in Subnet
subnet_1	2	PMU_1 PMU_2 substation_switch_1 substation_switch_2
subnet_2	2	PMU_3 PMU_4 substation_switch_1 substation_switch_2
subnet_3	2	PMU_5 PMU_6 substation_switch_5 substation_switch_6
subnet_4	1	PMU_7 substation_switch_8
subnet_5	2	PMU_8 PMU_9 substation_switch_8 substation_switch_9

control_center	1	PMU_10 substation_switch_10 control_center_switch PDC WAMC

The traffic generation from PMUs, PDC and the WAMC devices is similar in all scenarios. The PMUs generates 30 Packets per second of size 76 bytes. 76 bytes are broken down into 16 bytes for C37.118 Header and trailer [12], 32 bytes for the IP header and 28 bytes for phasor values (e.g. Real and imaginary phasors, etc) representing one of the possible data loads. The packets from all PMUs are sent to the PDC in the control_center subnet. The PDC receives these packets and generates 30 new packets per second which are sent to the WAMC. The WAMC receives these packets and discards them.

The WAMC also generates traffic that represents control signals going back to the process. The WAMC traffic is generated in discrete time intervals and is sent to a predetermined number of substation switches in various subnets. The difference between the models is in the capacity of the links and the protocols utilized. The scenarios varied in the configuration of devices the next two sections describe the dedicated network and the shared network communication scenarios.

B. DEDICATED COMMUNICATION SCENARIOS

The two dedicated communication scenarios are implemented to represent dedicated channels in utility communication networks. The main difference between the two scenarios, in this case, is the channel capacity. In one of the scenarios the channel Capacity is 64 Kbits per second while in the other scenario the channel capacity is 128 Kbits per second. The 64 Kb per second was chosen to verify previous studies, specifically in [11], where 64 Kb was estimated as the minimum capacity required. The model with 128 Kb per second channel capacity per phasor measurement stream was implemented to compare delays with the estimated minimum.

The dedicated network utilizes the IP protocol for network addressing and routing. In a purely dedicated model, IP protocol would not be needed, but in our case we have chosen to utilize the IP network to simplify the routing and addressing schemes, it is also assumed that the IP protocol would not introduce any delays. There are two main technologies used on the Data link layer, Ethernet and Point to Point. Ethernet communication is basically between PMU and substation switch and between PDC, WAMC and the control center Ethernet switch. In all other cases, Point-to-Point communication links representing fiber optic characteristics is used i.e. between switches and router, and router to router communication. The following Figure 7 represents the modular structure of the PMU, PDC and WAMC nodes in the dedicated network.

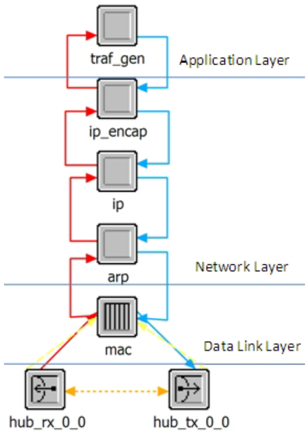

Figure 7: PMU, PDC and WAMC modular structure in the dedicated communication model

The traffic from PMUs, PDC and WAMC is generated in the Application layer by the traf_gen model, where it is then passed to the Network Layer. In the PDC and WAMC models the traf_gen model also acts as a sink (where packets are discarded). There are two main assumptions specific to the dedicated model. First, that each link to the PMU represents the channel capacity. I.e. the models of communication links are not divided into channels, the link itself is the channel. The second assumption is that when two links converge on a node, for example a switch, then the link exiting the router to the next router in the communication chain has a capacity which is equal to the two converging links. Figure 8 below illustrates these two assumptions.

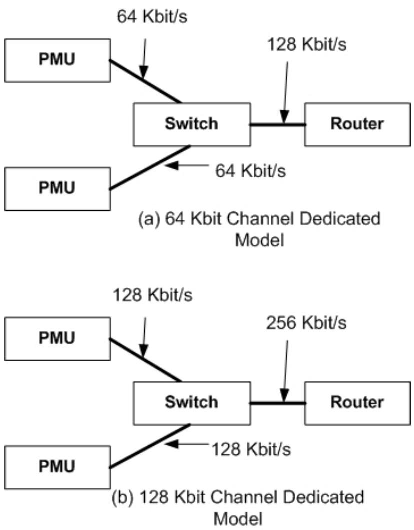

Figure 8: The channel capacity assumption in the dedicated communication models

C. SHARED COMMUNICATION SCENARIOS

The scenarios using shared communication represent shared utility networks, were the communication network is also utilized for other devices and functions on the network, this includes Remote Terminal Units (RTUs), Circuit Breakers and Switches and functions such as utility wide Voice-Over-IP (VOIP). The bandwidth on all communication links in this network is 2 MBits per second. Unlike the dedicated communication scenarios the attributes that vary between the two shared communication scenarios is background traffic. The background traffic utilization selected was 50% and 70% of the communication link bandwidth.

In the shared communication network scenarios the IP protocol is used for network addressing and routing just like in the dedicated communication scenarios. But a significant difference between the two sets of scenarios is the utilization of the Transport Control Protocol (TCP). TCP was used to study the reliability and delay of communication in the presence of a transport protocol and (in contrast to the dedicated model where no transport protocol is utilized).

There has been no configuration in the TCP parameters, such as Sliding window size and time out. The default configuration of these parameters in OPNET was used. A more detailed analysis of the behavior of TCP was beyond the scope of this project. The following Figure 9 illustrated the modular structure of the PMU, PDC and WAMC nodes in the shared communication scenarios.

The traffic generation is similar to the two dedicated scenarios, where the generation starts at the top module. In this case the traffic is generated in the Application Module[1] for the PMU, PDC and WAMC nodes. The traffic then is passed to the Transport layer modules and thereafter to the Network layer and so on. Figure 9 illustrates the structure of the PMU, PDC and WAMC nodes.

[1] The actual specification of PMU, PDC and WAMC application traffic in the shared communication scenarios was done using the Custom Application Configuration Module, for more information see the OPNET Manual.

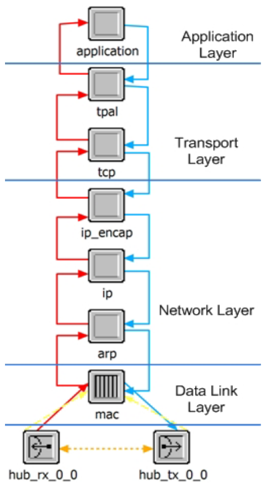

Figure 9: PMU, PDC and WAMC modular structure in the shared communication model

There are 3 traffic streams in the shared communication scenarios. First, traffic comes from the PMU, where the PMU generates 30 Packets per second destined to the PDC. The PDC also generated 30 packets per second to the WAMC generating 30 packets per second. The WAMC also generated packets that represent control signals to various nodes on the network. Furthermore background traffic was also introduced into the scenarios. This was used to represent traffic that is due to other devices that may exist in a shared power system communication network, for example, RTUs/IEDs and Voice-Over-IP. Depending on the shared communication scenario, the background traffic can either be 50% or 70 % of the link bandwidth. This traffic background traffic was configured to be in the direction of the control center. On the other hand, the traffic in the direction of the substations is 20% in both scenarios. This is done to represent other control signals on the network or to represent remote configuration being sent to remote devices, such as RTUs.

IV. SIMULATION RESULTS

End to End (ETE) delays statistics between all PMUs and the PDC was collected. Furthermore, statistics on the transmission time for control signals from the WAMC system to three preselected substation switches was also collected. These preselected substation switches are in substation_3, substation_6 and substation_8, PMUs in those substations are PMU_3, PMU_6 and PMU_8. The control signals sent back to the substations switches are not destined for the PMUs on these substations but rather to IEDs or RTUs on these networks where it is assumed these devices would execute a control scheme, such as opening a set of breakers.

A. 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 thirteen ETE delays. Among them, ten were captured from the links from PMUs to PDC and three were captured from the control commands.

1) *END TO END DELAYS FROM PMUS TO PDC IN DEDICATED COMMUNICATION SCENARIOS*

ETE delay statistics were collected from both the dedicated communication scenarios simulations. As mentioned earlier, ten PMUs, in both scenarios, generated a constant traffic of 30 samples per second destined to the PDC. 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.

TableTable 3 illustrates the collected ETE delays from PMUs to PDC in the 64Kb and 128Kb scenarios. The differences between ETE delays within the same scenario were related to geographical distances between PMUs and PDC. Whereas when comparing the ETE delays collected in the 64Kb and the 128Kb scenarios, the delays were reduced, in most cases, approximately by half. In other words, when the channel capacity was doubled, the ETE delay was approximately reduced by half.

Table 3: ETE delays from PMUs to PDC in the dedicated communication scenarios.

ETE delays 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[2]	0.042	0.042
PMU_8	0.046	0.025
PMU_9	0.039	0.020
PMU_10	0.015	0.008

[2] Errata: this value was due to misconfiguration of parameters for PMU_7 in these two scenarios.

2) *END TO END DELAYS FROM PMUS TO PDC IN THE SHARED COMMUNICATION SCENARIOS*

ETE delay statistics was also collected for both the shared communication scenarios. Like in the dedicated communication scenarios, each PMU generating constant traffic of 30 samples per second destined to the PDC. 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%.

As mentioned in section II, in shared communication networks, there would be other traffic on the network coming from other devices (e.g. RTUs) or services (Voice-Over-IP). By adding the constant background traffic to the links in the both scenarios we could analyze the delays variation of PMU traffic between the two scenarios in the presence of different background traffic loads. In a real network, PMUs generate constant traffic in all cases, but the background traffic will actually fluctuate. Table 4 shows the ETE delays collected from the PMUs to PDC links for the 50% and 70% scenarios.

Table 4: ETE delays from PMUs to PDC in the shared communication scenarios

ETE delays 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

3) *END TO END DELAYS FROM WAMC TO SUBSTATIONS*

The ETE delays for the simulated control signals in the dedicated and shared communication scenarios 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.

Referring to Table 2 and Figure 4 that respectively list and illustrate the content and location of subnets in the simulation model, the substations selected from different regions of the simulated network, substation_3 located in the bottom right in subnet_2, while substation_6 is located in subnet_3 and substation_8 in subnet_5, respectively, in the top right and left part of the model. This was done to draw measurements from substations that are from different parts of the model.

For the 50% and 70% shared communication scenarios, 20% background traffic was introduced in the direction from the control center to the substations. Table 5 shows the ETE delays of the control commands for the shared and dedicated communication scenarios, The ETE delay from WAMC to substation_switch_3, substation_switch_6 and substation _switch_8 is 7.1 ms, 10.7 ms and 9.3 ms respectively for both shared communication with 50% and 70% background traffic scenarios. The difference in delay between the substations, in this case, is most likely related to the geographical location of the respective substation and its proximity to the control center where the WAMC is located.

Table 5: ETE delays of the control commands for the shared and dedicated communication scenarios

Scenario	substation_switch_3	substation_switch_6	substation_switch_8
50% background traffic	0.0071	0.0107	0.0093
70% background traffic	0.0071	0.0107	0.0093
64Kb dedicated channel	0.042	0.042	0.042
128Kb dedicated channel	0.021	0.022	0.021

In the dedicated communication scenarios the ETE delays of the control signal commands is 42ms, 43ms and 43ms from the WAMC system to substation_switch_3, substation_switch_6 and substation_switch8 respectively in the case of the dedicated communication with 64 kb channels scenario. On the other hand, the ETE delays when the channels capacity is 128kb is 21ms, 22ms, and 21ms from the WAMC to substation_switch_3, substation_switch_6 and substation_ switch_8 respectively. Again it can be observed the delay decreases nearly by half when increasing the channel capacity from 64 Kb to 128Kb,

B. TOTAL WAMC RESPONSE TIME

The simulation model provided input measurements which could be used for estimating both the transmission delay and the control signal delay. This better improves the computation for total delay or response time the WAMC system would have when responding to anomalies in the power system process.

Table 6 illustrates estimations of the total response time of the WAMC system for the shared communication with 50% background traffic, using estimates from [9] and [10] and modifying only transmission time of information and control signal transmission.

Table 6: Response time of the shared model in 50% scenario

50% background traffic (ms)	Substation _3	Substation _6	Substation _8
Sensor processing time	5	5	5
Transmission time of information	12	19	17
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	184.1	194.7	191.3

The result is for substation_3 substation_6 and substation_8, which are approximately 184 ms, 194.7 ms and 191.3 ms respectively in the 50% background traffic scenario.

Applying the same technique used in calculating the total response time in Table 6 the total response time for all the remaining scenarios can be derived. Table 7 displays the results for all scenarios including the shared communication with 50% background traffic previously illustrated in Table 6.

Table 7: Total Response Times for All Scenarios (in ms)

Scenario	Substation _3	Substation _6	Substation _8
50% background Traffic	184	194	191
70% background Traffic	193	208	203
64Kb Channel	244	280	253
128 Kb Channel	206	226	211

V. DISCUSSION

In both the dedicated and shared communication scenarios, an important observation is the PMU that has the longest delay, this is especially true if we assume that the PDC will wait for values from that PMU before it synchronizes and forwards the information to the WAMC. The PMU with the longest delay could actually be a bottleneck that would increase the amount of time the values would need to reach the monitoring or assessment application in the WAMC.

The highest delays were observed for PMU_6 in the 64kb channel dedicated communication scenario and PMU_7 in the case of the 128 kb dedicated communication model. On the other hand longest delays were in PMU_5 and PMU_6 in both the 50% and 70% shared communication scenarios.

In general the delays in the dedicated communication scenarios are larger than the shared communication mainly due to the available capacity in the shared communication links. While the links in the shared communication model have background traffic utilization the remaining capacity is still much larger than the capacity in the dedicated communication scenarios. In the 70% background traffic shared communication scenario, the remaining available bandwidth for PMU data out of the 2 Mbit capacity is approximately 614.4Kb which nearly five times as much as the capacity in the 128 Kb dedicated communication scenario.

While the total response time delays in Table 7 is not large when comparing the different scenarios, factors such as the amount of traffic, link capacity and distance of PMUs to the control center may cause significant delay. This first iteration of the model did not take into account errors introduced into the phasor measurements due to the network nor was information loss accounted for. Furthermore no assumptions on Quality of Service mechanisms or prioritizations that, could potentially minimize delay, was made.

The results in Table 7 show that the simulation results are generally, in line with approximations used in [6] and those used in NASPI in [9]. Furthermore, even though the difference is not substantial the main factor to improve to minimize delay is to increase bandwidth and minimize or possibly to prioritize traffic in the presence of background traffic.

VI. CONCLUSION

This paper presented an implementation of PMU communication models to approximate the delay on phasor measurements sent from PMUs to PDC and control signals from the WAMC system back to substation switches. These approximations were based on lower level protocols and media as well as distances associated with the placement of the PMUs to the PDC. Furthermore some parameters were varied, specifically, bandwidth capacity and background traffic utilization to observe the impact on delays.

The results of these simulations were fairly similar to previous estimations. Further iterations on the current PMU communication models to address application delays and performances issues are ongoing. Specifically, the models are being enhanced to allow analysis on the impact of delays and measurement loss or errors due to communication on the behavior of the PDC in sorting and synchronization.

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Paper C

Investigation of Communication Delays and Data Incompleteness in Multi-PMU Wide Area Monitoring and Control Systems

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Abstract

Phasor based Wide Area Monitoring and Control Systems (WAMC) are becoming a reality with increased international research and development. Many potential control applications based on these systems are being proposed and researched. An aspect which is less well investigated is the WAMC system's dependence on high performance communication systems. This paper presents the results of simulations performed in order to determine the characteristics of communication delays incurred in WAMC systems using multiple PMUs distributed over a large geographic area. Such systems normally include one or several Phasor Data Concentrator (PDC) that collect and sort the data from the PMUs. Two specific parameters, completeness and currency of the PMU data has been studied as part of the simulations. The results indicate that configuration of central nodes such as the PDC needs to be optimized based on the intended WAMC application being supported

Keywords: Wide Area Monitoring System, Wide Area Monitoring and Control Systems Performance, Monitoring Systems Data Quality, PMU based Application

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I. INTRODUCTION

Electrical power networks are a part of the critical infrastructure in modern society. Our dependence and demand on electricity has risen sharply while recently this rising demand for electricity has been met with a serious strain in terms of production and expansion of transmission capacity. This is, among other factors, due to increasing environmental policies and costs. Furthermore, the re-regulation of the electrical market and the connection of national grids with neighbouring nations have resulted in a more complex and dynamic environment, in which multiple organizations coordinate and cooperate in the operation and control of the power system.

There is an international interest and implementation drive, in both academia and industry, on the prospects of Phasor Measurement Unit (PMU) based monitoring and control technology [1], [2]. These systems promise to offer more accurate and timely data on the state of the power system increasing the possibilities to manage the system at a more efficient and responsive level and apply wide area control and protection schemes.

Generally, most of the effort internationally e.g. [1][2][3] [5], has been on developing monitoring and assessment application based on PMU measurements, in addition to platforms that would support these applications, e.g. the Gridstat project [6]. Monitoring and assessment applications are known as Wide Area Monitoring Systems (WAMS), these new application were previously not possible with SCADA measurements due to its generally low data sampling rate quality and lack of exact time synchronization. There has been generally less work on developing protection systems for PMU based monitoring and assessment application, and even less so for wide area control applications. This second group of systems which not only *monitor* the power system states are referred to as Wide Area Monitoring and Control Systems (WAMC).

A. PURPOSE

The purpose of this paper is twofold. First to specify the delays experienced in wide area monitoring and control systems, and secondly to study the impact of delays and parameters on the incompleteness of the data sent from the PMUs to the Phasor Data Concentrator (PDC). Finally a simulation model implemented in OPNET to model the ICT infrastructure and its behavior is used to verify and illustrate the delay and incompleteness attributes of data in WAMC systems. In terms of time delays, previous studies in this field have not considered the impact of certain important architectural components (specifically the PDC) and their parameters on the overall delay. In this paper these components and there parameters are taken into consideration

B. OUTLINE

The rest of the paper is structured as follows; Section II presents an overview of WAMC architectures outlining the main components of such systems. Section III presents the communication system model and discusses the delays in WAMC communication. Section IV describes the simulation model scenarios that were built and the parameters varied in these scenarios. The analysis of the results of the simulation and a discussion can be found in Section V. Finally, related works is discussed in Section VI and the paper is concluded in Section VII.

II. WAMC ARCHITECTURES

A complete PMU based Monitoring and Control Systems is a system in which PMU measurements are collected from various locations in the electrical grid in a nation or region. The measurements are then communicated to a central location where they are used by an assessment or monitoring application that would raise alarms or calculate results. The alarms raised and results calculated by these monitoring systems are in turn used to provide corrective actions or control on the power grid. Such a complete PMU based system is known as a WAMC. Alternative architectures, such as using a few remote PMU signals in a local system for a specific protection application is also possible, but are outside the scope of this study.

A. WAMC COMPONENTS

WAMC system includes four basic components: A PMU, a PDC, the PMU-based application system and finally the communication network [9].

Logically, there are three layers in a WAMC which in essence is very similar to more traditional SCADA systems Figure 1 illustrates the logical architecture of WAMC systems. Layer 1 where the WAMC system interfaces with the power system on substation bars and power lines is called the Data Acquisition layer this is where the PMUs are placed. Layer 2 is known as the Data Management layer and that is where the PMU measurements are collected and sorted into a single time synchronized dataset. Finally Layer 3 is the Application Layer that represents the real time PMU based application functions that process the time synchronized PMU measurements provided by the Layer 2.

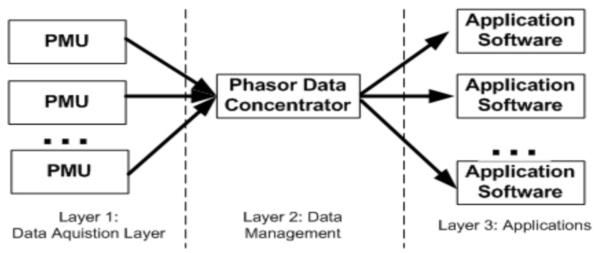

Figure 1: Layers and components of WAMC system.

A. COMMUNICATION INFRASTRUCTURE

The communication infrastructure is an important component in the architecture of a WAMC system. This is because PMU devices are distributed over a wide area, covering various locations within a power system's boundaries. The PMU devices are then connected to a central control center or several control centers over the communication network. Therefore, the communication network is a possible bottleneck in the architecture of these systems, since the delays and data quality of the remote data from PMUs would depend on the communication infrastructure's capabilities and architecture.

III. COMMUNICATION SYSTEM MODEL

The communication infrastructure has in this project been simplified as illustrated in Figure 2 below. The PMUs are assumed to reside in substations, connected to a Local Area network (SS LAN). The SS LAN is in turn connected via a substation router to a Wide area Network (WAN). The application that utilizes the PMU data resides at a central location connected to a Local Area Network (CC LAN). Since the application is dependent on data from several PMUs, the data from the PMUs are first passed to the PDC for sorting after which they are sent to the application.

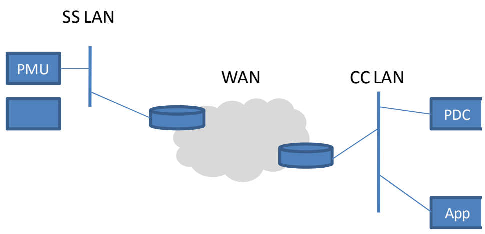

Figure 2: Utility communication model, showing substation LAN and control center LAN connected by wide area network (WAN).

A. TRANSMISSION DELAYS

To specify the transmission delays we define the following parameters:

N = *Total number of PMUs*

$i = 1..N$

d = *Number of PMUs experiencing exceptional delays*

T_i = *Total end to end transmission time for PMU i.*

T_{PDC} = *Processing time in PDC*

T_{SS} = *Nominal transmission time on SS LAN*

T_{CC} = *Nominal transmission time on CC LAN*

T_{WAN} = *Nominal transmission time through WAN including routing delays.*

Given the above, the total end to end transmission time T_i *for a specific PMU i* can be expressed as:

$$T_i = T_{SSi} + T_{WANi} + 2T_{CCi} + T_{PDCi}$$

Assuming that $T_{SSi}=T_{CCi} << T_{WANi}$ for all i we chose to represent the transmission time in the WAN T_{WANi} as a normal distribution with varying mean and standard deviation based as identified in a reference network, and previous simulation studies. The values used for μ and σ^2 are given in Section IV. Note that in the above model, delays related to transducers, DFT processing of phasor values are not included [6].

With the assumptions above we now have

$$T_i = T_{WANi} + T_{PDCi}$$

The processing time in the PDC depends in turn on the implementation of the sorting algorithm in the PDC. Here a number of variations are possible, and these are discussed in the following section.

B. PDC MODEL

The most important function of the PDC is to collect or receive the phasor measurements from connected PMUs and to sort them according to the GPS time stamp. Once a time stamp set, i.e. all phasors with the same time stamp, is complete the PDC forwards the phasor set to the applications consuming the data. The PDC can also have other functionality, such as error checking and archiving for offline and historical data analysis [7]. In this paper we consider only the time synchronization functionality .Generally, there are no specified published algorithms and most vendors consider the algorithms as confidential. On the other, hand the main time synchronization algorithm can be derived from descriptions [8] and the actual requirement of the sorting and synchronization task.

In the generic algorithm the PDC will group together measurements from the same time stamp in to a set. This is done as the measurements arrive to the PDC. In some cases the measurements may be delayed so there will be more than one time stamped buffer. When the buffer is full the PDC will forward the set in the buffer to the applications consuming it. The drawback of this algorithm is that the PDC has to wait for the buffer to be full before forwarding it to the applications. In a perfect network where delay is negligible and no packet loss occurs this algorithm would work fine. On the other hand, if the network was to experience significant delays or packet loss, there is no way to determine the amount of time the phasor data would have to wait in the buffer.

A slight variation of this algorithm is to add a time-out per time stamped buffer. The time-out would be the amount of time the buffer is actively waiting for the rest of the phasor measurements with the same time stamp. The countdown to the time-out is initiated when the first phasor measurement of a certain time stamp arrives at the PDC. The PDC assigns this newly arrived measurement to a new buffer, and begins the time-out counter for that buffer. In this case when the time-out is up the PDC will forward the set without waiting for the rest of the phasor measurements to arrive.

This small addition to the algorithm introduces a ceiling in terms of the delay that can be experienced and is more deterministic. If the PMU communication network were to experience abnormal delays or packet loss then the waiting time parameter insures that the PDC forwards the phasor measurements in an acceptable time range without waiting for the delayed measurements to arrive.

On the other hand, the issue of incomplete data arises where the phasor measurements forwarded to the applications would be incomplete and missing certain measurements from PMUs on the grid. Figure 3 below illustrates this algorithm.

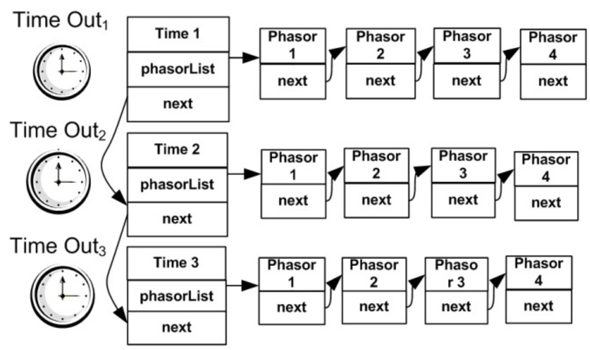

Figure 3: Time stamped buffers in the PDC holding measurements in a linked list representation.

In the second algorithm where time-out time is employed, the amount of time a packet is delayed in the PDC depends on the following parameters:

- When it arrives (early packets have to wait until all packets form the same time-stamp have arrived)
- How many PMUs are sending (more PMUs to wait for)
- How long to wait for the last PMU packet for that time stamp
- The time-out setting.

This linked-list sorting algorithm can be described as

$$T_{PDCi} = f(T_{TO}, T_{WANi})$$

Where T_{TO} represents the time -out parameter in the PDC sorting algorithm. In the implemented algorithm the PMU packet with the longest transmission time, T_{WANi}, determines the maximum time that all packets will have to wait

$$T_w = Max\ (T_{WANi}) \qquad i=1..N$$

Finally, this gives the complete expression for T_{PDCi}.

$$T_{PDCi} = T_{sort} + Min(T_w \mid T_{TO})$$

To study the characteristics of T_{PDCi} in different system architectures and with different settings for T_{TO} in networks experiencing different amounts of delay a simulation study as described in the following section was performed.

IV. WAMC COMMUNICATION SIMULATIONS

To get a better estimation of the delays and utilization in PMU communication a model representing such communication was implemented in OPNET Modeler [9] a communication network simulator.

A. THE SIMULATION MODEL.

The overall communication model is made up of sub models that represent PMU devices, the PDC and the WAMC application server. The PMU devices are assumed to be in substation (one PMU per substation), furthermore the PDC and WAMC application server are assumed to be located at the control center. Figure 4 below illustrates the simulation model in a scenario with four PMUs. The number of PMUs varies depending on the scenario set. There are three scenario sets, with four, eight and sixteen PMUs.

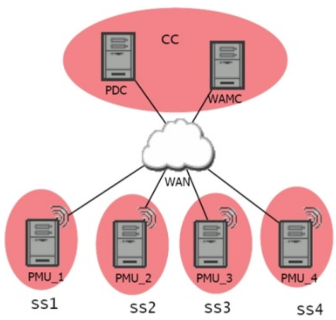

Figure 4: Topology of scenarios with four PMUs

B. THE PMU, PDC AND WAMC MODELS

Figure 5 illustrates the internal modules of the PMU models used in the simulation. The "src" module generates 30 samples per second directed to the PDC model in the control center. Each sample is encapsulated in a IEEE C37.118 packet of size 52 Bytes. The "rcv" and "xmt" modules are interfaces to the network, representing receiving and transmission modules respectively.

The “proc” module adds the creation time to the IEEE C37.118 packet and introduces the delay the packet will experience in the network. This is done by computing a random value from a predefined normal distribution, which would be used to delay the packet before sending it. The link and switches to the control center do not introduce any delay, the delays in these components is represented by the delay introduced in the “proc” module.

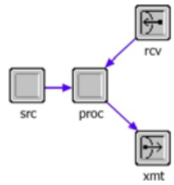

Figure 5: the modules making up the PMU model

Figure 6 below illustrates the internals of the (a) PDC model and (b) the WAMC application server.

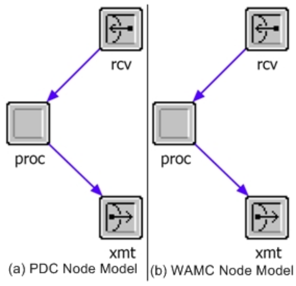

Figure 6: The PDC and WAMC node models

In “proc” module, in the case of the PDC and WAMC models, implements the functionality in these nodes. The PDC “proc” module implements the PDC functionality of time synchronization and sorting with adjustable waiting time as described in Section IIIThe functionality is implemented using OPNET’s process models (an implementation of Finite State Machines) utilizing a variant the C programming language. The process model for the PDC functionality is depicted in Figure 7.

The process model for the PDC functionality is initialized at the beginning of the simulation at the init state (the circle with a dark arrow directed at it). After the process has been initialized the system waits at the “idle” state for phasor measurement packets to arrive. When a packet arrives the “RCV_ARRVL” condition becomes true and the process model goes in to a state of “phasesort” where the packet is placed in a new formed buffer if the time stamp has not been encountered previously.

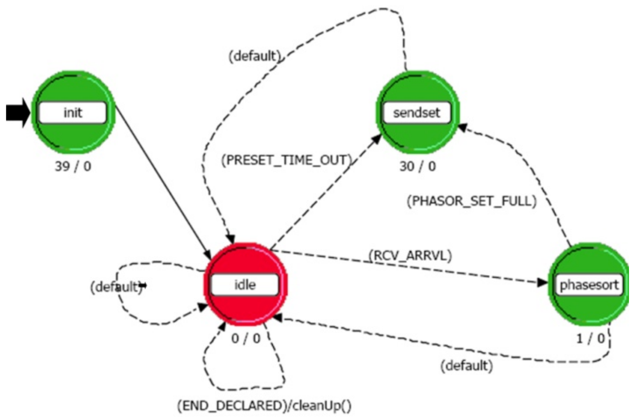

Figure 7: Process Model for Sorting Algorithm

If the time stamp has been encountered previously the process assigns the new packet to an existing buffer. This is done until either the buffer is full in which case “PHASOR_SET_FULL” becomes true and the process goes into a transitions to the “sendset” state where the full buffer is sent to the WAMC, or if the time-out time for the buffer is up, the process simulation environment would generate a time-out interrupt which make the “PRESET_TIME_OUT” transition true forcing the process to the state of “sendset” where the incomplete buffer is forwarded to the WAMC.

There is no real functionality implemented in the WAMC module (cite Figure 6 (b)) except to collect End to End delay statistics and to act as a “sink” whereby the packets are destroyed.

C. Simulation Model Scenarios and Parameters

There are a total of 42 scenarios in the simulation model, with different combination of values for the parameters. The main parameters that vary in these scenarios are:

- The delay experienced by measurements (from the PMU) traveling to the PDC (T_{WAN}).
- The time-out (T_{TO}) that determines the maximum waiting time at the PDC.
- The number of PMUs in the communication network (*N*).

The main parameter that is varied in the 42 Scenarios is the time-out time. Table 1 lists the values chosen for the PDC time-out.

Table 1 : Time-out (T_{TO}) parameters used for the PDC model

T_{TO} – time-out parameters (seconds)						
0.015	0.025	0.03	0.035	0.045	0.05	0.055

The time-out time was used in conjunction with two main delay parameters. The delay parameters are used in the simulation to introduce delay in the transmission of the phasor measurement packets from the PMU to the PDC. The delay parameter is a mean and variance input to a normal probability distribution function which generates random values from the distribution. These values are assigned to the every packet that is sent. Table 2 below illustrates the two delay parameters used in the simulation.

Table 2: Normal Delay Distribution Parameters

	Mean	Variance
Base	0.0147	0.00002
Extended	0.0454	0.000112

The "Base" mean and variance are selected from previous work aimed at studying transmission delay in communication networks for wide area monitoring and control systems [10]. This delay parameter is selected to be the standard or base in the simulations. The "Extended" mean and variance were calculated for usage, as values to represent the case of "abnormal" delays that could be experienced in high speed power system communication networks. The extended delay was applied to a specific number of PMUs and not to all PMUs in any given scenario. This was done to represent the possible delay only from a subset of PMUs, that could have been a result from various network or hardware conditions, such as increased traffic on the network segment where the PMUs with extended delay are placed.

Finally, using the combination of delay and time-out parameters, the number of PMUs on the network was varied. For example, there are 14 scenarios with 4 PMUs. 7 scenarios each have a value from the time-out parameters outlined in Table 1, and the delay parameter with a normal distribution with the "Base" values in Table 2. The other 7 scenarios have the same parameter expect that one PMU is delayed with the extended normal distributed delay using the "Extended" delay parameters. Table 3 below illustrates this.

Table 3: 4 PMU Scenario Set parameter settings

Scenario	Delay Parameter	Time-Out Parameter (T_{TO})	number of PMUs with Extended Delay
1	Base	0.015	0
2	Base	0.025	0
3	Base	0.030	0
4	Base	0.035	0
5	Base	0.045	0
6	Base	0.050	0
7	Base	0.055	0
8	Base, Extended	0.015	1
9	Base, Extended	0.025	1
10	Base, Extended	0.030	1
11	Base, Extended	0.035	1
12	Base, Extended	0.045	1
13	Base, Extended	0.050	1
14	Base, Extended	0.055	1

The rest of the scenarios have the same configurations. The number of PMUs with extended delays is increased for the 8 PMUs scenario set to 2 PMUs with extended delay and in the 16 PMU scenario set to 4 PMUs with extended delay. In short in the extended delay scenarios 25% of the PMUs in the network were configured to experience extended delays

V. ANALYSIS

From the simulations, the mean End to End (ETE) delay to the WAMC and the incompleteness was collected for all the scenarios. Figures 8, 9 and 10 below illustrate the results for scenarios with 4, 8 and 16 PMUs respectively.

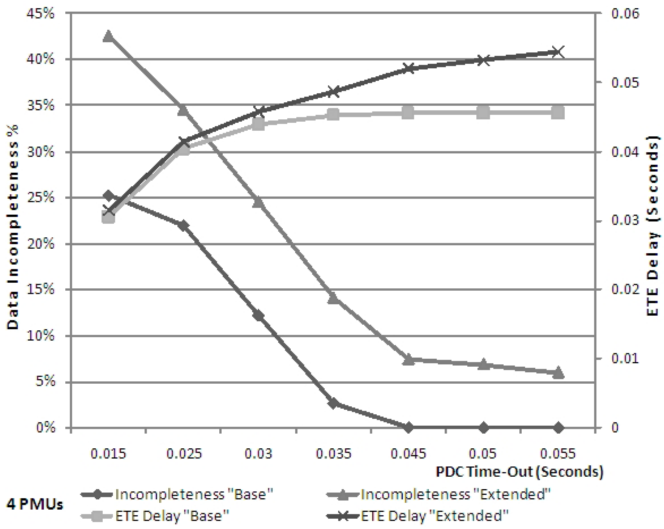

Figure 8: 4 PMUs scenarios

The incompleteness measure in this paper is measured as the percentage of data that are lost or extensively delayed and that it is not included in the measurement set that is forwarded to the WAMC applications. Therefore incompleteness can be defined as the ratio of generated PMU packets that do not reach the WAMC application to the total amount of generated PMU packets.

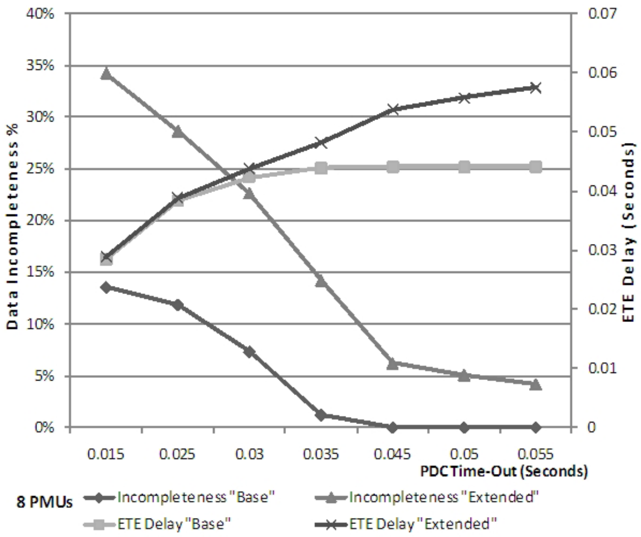

Figure 9: 8 PMUs scenarios

The graphs have 4 curves each. 2 curves illustrate the ETE delay for scenarios with only "Base" delay and "Extended" delay. The other two curves illustrate the incompleteness of the data for the corresponding "Base" and "Extended" delays. In the scenarios with all PMUs experiencing "Base" delays the incompletes levels off at approximately the same time the delay levels off, that is, when the PDC waiting time is 0.045 seconds. The value for the waiting time is nearly double the transmission time required for the measurements to travel from the PMUs to the PDC.

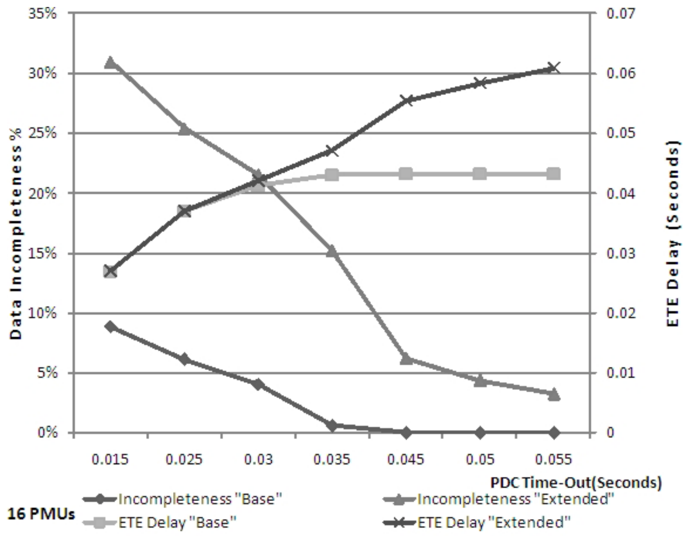

Figure 10: 16 PMUs scenarios

In the "Extended" delay scenarios, the delay and incompleteness both increase, and in all case the incompleteness does not decrease to zero. The data from PMUs with "Extended" delays in all scenarios cause the PDC to wait for the entire waiting time parameter assigned, and send the data to the WAMC when the waiting time is up. But as seen from the curves the there is significant packet loss resulting in incomplete measurements sets being forwarded to the PDC.

While the total packets lost increases as the number of PMUs are added, the percentage of the packet loss from the packets sent to the PDC decreases. This is due to the probability of extensive delays decreases as the number of PMUs increase.

In [11] a study on TSO requirements was conducted for wide area applications such as oscillation detection, line temperature monitoring and voltage instability. Specifically performance requirements and measurement sample rates were collected for these applications. The requirements show that the currency and completeness of the data is an important consideration and the requirements vary depending on the application.

For example, for oscillation damping, the completeness is important but not currency, since the physical changes are not that fast. On the other hand, in transient stability, the timeliness of data is important, but completeness may not be critical, assuming that the critical PMUs located at important measurement location (a subset of all) are received. Some application would require both qualities such as voltage stability especially in situation where the phenomenon evolves rapidly.

VI. RELATED WORKS

In [12] data flows of NASPI's NASPInet network were simulated to determine communication bandwidth requirements, impact of security mechanisms on the bandwidth and the ETE delays. The data flows come from the PMUs and are sent to a PDC. The PDC forwards the data to a Phasor Data Gateway (PDG) that acts as a publisher of PMU data, sharing and distributing PMU data to authorized subscribers. This model is implemented in the Network Simulator 2 (NS2) [13]. The scenarios implemented represented NASPInet as the main communication network for the Western Interconnect grid in the USA.

The work in this paper has two main differences. Firstly, the PDC model is more elaborate and is described in detail in the paper, it includes configurable parameters such as time-out configurations and phasor set size. It is not clear how the PDC model in the NASPInet simulations time-aligns the phasor sets received. Secondly, the impact of PDC's time-out parameter and the delay in the wide area network on the data loss or phasor set incompleteness was studied. This was not the case in the NASPInet simulations, but the authors claim that it could be possible to reconfigure the simulation framework to measure such data loss.

VII. CONCLUSIONS AND FURTHER WORK

WAMC systems are promising next generation monitoring and control systems that can offer greater resolution and real-time observation and control of electrical power networks. A reliable, high performance ICT infrastructure is an important component and enabler of such systems.

In this paper the delays that could be experienced in WAMC systems are investigated and the related parameters, such as, time-out and number of PMUs, are outlined. Furthermore, models to study these systems were implemented to illustrate the impact of delays in the communication network on the overall WAMC delay and data incompleteness.

In addition, the impact of PDC and delay parameters on the incompleteness of the data was studied. The results from the simulation showed the tradeoff between delay and the incompleteness of the data with the change of the time-out (T_{TO}) parameter in the PDC.

These results point out that the communication infrastructure between the PMU and the PDC is not the only bottleneck in the architecture of these systems, and that the PDC settings and performance should also be taken into consideration. The actual use of the

PDC model in the study is an important distinction from previous works in the field where the PDC was not taken into account or assumed an insignificant part.

Future work will be focused on refinement of these models and possibly on assessing the impact of the delay and data quality on the actual WAMC applications and algorithms. This can be done using the results provided in this paper and to applying other techniques such as prioritizing important PMUs and apply network Quality of Service (QoS) mechanisms and strategies to these priorities. Another interesting study will be on the optimization of incompleteness versus the currency/delay of the data from the PMUs and how such optimization can be built in to the architectures of WAMC systems.

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PAPER D

MODELING AND SIMULATION OF WIDE AREA COMMUNICATION FOR CENTRALIZED PMU-BASED APPLICATIONS

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ABSTRACT

Phasor based Wide Area Monitoring and Control Systems (WAMC) are becoming a reality with increased research, development and deployments. Many potential control applications based on these systems are being proposed and researched. Such applications are either local applications using data from one or a few PMUs or centralized utilizing data from several PMUs. An aspect of these systems which is less well researched is the WAMC system's dependence on high performance communication systems. This paper presents the results of research performed in order to determine the requirements of TSOs on the performance of WAMC systems in general as well as the characteristics of communication delays incurred in centralized systems that utilize multiple PMUs distributed over a large geographic area. The paper presents a summary of requirements from transmission system operators with regards to a specific set of applications and simulations of communication networks with a special focus on centralized applications. The results of the simulations indicate that configuration of central nodes in centralized WAMC systems needs to be optimized based on the intended WAMC application. This is especially apparent for applications intended to create situational awareness for control room operators.

Keywords: Wide Area Monitoring and Control Systems Power System Communication, Performance, Data Quality, PMU based Application.

I. INTRODUCTION

Electrical power networks are a part of the critical infrastructure in modern society. Our dependence and demand on electricity has risen sharply while recently this rising demand for electricity has been met with a serious strain in terms of production and expansion of transmission capacity. This is, among other factors, due to increasing environmental policies and costs. Furthermore, the re-regulation of the electrical market and the connection of national grids with neighbouring nations have resulted in a more complex and dynamic environment, in which multiple organizations coordinate and cooperate in the operation and control of the power system.

There is an international interest and implementation drive, in both academia and industry, on the prospects of Phasor Measurement Unit (PMU) based monitoring and control technology [1], [2]. These systems promise to offer more accurate and timely data on the state of the power system increasing the possibilities to manage the system at a more efficient and responsive level and apply wide area control and protection schemes.

Generally, most of the effort internationally e.g. [1][2][3] [5], has been on developing monitoring and assessment application based on PMU measurements, in addition to platforms that would support these applications, e.g. the Gridstat project [6]. Monitoring and assessment applications are known as Wide Area Monitoring Systems (WAMS), these new application were previously not possible with SCADA measurements due to its generally low data sampling rate quality and lack of exact time synchronization. There has been generally less work on developing protection systems for PMU based monitoring and assessment application, and even less so for wide area control applications. This second group of systems which not only *monitor* the power system states are referred to as Wide Area Monitoring and Control Systems (WAMC).

A. SCOPE OF THE PAPER

The scope of this paper is to present a study conducted regarding the architecture of WAMC system utilizing large number of PMUs. The hypothesis is that the large amounts of data coupled with strict real-time requirements limits the choices of architectures for implementing centralized WAMC systems. Based on requirements from TSO with regards to WAMC applications, a simulation model of the wide area communication and ICT infrastructure has been built. This model has been used to simulate the effect of different architectures with regards to dedicated or shared communication links and different data sorting algorithms. With regards to time delays, previous studies in this field have not considered the impact of certain important architectural components, specifically the Phasor Data Concentrator (PDC), and their parameters on the overall delay. In this work these components and their impact are taken into consideration

B. OUTLINE

The paper is structured as follows; Section II presents an overview of WAMC architectures outlining the main components of such systems. Section III presents a summary of a survey carried out in the Nordic region to determine the overall requirements of WAMC systems. Section IV describes the simulation model scenarios built to study wide area communication delays in WAMC systems. The delays are then applied to study the impact of the PDC on the currency and completeness of the measurement set received at the WAMC application in the control system, this is described in Section V. Finally the paper is concluded in Section VI.

II. WAMC ARCHITECTURES

A complete PMU based Monitoring and Control Systems is a system in which PMU measurements are collected from various locations in the electrical grid in a nation or region. The measurements are then communicated to a central location where they are used by an assessment or monitoring application that would raise alarms or calculate results. The alarms raised and results calculated by these monitoring systems are in turn used to provide corrective actions or control on the power grid. Such a complete PMU based system is known as a WAMC. Alternative architectures, such as using a few remote PMU signals in a local system for a specific protection application is also possible, but are outside the scope of this study.

A. WAMC COMPONENTS

A WAMC system includes four basic components: A PMU, a PDC, the PMU-based application system and finally the communication network [9].

Logically, there are three layers in a WAMC which in essence is very similar to more traditional SCADA systems. Figure 1 illustrates the logical architecture of WAMC systems. Layer 1 where the WAMC system interfaces with the power system on substation bars and power lines is called the Data Acquisition layer this is where the PMUs are placed. Layer 2 is known as the Data Management layer and that is where the PMU measurements are collected and sorted into a single time synchronized dataset. Finally Layer 3 is the Application Layer that represents the real time PMU based application functions that process the time synchronized PMU measurements provided by the Layer 2.

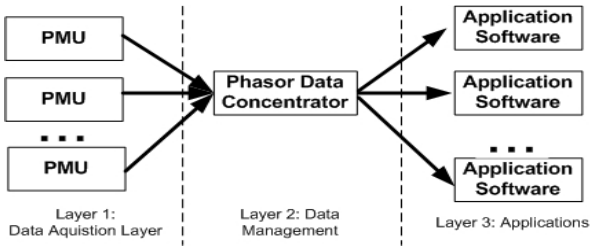

Figure 1: Layers and components of WAMC system.

B. COMMUNICATION INFRASTRUCTURE

The communication infrastructure is an important component in the architecture of a WAMC system. This is because PMU devices are distributed over a wide area, covering various locations within a power system's boundaries. The PMU devices are then connected to a central control center or several control centers over the communication network. Therefore the communication network is a possible bottleneck in the architecture of these systems. The delays and data quality of the remote data from PMUs is dependent on the communication infrastructure's capabilities and architecture.

III. PMU BASED APPLICATION REQUIREMENTS IN THE NORDIC REGION

To gather data for building the simulation model and establish a platform for the study a survey with thirteen semi-structured questions was sent out to TSOs and researchers in the Nordic Region involved in PMU projects. The survey was in the form of emails, as well as face to face interviews conducted on the TSOs/researchers' premises, the following two sections discuss parts of that survey, a full discussion of the survey can be found in [7]. The purpose of the survey was to gather communication requirements and characteristics of possible monitoring and control applications based on PMUs.

A. APPLICATION PRIORITIZATION IN THE NORDIC REGION

Five PMU based application were presented. The five application functions were: Oscillation detection, Voltage stability assessment of transmission corridors, Voltage stability assessment of meshed networks, Frequency instability assessment, and Line temperature monitoring [8]. The TSO and researchers were asked to prioritize the importance of each application function in terms of their needs.

Figure 2 presents the priorities of TSOs in the Nordic region. The figure illustrates the similarities in priorities. There is only a slight variation between the priorities and this can be due to the configuration of the power grid and to the presence of different generation portfolio. E.g. Denmark (Energinet.dk) has a larger percentage of wind power generation than any other nation, which could explain why voltage stability applications is critical to them.

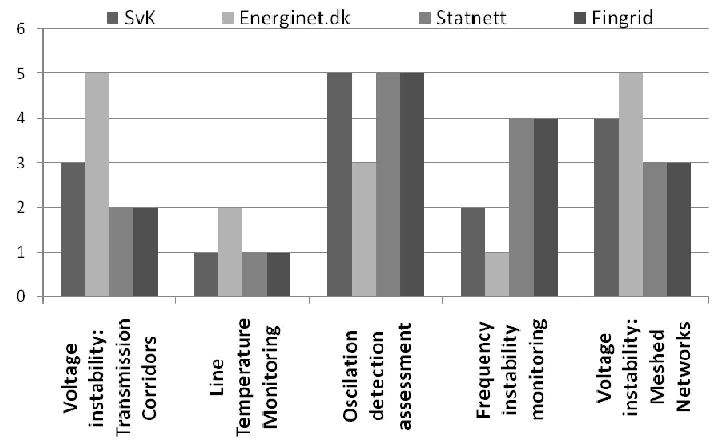

Figure 2: Applications Prioritizations in the Nordic Region

B. WAMC APPLICATIONS REQUIREMENTS IN NORDEL

The participants were presented with the same thirteen questions for each application function. The purpose of the questions was to collect requirements on such issues as time to complete assessment, time window for response to

Interviewees	Expected Latency	Expected Resolution	Expected Time Window for Response	Format/ Protocol	Time Delay for Current/Tested Control Schema	Expected Execution Time for Control Schema
TSO 1		10 Hz	Less than 0.3 seconds	IEEE 1344 /updating to C37.118	To be determined	
TSO 2	Less than 2 seconds	10 Hz	Fractions of seconds	C37.118	Not applicable	Fractions of seconds
TSO 3						
TSO 4	0.25-2 or 3 seconds	10/50 Hz for online/offline applications		C37.118	0.25 seconds	0.25 seconds
Research Institute 1	Seconds		Seconds/Minutes for automatic/manual control			Seconds
Research Institute 2	Fractions of seconds	Above 10 Hz	Less than 1/10 of the cycle time of studied oscillation	C37.118		
Research Institute 3	1 second	50 Hz	Less than 0.2/5 seconds for POD/SPS		Less than 1 second	
NASPI	1-5 seconds	10 Hz	Seconds	PDC Stream/ C37.118		

Figure 3: Oscillation Detection requirements from interviewees

phenomenon, PMU sample rate requirements and protocols as well as possible control functions that could be based on these applications. The answers were then compared with existing application classifications and requirements from North American SynchroPhasor Initiative (NASPI) [9].

An example of the results collected is depicted in Figure 3, the column headings are requirements that were collected for each application. The "Expected Latency" requirement is the amount of time it takes for the phasors to be sent from the PMU until they arrive at the application processing this information. "Data resolution" is the number of phasor samples required by the application.

The participants also were asked about the format of the data i.e. which protocol would be used for the transmission of information from the PMU to the WAMC. The third column indicates the time required for the execution of currently implemented control schemes used to remedy anomalies, e.g. voltage instability control schemes. Finally, the last column indicates the time required for the execution of control schemes that would be based on the results of the PMUs based application.

In general, the requirements collected from the TSOs and researchers dealing with PMU-based application are similar to specifications outlined by NASPI. But there are some differences, for example, in terms of voltage instability monitoring, TSOs in Nordic countries generally have a higher ambition considering the response time window in comparison to the NASPI classifications. The requirements for frequency instability monitoring from TSOs in the Nordic region, are fairly similar to NASPI classifications. While their requirement on response time window was again longer, when compared to the NASPI classifications.

In terms of line temperature monitoring, the TSO and researchers in the Nordic region have a tighter requirement on response time of the application with is in the order of seconds while in comparison to NASPI's recommendation the response time is approximately 1 hour. Another difference is in the required phasor data resolution where in the Nordic region, it is believed that a low data rate (without specifying exactly) is sufficient while NASPI suggestion 30 samples per second.

IV. MODELING DEDICATED AND SHARED COMMUNICATION NETWORKS FOR WAMC

Two simulation projects were built to model WAMC system communication. The first simulation project intended to illustrate the transmission time of phasor measurement and feedback control signals. By analyzing these low level qualities a base is established on which PMU based systems could be analyzed on a higher level. The simulations are promising and show good correlation with similar studies in other systems.

A. IMPLEMENTING A PMU COMMUNICATION MODEL IN OPNET

To get a better estimation of the delays and utilization in PMU communication a model representing such communication was implemented in OPNET Modeler [10] a communication network simulator. This model was based on possible locations of PMUs in Sweden [11]. The model contains different scenarios corresponding to both dedicated and shared network paradigms. The dedicated network paradigm is when network is utilized solely for PMU communication and where PMUs each have a dedicated channel in the network [12], [13]. On the other hand, the shared communication paradigm is when the PMU traffic is sent over a TCP/IP network sending other traffic from RTUs, IEDs or utility Voice-Over-IP (VOIP).

It is important to note that the communication model built is not the actual communication networks used by the Swedish TSO. Geographical placement in the simulation model is important since the model utilizes OPNET's distance based delay, where the delay due to distance is a component of the total delay between to network devices.

B. THE PMU COMMUNICATION NETWORK MODEL

The PMU Communication network model has 4 scenarios representing different configurations, two support the dedicated and two the shared communication paradigms. Figure 4 gives a high level view of topology and illustrates geographical scope of the models.

The octagons on the map represent subnets. Subnets are a logical grouping of communication networks. There are two core subnets, core_1 and core_2. The core subnets represent a network or meshed router (or Synchronous Digital Hierarchy (SDH) switches in the case of the dedicated communications scenario). This was done to represent the complexity and meshed topology that exits in real world networks

The traffic generation from PMUs, PDC and the WAMC devices is similar in all scenarios. The PMUs generates 30 Packets per second of size 76 bytes. 76 bytes are broken down into 16 bytes for C37.118 Header and trailer [12], 32 bytes for the IP header and 28 bytes for phasor values (e.g. Real and imaginary values, etc) representing one of the possible data loads. The packets from all PMUs are sent to the PDC in the control_center subnet. The PDC receives these packets and generates 30 new packets per second which are sent to the WAMC. The WAMC receives these packets and discards them.

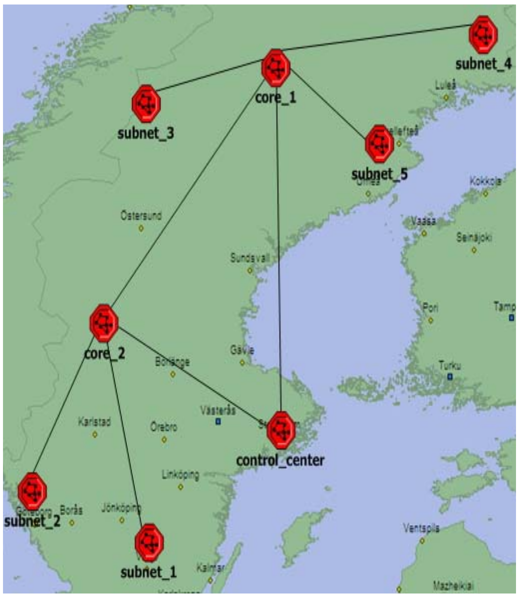

Figure 4: The fictitious PMU Communication Network

The WAMC system also generates traffic that represents control signals going back to the process. The WAMC traffic is generated in discrete time intervals and sent to a predetermined number of substation switches in various subnets. The difference between the models is in the capacity of the links and the protocols utilized. The scenarios varied in the configuration of devices and communication links, a detailed account of the scenarios and parameters discussed in this section can be found in [15].

C. SIMULATION RESULTS

End to End (ETE) delay statistics between all PMUs and the PDC was collected. Furthermore, statistics on the transmission time for control signals from the WAMC system to three preselected substation switches was also collected. These preselected substation switches are in substation_3, substation_6 and substation_8, PMUs in those substations are PMU_3, PMU_6 and PMU_8. The control signals sent back to the substations switches are not destined for the PMUs on these substations but rather to IEDs or RTUs on these networks where it is assumed these devices would execute a control scheme, such as opening a set of breakers.

1) END TO END DELAYS FROM PMUS TO PDC

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 thirteen ETE delays. Among them, ten were captured from the links from PMUs to PDC and three were captured from the control commands.

ETE delay statistics were collected from dedicated communication scenarios simulations. As mentioned earlier, ten PMUs, in both scenarios, generated a constant traffic of 30 samples per second destined to the PDC. Different channel capacities were used in the simulations based on the existing control network capacity.

Table 1 illustrates the collected ETE delays from PMUs to PDC in the 64Kb and 128Kb scenarios. The differences between ETE delays within the same scenario were related to geographical distances between PMUs and PDC. Whereas when comparing the ETE delays collected in the 64Kb and the 128Kb scenarios, the delays were reduced, in most cases, approximately by half. In other words, when the channel capacity was doubled, the ETE delay was approximately reduced by half.

Table 1: ETE delays from PMUs to PDC in the dedicated communication scenarios.

ETE delays PMUs to PDC(Sec)	Channel capacity 64Kb	Channel capacity 128Kb	50% Background traffic	70% Background traffic
PMU_1	0.041	0.021	0.016	0.028
PMU_2	0.045	0.024	0.016	0.028
PMU_3	0.037	0.02	0.012	0.021
PMU_4	0.031	0.016	0.012	0.021
PMU_5	0.065	0.035	0.019	0.033
PMU_6	0.072	0.039	0.019	0.033
PMU_7	0.042	0.042	0.018	0.031
PMU_8	0.046	0.025	0.017	0.029
PMU_9	0.039	0.02	0.013	0.023
PMU_10	0.015	0.008	0.005	0.011

As mentioned earlier, in shared communication networks, there would be other traffic on the network coming from other devices (e.g. RTUs) or services (Voice-Over-IP). By adding the constant background traffic to the links in both scenarios we could analyze the delays variation of PMU traffic between the two scenarios in the presence of different background traffic loads. In a real network, PMUs generate constant traffic in all cases, but the background traffic will actually fluctuate.

2) *END TO END DELAYS FROM WAMC TO SUBSTATIONS*

The ETE delays for the simulated control signals in the dedicated and shared communication scenarios 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.

Table 2: ETE delays of the control commands for the shared and dedicated communication scenarios

Scenario	substa-tion_switch_3	substa-tion_switch_6	substa-tion_switch_8
50% background traffic	0.0071	0.0107	0.0093
70% background traffic	0.0071	0.0107	0.0093
64Kb dedicated channel	0.042	0.042	0.042
128Kb dedicated channel	0.021	0.022	0.021

In the dedicated communication scenarios the ETE delays of the control signal commands is 42ms, 43ms and 43ms from the WAMC system to substation_switch_3, substation_switch_6 and substation_switch8 respectively in the case of the dedicated communication with 64 kb channels scenario. On the other hand, the ETE delays when the channels capacity is 128kb is 21ms, 22ms, and 21ms from the WAMC to substation_switch_3, substation_switch_6 and substation_ switch_8 respectively. Again it can be observed the delay decreases nearly by half when increasing the channel capacity from 64 Kb to 128Kb.

V. TIME DELAY AND DATA INCOMPLETENESS IN WAMC SYSTEMS

Using the data on the delays collected from the wide area communication simulation discussed in section IV, and adding functionality of the PDC for sorting and synchronization a better understanding of the dynamics of WAMC systems can be studied. The communication infrastructure in this part has been simplified as illustrated in Figure 5, in this abstraction we assume the shared communication paradigm is used for PMU communication with the control center.

The PMUs are assumed to reside in substations as previously, connected to a Local Area network (SS LAN). The SS LAN is in turn connected via a substation router to a Wide area Network (WAN). The Application that utilizes the PMU data resides at a central location connected to a Local Area Network (CC LAN). Since the application is dependent on data from several PMUs the data from the PMUs are first passed to the PDC for sorting after which they are sent to the application.

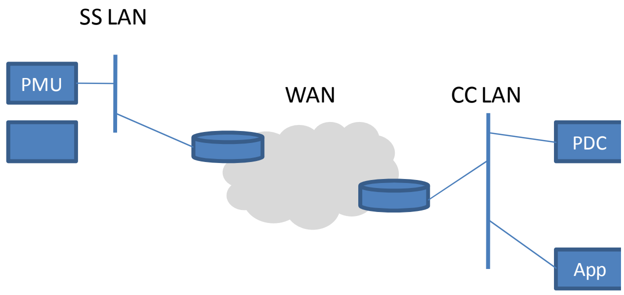

Figure 5: Utility communication model, showing substation LAN and control center LAN connected by wide area network (WAN).

A. TRANSMISSION DELAYS

To specify the transmission delays we define the following parameters:

N = Total number of PMUs
i = 1..N
d = Number of PMUs experiencing exceptional delays
T_i = *Total end to end transmission time for PMU i.*
T_{PDC} = *Processing time in PDC*
T_{SS} = *Nominal transmission time on SS LAN*
T_{CC} = *Nominal transmission time on CC LAN*
T_{WAN} = *Nominal transmission time through WAN including routing delays.*

Given the above, the Total end to end transmission time T_i *for a specific PMU i* can be expressed as:

$$T_i = T_{SSi} + T_{WANi} + 2T_{CCi} + T_{PDCi}$$

Assuming that T_{SSi}=T_{CCi} <<T_{WANi} for all *i* we chose to represent the transmission time in the WAN T_{WANi} as a normal distribution with varying mean and standard deviation based as identified in a reference network, and previous simulation studies. The values used for μ and σ^2 are given in Section IV, Note that in the above model, delays related to transducers, DFT processing of phasor values are not included [6].

With the assumptions above we now have

$$T_i = T_{WANi} + T_{PDCi}$$

The processing time in the PDC depends in turn on the implementation of the sorting algorithm in the PDC. Here a number of variations are possible, and these are discussed in the following section.

B. PDC MODEL

The most important function of the PDC is to collect or receive the phasor measurements from connected PMUs and to sort them according to the GPS time stamp. Once a time stamp set, i.e. all phasors with the same time stamp, is complete the PDC forwards the phasor set to the applications consuming the data. The PDC can also have other functionality, such as error checking and archiving for offline and historical data analysis [6]. In this paper we consider only the time synchronization functionality .Generally, there are no specified published algorithms and most vendors consider the algorithm as confidential. On the other hand the main time synchronization algorithm can be derived from descriptions [8] and the actual requirement of the sorting and synchronization task.

The algorithm used in the simulation described in this paper is as follows. The PDC will group together measurements from the same time stamp in to a set. This is done as the measurements arrive to the PDC. Furthermore, the PDC assigns a time-out for the each set when the first measurement for each set arrives. The time-out would be the amount of time the buffer is actively waiting for the rest of the phasor measurements with the same time stamp. In some cases the measurements may be delayed so there will be more than one time stamped buffer. When the set is full or the set time-out has expired, the PDC will forward the set in the buffer to the applications consuming it.

The time-out per set introduces a ceiling in terms of the delay that can be experienced. If the PMU communication network were to experience abnormal delays or packet loss then the waiting time parameter insures that the PDC forwards the phasor measurements in an acceptable time range without waiting for the delayed measurements to arrive ensuring that available data, although incomplete, is kept current.

On the other hand, the issue of incomplete data arises where the phasor measurements forwarded to the applications would be incomplete and missing certain measurements from PMUs on the grid. Figure 6 below illustrates this algorithm.

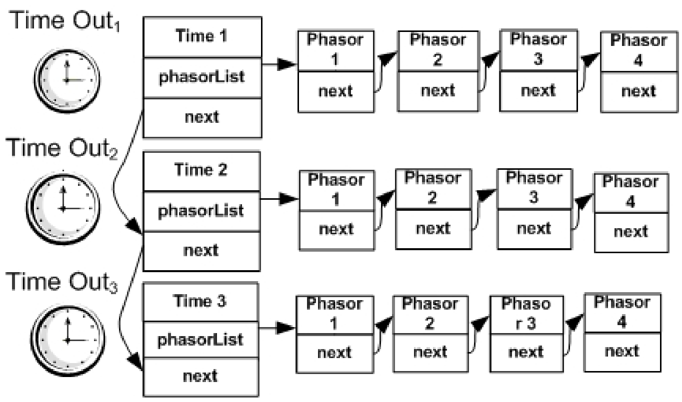

Figure 6: Time stamped buffers in the PDC holding measurements in a linked list representation.

The amount of time a packet is delayed in the PDC depends on the following parameters:

- When it arrives (early packets have to wait until all for a specific timestamp have arrived)

- How many PMUs are sending (more PMUs to wait for)
- How long to wait for the last PMU packet for that time stamp
- The time-out setting.

This linked-list sorting algorithm can be described as

$$T_{PDCi} = f(T_{TO},T_{WANi})$$

Where T_{TO} represents the time -out parameter in the PDC sorting algorithm. In the implemented algorithm the PMU packet with the longest transmission time, T_{WANi}, determines the maximum time that all packets will have to wait

$$T_w = Max\ (T_{WANi}) \qquad i=1..N$$

Finally, this gives the complete expression for T_{PDCi}.

$$T_{PDCi} = T_{sort}+Min(T_w\,|\,T_{TO})$$

To study the characteristics of T_{PDCi} in different system architectures and with different settings for T_{TO} in networks experiencing different amounts of delay a simulation study as described in the following section as performed.

C. WAMC COMMUNICATION SIMULATIONS

To get a better estimation of the delays and utilization in PMU communication a model representing such communication was implemented in OPNET Modeler, a communication network simulator.

1) THE SIMULATION MODEL.

The overall communication model is made up of sub models that represent PMU devices, the PDC and the WAMC application server. The PMUs devices are assumed to be in substation (one PMU per substation), furthermore the PDC and WAMC application server are assumed to be located at the control center. Figure 7 illustrates the simulation model in a Scenario with four PMUs. The number of PMUs varies depending on the scenario set. There are three Scenario sets, with four, eight and sixteen PMUs.

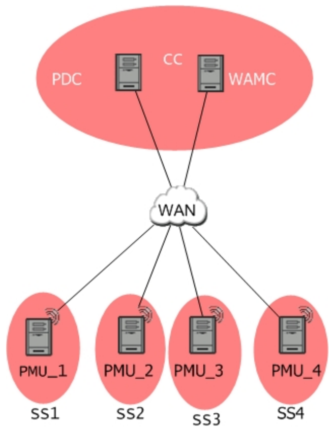

Figure 7: Topology of Scenarios with four PMUs

2) *SIMULATION MODEL SCENARIOS AND PARAMETERS*

There are a total of 42 scenarios in the simulation model, with different combination of values for the parameters. The main parameters that vary in these scenarios are:

- The delay experienced by measurements (from the PMU) traveling to the PDC (T_{WAN}).
- The time-out (T_{TO}) that determines the maximum waiting time at the PDC.
- The number of PMUs in the communication network (*N*).

The main parameter that is varied in the 42 Scenarios is the time-out time. Table 3 lists the values chosen for the PDC time-out.

Table 3 : Time-out (T_{TO}) parameters used for the PDC model

T_{TO} – time-out parameters (seconds)						
0.015	0.025	0.03	0.035	0.045	0.05	0.055

The time-out time was used in conjunction with two main delay parameters. The delay parameters are used in the simulation to introduce delay in the transmission of the phasor measurement packets from the PMU to the PDC. The delay parameter is a mean and variance input to a normal probability distribution function which generates random values from the distribution. These values are assigned to every packet that is sent. Table 4 below illustrates the two delay parameters used in the simulation.

Table 4: Normal Delay Distribution Parameters

	Mean	Variance
Base	0.0147	0.00002
Extended	0.0454	0.000112

The Base mean and variance are selected from previous work aimed at studying transmission delay in communication networks for wide area monitoring and control systems [10]. This delay parameter is selected to be the standard or base in the simulations. The Extended mean and variance were calculated for usage as values to represent the case of "abnormal" delays that could be experienced in high speed power system communication networks. The extended delay was applied to a specific number of PMUs and not to all PMUs in any given scenario. This was done to represent the possible delay only from a subset of PMUs, that could have been a result from various network or hardware conditions, such as increased traffic on the network segment where the PMUs with extended delay are placed.

Finally, using the combination of delay and time-out parameters, the number of PMUs on the network was varied. For example Table 5 illustrates the scenarios for 4 PMUs. There are 14scenarios for 4 PMUs, 7 scenarios experiencing base delay as specified in Table 4, each scenario has a different timeout parameters. The next 7 scenarios also have the same time out parameter, but in each scenario 1 PMU will experience extended delay.

Table 5: 4 PMU Scenario Set parameter settings

Scenario	Delay Parameter	Time-Out Parameter (T_{TO})	Number of PMUs with Extended Delay
1	Base	0.015	0
2	Base	0.025	0
3	Base	0.030	0
4	Base	0.035	0
5	Base	0.045	0
6	Base	0.050	0
7	Base	0.055	0
8	Base, Extended	0.015	1
9	Base, Extended	0.025	1
10	Base, Extended	0.030	1
11	Base, Extended	0.035	1
12	Base, Extended	0.045	1
13	Base, Extended	0.050	1
14	Base, Extended	0.055	1

The rest of the scenarios have the same configurations. The number of PMUs with extended delays is increased for the 8 PMUs scenario set to 2 PMUs with extended delay and in the 16 PMU scenario set to 4 PMUs with extended delay. In short in the extended delay scenarios, 25% of the PMUs in the network were configured to experience extended delays

D. ANALYSIS

From the simulations, the mean End to End (ETE) delay to the WAMC and the incompleteness was collected for all the scenarios. Figures 8 and 9 below illustrate the results for scenarios with 4 and 8 PMUs respectively. The incompleteness measure in this paper is measured as the percentage of data that lost or extensively delayed that it is not included in the measurement set that is forwarded to the WAMC applications. Therefore incompleteness can be defined as the ratio of generated PMU packets that do not reach the WAMC application to the total amount of generated PMU packets.

The graphs have 4 curves each. 2 curves illustrate the ETE delay for scenarios with only base delay and extended delay. The other two curves illustrate the incompleteness of the data for the corresponding base and extended delays. In the scenarios with all PMUs experiencing base delays the incompletes levels off at approximately the same time the delay levels off, that is, when the PDC waiting time is 0.045 seconds. The value for the waiting time is nearly double the transmission time required for the measurements to travel from the PMUs to the PDC.

In the extended delay scenarios, the delay and incompleteness both increase, and in all case the incompleteness does not decrease to zero. The data from PMUs with extended delays in all scenarios cause the PDC to wait for the entire waiting time parameter assigned, and send the data to the WAMC when the waiting time is up. But as seen from the curves the there is significant packet loss resulting in incomplete measurements sets being forwarded to the PDC.

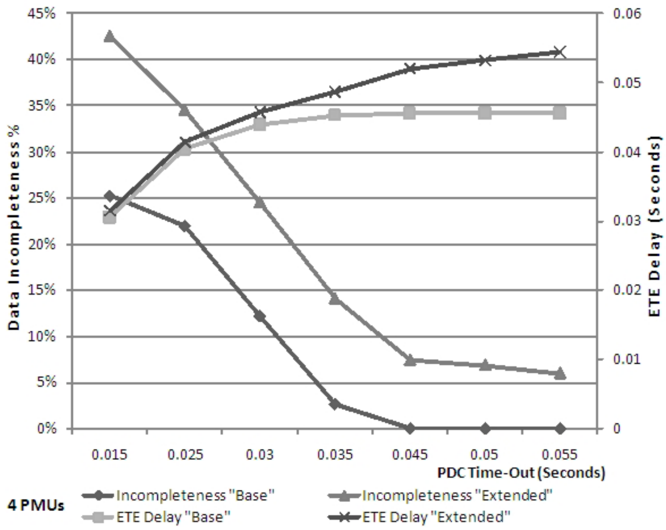

Figure 8: 4 PMUs Scenarios

While the total packets lost increases as the number of PMUs are added, the percentage of the packet loss from the packets sent to the PDC decreases. This is due to the probability of extensive delays decreases as the number of PMUs increase.

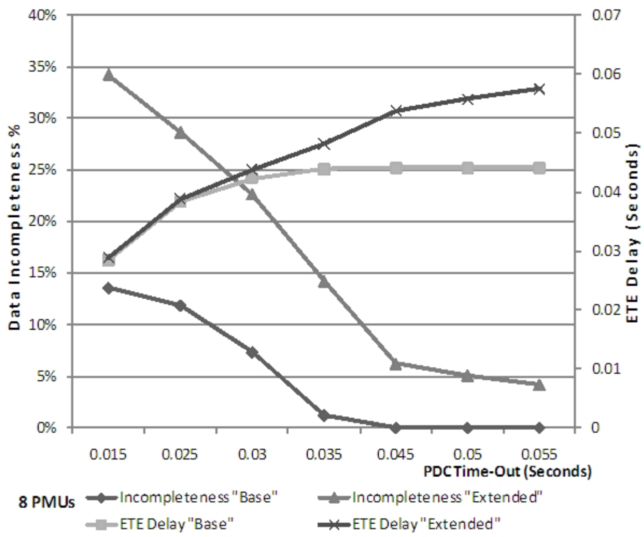

Figure 9: 8 PMUs Scenarios

In [7] a study on TSO requirements was conducted for wide area applications such as Oscillation detection, line temperature monitoring and voltage instability. Specifically performance requirements and measurement sample rates were collected for these applications. The requirements show that the currency and completeness of the data is an important consideration and the requirements vary depending on the application.

For example, for oscillation damping, the completeness is important but not currency, since the physical changes are not that fast. On the other hand, in transient stability, the timeliness of data is important, but completeness may not be critical, assuming that the critical PMUs located at important measurement location (a subset of all) are received. Some application would require both qualities such as voltage stability especially in situation where the phenomenon evolves rapidly.

VI. CONCLUSIONS AND FURTHER WORK

Wide Area Monitoring and Control systems intended for centralized applications such as Situational Awareness require data from several separate locations within the power system. The simulations presented in this paper indicate that the geographic distances, background traffic and architecture of the WAMC system will have an impact on the delay and/or completeness of the PMU data provided to the applications at the central location. Depending on configuration of the Phasor Data Concentrator (PDC) and the characteristics of the network in terms of delay, some central applications may not receive data of a sufficient quality to provide useful support in transient situations.

The results point out that the communication infrastructure between the PMU and the PDC is not the only bottleneck in the architecture of these systems, and that the PDC settings and performance should also be taken into consideration. The actual use of the PDC model in the study is an important distinction from previous works in the field where the PDC was not taken into account or assumed to be an insignificant part.

Future work will be focused on refinement of these models and possibly on assessing the impact of the delay and data quality on the actual WAMC applications and algorithms. This can be done using the results provided in this paper and to applying other techniques such as prioritizing important PMUs and apply network Quality of Service (QoS) mechanisms and strategies to these priorities. Another interesting study will be on the optimization of incompleteness versus the currency/delay of the data from the PMUs and how such optimization can be built in to the architectures of WAMC systems.

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APPENDIX

This Appendix contains code for the design of the PDC simulation described in Paper C.

PDC MODEL

Process Model Report: mc_PDC_nd_proc_TimeSlotBuff_wamc_0803123#
external file set: link_delay
==
Process Model Attributes
==
Attribute: Phasor set size
Data Type: integer
Attribute: Phasor set waiting time
Data Type: double
Attribute: Number of PMUs
Data Type: integer
Attribute: Phasor Buffer Type
Data Type: integer
Attribute: Late Packet Policy
Data Type: integer
==
Process Model Interface Attributes
==
Interface Attribute: begsim intrpt
Assign Status: set
Initial Value disabled
Data Type: toggle
Comments: YES
This attribute specifies whether a 'begin simulation interrupt' is generated for a processor module's root process at the start of the simulation.

Interface Attribute: doc file
Assign Status: set
Initial Value nd_module
Data Type: string
Comments: YES
This attribute defines the name of the product help file which will be displayed when the user invokes help for this object.

Interface Attribute: endsim intrpt
Assign Status: set
Initial Value enabled
Data Type: toggle
Comments: YES
This attribute specifies whether an 'end simulation interrupt' is generated for a processor module's root process at the end of the simulation.

Interface Attribute: failure intrpts
Assign Status: set
Initial Value disabled
Data Type: enumerated
Comments: YES
This attribute specifies whether failure interrupts are generated for a processor module's root process upon failure of nodes or links in the network model.

Interface Attribute: intrpt interval
Assign Status: set
Initial Value disabled
Data Type: toggle double

Comments: YES
This attribute specifies how often regular interrupts are scheduled for the root process of a processor module.

Interface Attribute: priority
Assign Status: set
Initial Value 0
Data Type: integer
Comments: YES
This attribute is used to determine the execution order of events that are scheduled to occur at the same simulation time.

Interface Attribute: recovery intrpts
Assign Status: set
Initial Value disabled
Data Type: enumerated
Comments: YES
This attribute specifies whether recovery interrupts are scheduled for the processor module's root process upon recovery of nodes or links in the network model.

Interface Attribute: subqueue
Assign Status: set
Initial Value (...)
Data Type: compound
Comments: YES
This operation attribute permits the addition and deletion of subqueues within the queue module.

Interface Attribute: super priority
Assign Status: set
Initial Value disabled
Data Type: toggle
Comments: YES
This attribute is used to determine the execution order of events that are scheduled to occur at the same simulation time.
==
Header Block
==

```
/***** packet stream definitions *******/
#define RCV_IN_STRM 0
#define SRC_IN_STRM 1
#define XMT_OUT_STRM 0
/***************Other Constants*************/
#define WAITING_TIME_UP 0
#define PHASOR_SET_FULL (phasorSetFull)
#define SINGLE_SIZED_BUFFER 0
#define TIMED_MULTIPLE_BUFFER 1
/******** transition macros ***************/
#define SRC_ARRVL (op_intrpt_type () == \
    OPC_INTRPT_STRM && op_intrpt_strm () == SRC_IN_STRM)
#define RCV_ARRVL (op_intrpt_type () == \
    OPC_INTRPT_STRM && op_intrpt_strm () == RCV_IN_STRM)
#define PRESET_TIME_OUT (op_intrpt_type()== OPC_INTRPT_SELF )
#define END_DECLARED (op_intrpt_type() == OPC_INTRPT_ENDSIM)
/*****Structure variables***********/
struct packList
{
    Packet* pkt;
    int pmuId;
    double ctime;
    struct packList* next;
};
struct timedPackList
{
    unsigned int listId;
```

```
    int numPhasorsInList; // 1 and above 0 means nothing in the list
    double timeStamp;
    struct packList* listOfPacks;
    struct timedPackList* next;
};
struct stat_pmu_pdc_ete  //Not Used
{
    int   pmuId;
    double etePDC;
    struct stat_pmu_pdc_ete * next;
};
struct packList* headPack;
struct timedPackList* headList;
struct stat_pmu_pdc_ete stat_pdc_ete;
=================================================================
State Variable Block
=================================================================
Stathandle    \pete_gsh;
Stathandle    \pdc_packs_receive;
Stathandle    \pdc_packs_sent;
/* Number of PMUs this PDC will be collecting measurments from SET By User??? */
int   \numPMUs;
/* waiting time is time to wait for data set from all pmu recieved for a specific interval of time */
/* at this could depend on the number of phasors per second.                */
double    \waitingTime;
/*FOLLOWING SET BY USER */
int   \phasorListSize;
int   \bufferType;
int   \latePackPolicy;
/* indicator to compare with use setting "phasorListSize" to enable "phasorSetFull" */
int   \phasorsInList;
/* flag that the list is full boolean 1, 0 */
int   \phasorSetFull;
/* flag to indicate the number of sublists active */
int   \cSubLists;
/* flag to indicate the total number of sublists in the simulation */
int   \tSubLists;
/* id of the active sublist,           */
/* this is necessary unique over the life time */
/* of the simulation                   */
int   \subListId;
/* time interval measured from current time where if the data falls in between it is acceptable other wise it is old
data */
double    \oldDataTime;
/* variable for number of packets recieved statistic */
int   \packRecvCount;
/* variable for number of packets sent statistic */
int   \packSentCount;
/* variable to count number of old packets */
int   \packOld;
/* packets Discarded */
int   \packsDiscarded;
int   \old_intrpt_code;
int   \fullListIndex;
Stathandle    \PDC_PMU_ETE_delay[16];
double    \accumETEDelay;
Stathandle    \mean_PMUPDC_delay;
Stathandle    \packetsLost;
Stathandle    \completePhasorSets;
Stathandle    \incompletePhasorSets;
Stathandle    \PDCoverallSetCompletness;
Stathandle    \PDCoverallDataCompletness;
int   \completePhasors;
```

```
int   \incompletePhasors;
Stathandle     \PDC_PMU_PACKS_RECV[16];
Stathandle     \PDC_PMU_PACKS_DROPPED[16];
int   \pmuPackRecv[15];
int   \pmuPackDropped[15];
Stathandle     \incompleteness;
====================================================================
Temporary Variable Block
====================================================================
int intrpt_code;
====================================================================
                         Function Block
====================================================================
 void schedIntrpt(int listId) /*** Check this function***/
{ //schedule an interrupt for a specific sublist.
     FIN(schedIntrpt int)
     if (listId>0 && waitingTime >0) // Multiple buffer with waiting time
     {
          op_intrpt_schedule_self(op_sim_time() + waitingTime,listId);
          printf("List %d is scheduled at %f\n", listId, op_sim_time() + waitingTime );
     }
     else if (bufferType==SINGLE_SIZED_BUFFER && waitingTime >0) //single sized buffer with waiting
time ****************
          op_intrpt_schedule_self(op_sim_time() + waitingTime,SINGLE_SIZED_BUFFER);
     else
          ;          //do nothing use has not set a waiting time

     FOUT

}
void cancelIntrpt(int listId)
{
     Evhandle thisEvent = op_ev_current ();
     Evhandle nextEvent = op_ev_next_local (thisEvent);
     Evhandle eventToCancel;
     FIN (cancelIntrpt int )

     /* Loop through all of the events scheduled for this module */
     /* and cancel any that are retransmission timers. */
     while (op_ev_valid (nextEvent))
     {
          if ((op_ev_type (nextEvent) == OPC_INTRPT_SELF) && (op_ev_code (nextEvent) ==listId))
          {
               eventToCancel = nextEvent;
               nextEvent = op_ev_next_local (eventToCancel);
               op_ev_cancel (eventToCancel);
               break;
          }
          else {
          /* Obtain the next event; if there are no more events, op_ev_next_local () */
          /* will return an invalid event handle and the loop will terminate. */
          nextEvent = op_ev_next_local (nextEvent);
          }
     }
     FOUT
}
int getListId(void)
{// get a number for the list ID. if the id is below 10,000 then it generates the next number,
  // else resets the counter and then generates the next number
  // List ID starts at 1
     FIN(getListId(void))
     if (cSubLists< 100000)
     {
```

```
        FRET (subListId)
    }
    else
    {
        subListId=1;
        FRET (subListId)
    }
}
void deleteSinglePacket(Packet** pkt)
{
    FIN(deleteSinglePacket Packet**)
    op_pk_destroy(*pkt);
    FOUT
}
void deleteList(struct packList** headRef)
{
    struct packList* current = *headRef; // deref headRef to get the real head
    struct packList* next;
    int i=0;
    FIN(deleteList(struct packList**))
    while (current != NULL)
    {
        printf("deleted from creation time %f\n ",current->ctime);
        next = current->next; // note the next pointer
        prg_mem_free(current); // delete the node
        current = next; // advance to the next node
        i++;
    }
    *headRef = NULL; // Again, deref headRef to affect the real head back
    printf("deleted %d\n ",i);
    FOUT;// in the caller.
}
void deleteTimedList(struct timedPackList** headRef)
{
    struct timedPackList* current = *headRef; // deref headRef to get the real head
    struct timedPackList* next;
    FIN(deleteList(struct timedPackList**))
    while (current != NULL)
    {
        next = current->next; // note the next pointer
        if (current->listOfPacks != NULL)
        {
            deleteList(&current->listOfPacks);
        }
        prg_mem_free(current); // delete the node
        current = next; // advance to the next node
    }
    *headRef = NULL; // Again, deref headRef to affect the real head back
    FOUT;// in the caller.
}
void registerPackCompStat(int phasors)
{
    FIN(registerPackCompStat int)

    printf("**NOW IN ->registerPaclCompStat<- **\n");
    if (phasors==numPMUs)
        op_stat_write(completePhasorSets,++completePhasors);
    else
    op_stat_write(incompletePhasorSets, ++incompletePhasors);
    tSubLists++; // what is this doing here, this is the total sublists
    op_stat_write(PDCoverallSetCompletness,(1-((double)incompletePhasors)/((double)tSubLists)));
    op_stat_write(PDCoverallDataCompletness,(1-(((double)packOld)/((double)(packRecvCount+packOld)))));
    FOUT
```

```
}
void registerETEStat(int pmuID, double ctime)
{
      double ete_delay;
      int i=0;
      FIN(registerETEStat( int, double))
      printf("**NOW IN ->registerETESstat<- **\n");
      ete_delay = op_sim_time () - ctime;
      op_stat_write (pete_gsh, ete_delay);
      accumETEDelay= accumETEDelay + ete_delay;
      i=pmuID-1;
      op_stat_write (PDC_PMU_ETE_delay[i], ete_delay);
      packRecvCount++;
      pmuPackRecv[i]++;
      op_stat_write (pdc_packs_receive, packRecvCount);
      op_stat_write (PDC_PMU_PACKS_RECV[i], pmuPackRecv[i]);
//    op_stat_write_scalar("Mean ETE PMU-PDC Delay", accumETEDelay/packRecvCount);
      FOUT
}
void sortedInsert(struct packList** headRef, struct packList* newNode)
{ // Special case for the head end
      FIN(sortedInsert(struct packList** headRef, struct packList* newNode ))
      if (*headRef == NULL || (*headRef)->ctime >= newNode->ctime)
      {
        newNode->next = *headRef;
       *headRef = newNode;
      }
      else
      {
            // Locate the node before the point of insertion
            struct packList* current = *headRef;
            while (current->next!=NULL && current->next->ctime<newNode->ctime)
            {
                  current = current->next;
            }
            newNode->next = current->next;
            current->next = newNode;
      }
      FOUT;
}
void sortedInsertTimed(struct timedPackList** headRef, struct packList* newNode,double timeStamp)
{
      int index;
      FIN(sortedInsertTimed(struct timedPackList**, struct packList*, double))
      if (timeStamp <= oldDataTime) // old data
      {
            printf("Old Data with timeStamp: %f arrived at time:%f\n",timeStamp, op_sim_time());
            packOld++;
            index=(newNode->pmuId)- 1 ;
            printf("***THE PACKET CAME FROM PMU %d **\n", index +1);
            pmuPackDropped[index]++;
            deleteSinglePacket(&newNode->pkt);
            op_stat_write(packetsLost,packOld);
            op_stat_write (PDC_PMU_PACKS_DROPPED[index], pmuPackDropped[index]);
      }
      else if (*headRef == NULL) // if the Ribbon is completely empty
                                   //   Create a new list and add the packet to the list
      {
            struct timedPackList* newList=prg_mem_alloc(sizeof(struct timedPackList));
        //newNode->next = *headRef;// this is because if the data was older then the current head of the ribbon
        subListId++;
        printf("First Time Slot! packet time stamp %f\n", timeStamp);
        newList->listId=getListId();
```

```
        newList->numPhasorsInList++;
        newList->timeStamp=timeStamp; //attach the timestamp of this packet as the list identifier
        newList->listOfPacks=newNode; // attach the new pack to the newly created subbuffer
        schedIntrpt(newList->listId);//Schedule an intrpt for the new sublist
    printf("List ID: %d\n", newList->listId);
      *headRef = newList; // point to the new head of the ribbon
    // oldDataTime=timeStamp; // first initialization of this global variable
    //NOTE: oldDataTime is only updated once in the creation of timedPackList and
    / /other subsequent times it is update in the ***send part***
        cSubLists++; //increment the current number of Sub lists
        registerETEStat(newNode->pmuId, timeStamp);
    }
    else // new data insert it in the right place, if list exists else create new list
    {       // Locate the node before the point of insertion
            struct timedPackList* current = *headRef;
            struct timedPackList* prev = *headRef;
            int found=0;
            while (current != NULL)
            {
                if (current->timeStamp==timeStamp)
                {
                    //insert into the sublist use the the standard list sortedInsert function
                    current->numPhasorsInList++; // update how many phasors there are in the sublist
                    registerETEStat(newNode->pmuId, timeStamp);
                    sortedInsert(&current->listOfPacks, newNode);
                    printf("Existing Time Slot! packet time stamp %f\n",timeStamp);
                    printf("listId: %d\n",current->listId);
                    printf("Phasor in list %d\n",current->numPhasorsInList);
                    found=1;
                    if (current->numPhasorsInList==numPMUs)
                    {
                        fullListIndex=current->listId;
                    }
                    else
                    {
                        fullListIndex=0;
                    }
                    break;
                }
                prev=current;
                current = current->next; // advance to the next node in the Ribbon
            }
            if (found==0 && current==NULL )
            {     //this is the case if there is no sublist existing for the current timestamp,
                //so we create a new node is created in the ribbon to accomodate new incoming
                //packets belonging to this timestamp
                struct timedPackList* newList=prg_mem_alloc(sizeof(struct timedPackList));
                printf("New time slot!, packet timestamp %f\n", timeStamp);
                subListId++;
                registerETEStat(newNode->pmuId, timeStamp);
                newList->listId=getListId();
                newList->numPhasorsInList++;
                newList->timeStamp=timeStamp; //attach the timestamp of this packet as the list identifier
                newList->listOfPacks=newNode; // attach the new pack to the newly created subbuffer
                prev->next=newList;
                cSubLists++; //increment the current number of Sub lists
              schedIntrpt(newList->listId); //Schedule an intrpt for the new sublist
        printf("listid: %d\n", newList->listId);
            }
    }
    FOUT;
}
static void packetArrived (void)
```

```
{
    int pmuId;
    //  This is the main entry point to the PDC here the packets are recieved,
    //  NOTE: Ete_gsh here will be ETE delay from PMU to PDC
    struct packList* inpacket=prg_mem_alloc(sizeof(struct packList));
    FIN (packetArrived (void));
    inpacket->pkt = op_pk_get (RCV_IN_STRM);
    inpacket->ctime=op_pk_creation_time_get (inpacket->pkt);
    printf("CURRENT    TIME:%f    .    PACKET    CREATION    TIME:    %f.    DIFFERENCE
    %f\n",op_sim_time(),inpacket->ctime, op_sim_time()-inpacket->ctime);
    op_pk_nfd_get_int32 (inpacket->pkt, "idcode", &pmuId);
    inpacket->pmuId=pmuId;
//  registerETEStat(pmuId, inpacket->ctime);
    op_pk_nfd_set_dbl (inpacket->pkt, "soc",op_sim_time());
    if (bufferType==SINGLE_SIZED_BUFFER)
    {
        sortedInsert(&headPack,inpacket);
        phasorsInList++;// phasorsInList counter increments after successful completion of insert
    }
    else
    {   //TIMED_MULTIPLE_BUFFER
        printf("New packet to SortedInsertTimed, packet timeStamp is %f\n",inpacket->ctime);
        sortedInsertTimed(&headList,inpacket, inpacket->ctime);
    }
    FOUT;
}
static void sendPhasorSet (struct packList** headRef)
{
    /*This function would send the packets to the WAMC*/
    /*sync here also used for destination address*/
    /*sending starts from the packet at the head of the list*/
    struct packList* current = *headRef; // deref headRef to get the real head
    struct packList* next;
    int i=0;
    FIN (sendPhasorSet (struct packList**))
    while (current !=NULL)
    {
        next = current->next; // note the next pointer
        op_pk_nfd_set_int32 (current->pkt,"sync",1);
        op_pk_send (current->pkt, XMT_OUT_STRM);
        current->pkt=NULL;
        prg_mem_free(current);
        current=next;
        packSentCount++;   //Statistic Sent
        op_stat_write (pdc_packs_sent, packSentCount);
        i++;
    }
    printf("sent %d\n ",i);
    FOUT;
}
static void sendSubPhasorSet(struct timedPackList** headRef, int listId) /*CHECK THIS*/
{
    /*This function would send the packets to the WAMC*/
    /*sync here also used for destination address*/
    /*sending starts from the packet at the head of the list*/
    struct timedPackList* current = *headRef; // deref headRef to get the real head
    struct timedPackList* prev;
    int i=0;
    int phasors=0;
    FIN (sendPhasorSet (struct timedPackList**, int))
    prev=current;
    while (current !=NULL) /*CHECK THIS*/
    {
```

```
                if (current->listId==listId)
                {
                    printf("sending list = %d, current sim time %f\n ",listId, op_sim_time());
                    oldDataTime=current->timeStamp;
                    printf("value of oldDataTime is now %f\n", oldDataTime);
                    registerPackCompStat(current->numPhasorsInList);
                    sendPhasorSet(&current->listOfPacks);
                    printf("Deletinglist = %d that has time stamp %f \n",listId, current->timeStamp);
                    deleteList(&current->listOfPacks);
                    break;
                }
                prev=current;
                current=current->next;
                i++;
            }
            if (i==0)
            {
                prev=current->next;
                prg_mem_free(current); // delete the element in the ribbon that was sent
                *headRef=prev;
            }
            else
            {
                prev->next=current->next;
                prg_mem_free(current); // delete the element in the ribbon that was sent
                *headRef=prev;
            }
            FOUT;
}
static void updateFinalStats(void)
{
    FIN(updateFinalStat(void));
    op_stat_write_scalar("Incompleteness", ((double)packOld)/((double)packRecvCount));
    printf("Number of Packets Received is: %d\n", packRecvCount);
    printf("Number of Packets Sent is:     %d\n", packSentCount);
    printf("Number of Old Packets Droped is %d\n", packOld);
    printf("Incompleteness= %f\n",(((double)packOld)/(((double)packRecvCount)+((double)packOld)))*100);
    FOUT;
}
static void cleanUp(void)
{ // for cleaning up memory and debugging
    FIN(cleanUp())
    //endsimDebug();

    updateFinalStats(); //record final Statistics
    if (bufferType==TIMED_MULTIPLE_BUFFER)
    {
        printf("Now Releasing Memory \n");
        deleteTimedList(&headList);
        if (headPack== NULL)
            printf("head pack is NULL\n");
        else
            printf("head pack is NOT NULL\n");
    }
    else
    {
        deleteList(&headPack);
        if (headPack== NULL)
            printf("head pack is NULL\n");
        else
            printf("head pack is NOT NULL\n");
    }
    printf("Phasor Set Size was %d\n",phasorListSize);
```

```
    printf("waiting time was %f\n",waitingTime);
    FOUT;
}
void rcv_init(void)  // called in the Enter Executive for phasesort
{
    FIN(rcv_init(void))
    packetArrived();
    if (bufferType==TIMED_MULTIPLE_BUFFER)
    {
        if (!(fullListIndex==0))
        {
            printf("fullListIndex= %d \n", fullListIndex);
            phasorSetFull=OPC_TRUE;
        }
    }
FOUT
}
void send_init(int code)  // called in the Enter Executive for phasesort
{
    FIN(send_init(int code))
    if (bufferType==SINGLE_SIZED_BUFFER)
    {
        if (op_intrpt_type()==OPC_INTRPT_SELF)
        {
            op_intrpt_schedule_self(op_sim_time() + waitingTime,0);
            printf("Next Interrupt Scheduled at %f\n", op_sim_time() + waitingTime);
        }
        if (phasorSetFull=OPC_TRUE)
        {
            phasorSetFull=OPC_FALSE;
        }
        sendPhasorSet(&headPack);
        deleteList(&headPack);
        phasorsInList=0;
    }
    else
    {
            sendSubPhasorSet(&headList,code);
            cSubLists--;
    }
    FOUT
}
```

==

Enter Execs for the forced state "init"

==i

```
int i=0;
//Process Model Attributes
op_ima_obj_attr_get(op_id_self(),"Phasor set size",&phasorListSize);
op_ima_obj_attr_get(op_id_self(),"Phasor set waiting time",&waitingTime);
op_ima_obj_attr_get(op_id_self(),"Number of PMUs",&numPMUs);
op_ima_obj_attr_get(op_id_self(),"Phasor Buffer Type",&bufferType);
op_ima_obj_attr_get(op_id_self(),"Late Packet Policy",&latePackPolicy);
/*******Statistics init*****/

pete_gsh = op_stat_reg ("ETE PDC Delay", OPC_STAT_INDEX_NONE,
    OPC_STAT_GLOBAL);
mean_PMUPDC_delay= op_stat_reg("Mean ETE PMU-PDC Delay",OPC_STAT_INDEX_NONE,
OPC_STAT_GLOBAL);
pdc_packs_receive=op_stat_reg("PDC Packets Re-
ceived",OPC_STAT_INDEX_NONE,OPC_STAT_LOCAL);
pdc_packs_sent=op_stat_reg("PDC Packets Sent",OPC_STAT_INDEX_NONE,OPC_STAT_LOCAL);
for (i = 0; i < numPMUs; i++)
    {
```

```
    PDC_PMU_ETE_delay[i] = op_stat_reg ("ETE PDC Delay Per PMU", i, OPC_STAT_GLOBAL);
    PDC_PMU_PACKS_RECV[i]= op_stat_reg ("Packets Received Per PMU",i,OPC_STAT_GLOBAL);
    PDC_PMU_PACKS_DROPPED[i]=op_stat_reg("Packets Dropped Per PMU",i,
OPC_STAT_GLOBAL);
  }
//packet Loss related
packetsLost=op_stat_reg("PDC Packet Loss",OPC_STAT_INDEX_NONE, OPC_STAT_GLOBAL);
completePhasorSets=op_stat_reg("Number of Complete Sets",OPC_STAT_INDEX_NONE,
OPC_STAT_GLOBAL);
incompletePhasorSets=op_stat_reg("Number of Incomplete
Set",OPC_STAT_INDEX_NONE,OPC_STAT_GLOBAL);
PDCoverallSetCompletness=op_stat_reg("PDC Overall Set Complet-ness",OPC_STAT_INDEX_NONE,
OPC_STAT_GLOBAL);
PDCoverallDataCompletness=op_stat_reg("PDC Overall Data Complet-
ness",OPC_STAT_INDEX_NONE,OPC_STAT_GLOBAL);
incompleteness=op_stat_reg("Incompleteness",OPC_STAT_INDEX_NONE,OPC_STAT_GLOBAL);
//Minimal acceptable PhasorListSize?
if (phasorListSize<=0)
  phasorListSize=4;
// process model variables. control flags etc
oldDataTime=0;
phasorSetFull=OPC_FALSE;
fullListIndex=0;
==================================================================
Exit Execs for the forced state "init"
==================================================================
NONE
==================================================================
transition   init -> idle
==================================================================
name:    tr_0
condition:
executive:
color:    black
drawing style:spline
doc file:  pr_transition
==================================================================
Enter Execs for the unforced state "idle"
==================================================================
NONE
==================================================================
Exit Execs for the unforced state "idle"
==================================================================
NONE
==================================================================
transition   idle -> idle
==================================================================
name:    tr_3
condition:     default
executive:
color:    black
drawing style:spline
doc file:  pr_transition
==================================================================
transition   idle -> phasesort
==================================================================
name:    tr_9
condition:     RCV_ARRVL
executive:
color:    black
drawing style:spline
doc file:  pr_transition
```

```
=================================================================
transition   idle -> sendset
=================================================================
name:     tr_11
condition:      PRESET_TIME_OUT
executive:
color:     black
drawing style:spline
doc file:  pr_transition
=================================================================
transition   idle -> idle
=================================================================
name:     tr_14
condition:      END_DECLARED
executive:      cleanUp()
color:     black
drawing style:spline
doc file:  pr_transition
=================================================================
                Enter Execs for the forced state "phasesort"
=================================================================
rcv_init();
=================================================================
Exit Execs for the forced state "phasesort"
=================================================================
NONE
=================================================================t
ransition   phasesort -> idle
=================================================================
name:     tr_10
condition:      default
executive:
color:     black
drawing style:spline
doc file:  pr_transition
=================================================================
transition   phasesort -> sendset
=================================================================
name:     tr_17
condition:      PHASOR_SET_FULL
executive:
color:     black
drawing style:spline
doc file:  pr_transition
=================================================================
Enter Execs for the forced state "sendset"
=================================================================
printf("has entered send sort \n");
if ((op_intrpt_type()==OPC_INTRPT_SELF) && (fullListIndex==0))
{
      intrpt_code=op_intrpt_code();
      printf("time out for list %d , sending immediately\n",intrpt_code);
      send_init(intrpt_code);
}
else if (!(fullListIndex==0) && (bufferType==TIMED_MULTIPLE_BUFFER))
{
      //may remove this and just pass the Full List Index
      intrpt_code=fullListIndex;
      printf("List %d is now complete canceling timeout and sending Immediately\n",intrpt_code);
      cancelIntrpt (intrpt_code);
      send_init(intrpt_code);
      //change still to send transition to false.
      phasorSetFull=OPC_FALSE;
```

```
    fullListIndex=0;
}
else
{
    intrpt_code=0;
        printf("in the else= %d\n",intrpt_code);
    send_init(intrpt_code);
    if (phasorSetFull=OPC_TRUE)
    {
        phasorSetFull=OPC_FALSE;
    }
}
intrpt_code=0;
=================================================================
Exit Execs for the forced state "sendset"
=================================================================
NONE
=================================================================
transition   sendset -> idle
=================================================================
name:     tr_13
condition:     default
executive:
color:     black
drawing style:spline
doc file:  pr_transition.
```