INFORMATION AND COMMUNICATION SYSTEM ARCHITECTURES FOR WIDE-AREA MONITORING AND CONTROL APPLICATIONS

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Abstract - This paper presents a review of work performed in the field of communication systems requirements for wide area monitoring and control applications. This includes studies performed both in the context of NASPI, the North American Syncrophasor Initiative, as well as other studies in the US and Europe. Presently a relatively large body of work has been done regarding the requirements on the communication infrastructure. Among the work included, are surveys among Transmission System Operators on the foreseen communication requirements, as well as other theoretical studies on acceptable delays and other performance characteristics, such as data loss, that Wide Area Control applications put on the Information and Communication System. Much of the above referenced work still needs verification either though experimental work or through simulations. It is especially important to simulate large scale communication infrastructures that consider background traffic under different operational conditions in the power system, such as under disturbances. The paper is concluded with some remarks on future direction of work within the field.

Keywords - Wide Area Monitoring and Control, Phasor Measurement Unit, Communication System Performance, ICT system Architecture, Quality of Service

1 Introduction

ELECTRICAL power networks constitute 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, among other factors, due to increasing environmental policies leading to large scale introduction of intermittent generation. Furthermore, the reregulation of electrical markets 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. To balance this challenges control systems for operation and control of the power system need to be improved. One development in this direction is the use of Wide Area Monitoring and Control (WAMC) systems allowing real-time control of the power system. Such systems use remote measurements of high quality and advanced control algorithms to control the whole or parts of a power system. A critical component in these WAMCs is the ICT infrastructure that provides access to measurements and enables fast computation of control signals.

1.1 Scope of the Paper

The scope of this paper is to present a review of the state of the art regarding information and communication system architectures for Wide Area Monitoring and Control systems. The focus lies on the performance, in terms of latency, of these systems in relation to the power system requirements. The paper also presents some examples of studies on the effect of communication system performance on the feasibility of power system functions and examples of measures taken to manage these effects.

1.2 Layout of the Paper

After this introductory section follows a section describing the fundamental assumptions and definitions used in this paper regarding Wide Area Monitoring and Control systems, Power system applications and Quality of ICT systems that are necessary for the presentation in the rest of the paper. The ensuing two sections (sections 3 and 4) contain the bulk of the presentation of presently ongoing activities and their approaches. The paper is concluded with a section discussing the future direction of research and development in the field.

1.3 A note on terminology

In this presentation, the term *Power System Application* is used to denote a control or monitoring function implemented in software fulfilling some purpose for monitoring, operation, control or planning of a power system. The core of the application is an algorithm using high quality measurements as inputs and providing either output signals to be sent to actuators or processed data to be presented to a human operator. The term *Supporting ICT* *system* is used to denote the communications and computing platform that the *Power System Application* relies upon for receiving data from local or remote locations, performing calculations and sending output signals. Together, these two constitute what we will refer to as a *Wide Area Monitoring and Control System (WAMC)*. Finally, the term *Interconnected Power System* will be used to denote a single synchronous power system operated by several organisational entities, typically ISOs or TSOs. The implication of this term is that several *Supporting ICT Systems*, owned and operated by separate ISOs/TSOs may be needed to support one *Power System Application* that performs a function within an *Interconnected Power System* thereby adding a level of complexity from an ICT architecture perspective.

2 Wide Area Monitoring and Control Systems

As implied above, Wide Area Monitoring and Control Systems (WAMC), are not singularly defined, but is often interpreted as systems that use remote time-synchronised measurements of high quality, generally from Phasor Measurement Units (PMU), for monitoring or control of the power system. In many cases, it is assumed that the control is done without a human in the loop. The term also include applications that are centralised and operate on complete measurement sets from the power grid as well as applications that are tied to a specfic part of the system. The following three dimensions can be used to better understand the scope of the system.

- Whether the function relies on a complete set of high quality measurements or if it is based on a subset of measurement as input to its algorithm.
- Whether the function is implemented centrally at a control centre, or locally in a substation or a power plant, close to either measurements, actuators or both.
- Whether it is a closed-loop function without a human in the loop, or if it provides information for human decision making.

It is important to keep in mind that all types of functions can and will co-exist within a single Interconnected power system. An optimal ICT system architecture must therefore be adaptable to several types of applications. This observation, together with the fact that the WAMC system may require data from external parties, constitute the main challenges to developing open, secure and reliable ICT architectures for WAMC systems.

2.1 WAMC architectures

The different categories of application naturally has different requirements on the supporting ICT systems. Figure 1 below illustrates a generic architecture for WAMC systems valid for the three types of power system applications listed above. The architecture also captures the specific case, where measurements are received from an external party (link B). In the figure, the high quality measurements are assumed to come from Phasor Measurement Units (PMU) and data collection and sorting is assumed to be performed in Phasor Data Concentrators (PDC). This choice of nodes is representative of present day solutions, but does not limit the architecture as such to only this specific type of measurement.

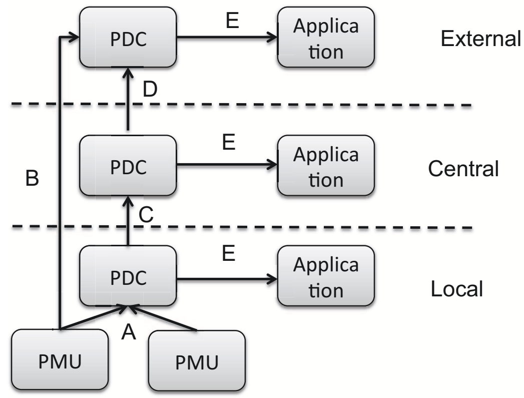

Figure 1: Generic architecture for Wide Area Monitoring and Control Systems

The three layers in the architecture are *local* including applications at the substation level using data from a subset of measurements points in the interconnected power system. Measurements are transmitted locally or over high speed links *A*, e.g. Ethernet over fibre optics, the latencies of these links T_A is assumed to be very low. For cases where the power system application works across control areas within the interconnected power system data is required from external parties, links *B*, here the links exist through a wide area communication system spanning two ISO/TSOs, resulting in latencies T_B. The *central* level applications are those that use a complete set of measurements, transmitted over links *C* from the control area in the power system, the latency for this group is T_C. Finally, *external* applications, are those that are built at a super-ISO level requiring collection of data from several control areas as well as from within its own area. It is reasonable to assume that $T_A < T_C < T_B$, however, since applications can be built out of components requiring communication through all three categories of links it is not sufficient to dimension the support ICT system based only on one of these latencies.

2.2 Power System Application Requirements

A number of research groups have conducted studies to characterise the types of power system applications inherent to WAMC systems and their requirements on the supporting ICT systems. An early paper on the topic [3] identifies two categories of WAMC applications, those that require complete network observability and those that do not. Two applications discussed in [3] that require complete network observability are frequency stability assessment and voltage stability assessment in meshed networks. Applications not requiring full network observability are oscillation damping, voltage stability in transmission corridors and line temperature assessment. The conclusion in the paper is that the performance of the supporting ICT system will be critical for being able to close the control loop. In [20] these applications have been used to determine more exact perforamnce requirements on the supporting ICT system and compared these with those presented in the NASPI project.

The most comprehensive work on power system application requirements has been conducted as part of the Gridstat.net project at Washington State University, and the results are reported extensively in [18]. In this report, thirteen types of power system applications, ranging from Traditional State Estimation via Transient Stability control to Research applications are presented together with their requirements on the supporting ICT systems. The work is interesting since it brings the requirements a step beyond merely latency and throughput, using the term QoS+ to denote a set of requirements including data criticality and quantity. The term Quality of Service, or QoS in short, usually denotes a variety of non-functional aspects of a communication service, such as latency, jitter, security and so on. the QoS+ requirements are classified and grouped in 5 distinct levels as illustrated in Figure 2 below.

Difficulty (5:hardest)	Latency (msec)	Rate (Hz)	Criticality	Quantity	Geography	Deadline (Bulk traf.)
5	5–20	240–720+	Ultra	Very High	Across a grid or multiple ISOs	<5 sec.
4	20–50	120–240	Highly	High	Within an ISO/ RTO	1 min.
3	50–100	30–120	Medium	Medium	Between a few utilities	1 hr.
2	100–1000	1–30	Low	Low	Within a single utility	1 day
1	>1000	<1	Very Low	Very Low (serial)	Within a substation	>1 day

Figure 2: Classification of QoS+ requirements, from [18]

These categories of QoS+ requirements are used in the project together with the thirteen applications presented in order to describe each application's requirements. The authors also take this a step further and specify design guidelines for Wide Area Monitoring and Control systems that consider these requirements.

In a study of similar scope, see [4], and specifically regarding communication latency requirements in [19], a range of applications utilising high quality remote measurements and their associated ICT system requirements are presented. The conclusions regarding data latency and volumes is similar to that of [18] and [20] with the most strict requirements being in the range of 50 ms for data delivery for most time critical applications, with more strict requirements for system integrity protection schemes.

Combined, the above presented studies of WAMC applications go a long way to categorise and describe the requirements on the supporting ICT systems put by power system applications. The studies are very comprehensive when it comes to latencies and data throughput, the most strict latency requirements are in the range of 5-20 ms data delivery delays for transient stability applications allowing for control actions within 50-100 ms. Additionally, large group of applications related to distributed control, islanding and special protection schemes are reported to require data deliveries within 50 ms. Of the studies [18] provides an additional analysis beyond that merely of communication system performance, by introduction of the QoS concept. However, this still does not include the additional challenges posed by for instance inter-ISO communication with the additional considerations that need to be taken with regards to cybersecurity and interoperability.

3 Quality of Information and communication systems

At the core of WAMCs are the power system applications, implemented as algorithms in software. These algorithms, are often the result of research and development driven by the requirement to improve som aspect of the power system. The focus during the development is purely the function as such. The quality of the supporting ICT system, is often expected to be sufficient, sometimes leading to proper quality in the power system function as such due to poor understanding of ICT limitations, see for instance [2]. Needless to say the functional focus leads to sub-optimal solutions when the entire ICT architecture is considered. Too large focus on the functions of ICT over their non-functional aspects leads to the stovepipe system architetures, see [22]. Furthermore, it can create a false sense of confidence, that one particular function's ICT system capabilities are sufficient for that of another function merely because they are similar in nature.

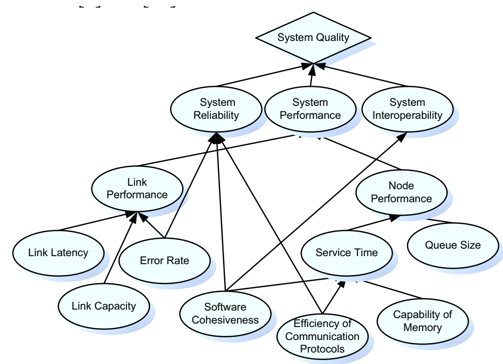

Figure 3: Influence Diagram illustrating the causal relation between attributes that constitute several non-functional aspects of ICT systems[21]

Additionally, there is clear interdependencies between the non-functional aspects and the attributes of the ICT system that comprise them, see [21]. In some cases there is even a negative coupling, for instance between interoperability and performance. A more complete analysis of ICT systems requires consideration of the fact that the non-functional aspects of ICT are interrelated, see [23] for an approach to this type of comprehensive analysis. In the following listing, some aspects of how these non-functional aspects are related, and how they impact the quality of the supporting ICT systems are presented.

Performance It is clear that the overarching concern with regards to supporting ICT systems is that of performance in the term of latency and throughput of data. The first order attempt to resolve this problem is to employ high capacity links at the physical level, i.e. fibre optics, between the points in the network requiring high speed access. Disregarding the costs invovled for such efforts, this effort is sometimes not sufficient if the causes for delays are not at the physical layer, but elsewhere in the communications solution such as in data sorting or application

processing. For a study that includes these aspects please see [24]. In general, extended performance management such as the QoS concepts presented in [15] are necessary to ensure sufficient quality in the ICT systems.
Cybersecurity Cybersecurity is perhaps the most discussed of the non-functional aspects of ICT systems, see for instance [27] or [28] . It also provides the best example of the dangers of focusing ICT development merely on the function to be fulfilled. No organisation would consider employing an ICT system completely without protection against cyber attacks. Furthermore, adding these protective measures once the system has been commissioned creates obvious risks to performance. The design of ICT systems need to incorporate cybersecurity defence mechanisms from start, thereby putting additional demands on understanding the performance implications at design time. A good example of such proactive developments can be found in the NITR program, see [29]. The cybersecurity issues is naturally more pressing for WAMCs systems that act across control areas and ISOs.
Interoperability With interoperability we understand the ease by which a system can exchange information with another system. As explained in [30] there are several layers of interoperability, for our discussion here, it suffices to say that the interoperability issues increases the larger the distance between the measurement source and the application. The distance is here not only geographical, but also has a context or organsiational dimension, meaning that if data transverses several networks within, or outside of an ISO additional latency may be experienced due to protocol conversions or communication gateways.
Reliability ICT system reliability differs significantly from reliability of hardware devices most explicitly because it does not exhibit the same type of fault probabilities. A piece of software may function perfectly until a certain input value is recieved and then stop functioning altogether. Studies on the reliability of WAMC systems are performed for example in [3] in which the individual component reliabilities are considered. In [2] the reliability analysis covers the ability of the ICT system to deliver data in time as a reliability issue, providing an expanded interpretation of the term.
In summary, the interdependecies between non-functional attributes, and their impact on the critical aspect of latency and throughput is difficult to predict at design time. The development of methods for analysis of how different ICT system architectures that consider these non-functional aspects of ICT and the effect on latency and throughput these architectures have is necessary. Examples of such developments are outlined in section 5.

4 Ongoing Research and Development

There is a multitude of activities ongoing to address the challenges with developing WAMC systems and their supporting ICT systems. In this section, we present a selection of these activities, grouped into three categories. First those activities which work to adapt the power system application in order to make it less dependent on the ICT system's capabilities.The second category are activites that aim at analysing and designing the ICT system to be able to fulfill stricter requirements. The third and final category presented is that of new paradigms, for dedsign of WAMCs and their ICT systems.

4.1 Application development

Fine tuning of the power system application to make it less dependent on the capabilities of the ICT system is a natural approaxh. This work normally includes compensating for the expected delay by increased robustness in control algorithms or filtering of input signals to improve measurement quality despite latency.
For example in [10] the design of a robust TCSC controller is presented, here the uncertainty due to ICT system latency is represented by an inverse input multiplicative model. To enhance the robustness of the controller, its parameters are optimized using a genetic algorithm. Along the same lines, in [12] a number of approaches that work to improve overall power system application functionality while increasing tolerance to latency are suggested and compared. The paper also presents a controller design technique, that allows the designer to consider varying amounts of latency in the ICT system. In [13], the authors present an alternative approach to managing latency by predictive control in which a recursive least-squares algorithm is used to identify the predictive model. The method has been verified in simulations, but there seems to be little indication of experimental verification of the concept. Similarly in [14] predictive control using model identification by means of a simultaneous recurrent neural network is employed in the design of a WAMC system. In general,in all the presented projects, the proposed algorithms improvements are verified in simulation set ups and the application fulfills its function despite the modeled ICT system limitations. The presented pieces of work should to be seen as good examples of the types of developments that are ongoing to adapt the applications to the capabilities of ICT system. The lack of experimental or empirical validation of the concepts does however make the approaches vulnerable to criticism regarding their validity for varied types of ICT system weaknesses beyond latency.

4.2 ICT development

An alternative to finetune the power system application is to analyse and design the ICT system so that it provides the needed level of quality for the power system applications. There exist a number of examples of this approach throughout literature. In an early paper [8], the capabilities of an IP based network was evaluated and was also through simulations verified to be sufficient for the intended applications at that time. In a completely different approach presented in [11], the characteristics of the communication system, assumed to be a dedicated sensor network, is modeled using three different methods from signal processing and communications theory. The approach is interesting since it uses the characteristics of the measurement data stream, and the requirements from the power system function as a basis for defining generic characteristics of the communication system. In [16] a method for analysis of dataflows in NASPInet is presented. Although developed specifically with NASPInet in mind, the utilised framework, and the components developed for the NS-2 simulator, can be used for other of WAMC architectures as well, the challenge lies in developing simulator models that represent components in these other architectures.

In general, adressing the performance challenge from the ICT system perspective serves the same purpose as that of finetuning the power system application. Which perspective to attack is very much dependent on the practical situation faced, in situations with a fixed ICT system solution it may be necessary to improve the power system application. While, if the ICT system is not yet deployed it may be worhtwile to apply a simpler power system application and instead design the ICT system accordingly. Support for such trade-offs need to be found in advanced modeling and simulation tool platforms, see section 5.

4.3 *New Paradigms*

From the above presentation of PMU based applications, it is apparent that for individual applications it is possible to develop a sufficiently good ICT system. Keeping in mind the constant development of new applications, reducing the risk of building stovepipe architectures is best done by a more comprehensive approach to building ICT systems. The NASPInet project presented in [31] is the most comprehenisive approach to these challenges. *NASPIs ultimate objective is to decentralize, expand, and standardize the current synchro-phasor infrastructure through the introduction of a NASPI network (NASPInet) that will be composed of Phasor Gateways (PGs) and a Data Bus (DB), both of which shall, where applicable, utilize, be compatible with, and integrate within the set of Common Services of the respective Requesters enterprise IT infrastructures.* As such, the NASPInet architecture adresses all of the non-functional aspects presented above in one comprehensive platform.

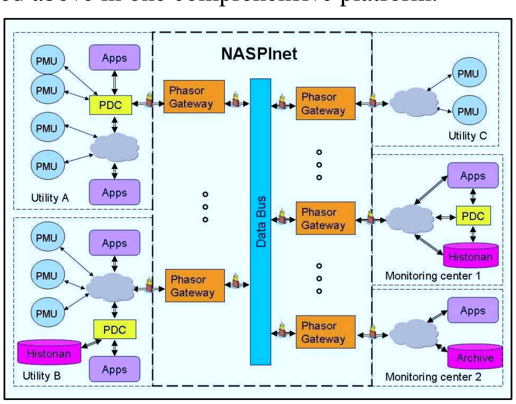

Figure 4: Overview of NASPInet architecture[25]

The NASPI architecture is built around a publish subscribe concept in which producers and consumers of data communicate using a common communication bus that goes across organisational boundaries. As such the NASPInet bus adresses all interfaces discussed in the WAMC architecture in section 2 above. The NASPInet architecture also includes services of cybersecurity and resiliency intended to manage the non-functional aspects of ICT listed in section 3 above. At the same time, full scale implementation of the proposed architecture is still not complete, and will require a significant effort. Also, the design of instances of the architecture will require analysis tools and simulations in order to verify the applicatibility of the design and its fulfilment of requirements.

A similar concept to the NASPInet architecture is the gridstat.net middleware being developed at Washington State University, see for instance [18]. The gridstat.net project adresses the same issues as NASPInet and through the use of the QoS+ concept described above, develops implementation guidelines for Wide Area Monitoring and Control systems. The Gridstat architecture is based on Quality of Serivce guarantees for Multicast communication, which is at the core of a publish-subscribe communication model such as that described in the NASPI architecture. The Gridstat architecture is based on a the concept of a management plane in which meta-level communication attributes are communicated between participating nodes in order to set up communication channels and manage changes in the communication or power system configurations.

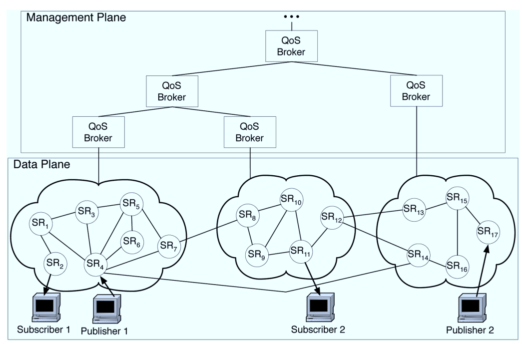

Figure 5: Overview of Gridstat.net architecture[15]

A similar, but not as well developed proposals is the PhasorNet outlined in [5] and the open system architecture presented in [6]. Both of these developments acknowledge the many aspects of designing ICT systems for WAMCs, and provides some examples of possible solutions to these problems. Neither of them provide complete solutions to the problem however, and do not provide the same depth and scope as the two preceeding examples.

5 R &D Challenges going forward

Given the amount of work going into development of new paradigms for wide area communication, it is reasonable to assume that the new paradigms for data communication will start to see implementation. Although promising as architectural specifications, they need to be complemented with methods for analysis and design of systems built according to the specifications. In short we would need methods for analysis of the ICT systems and specifically their performance aspects. With such analysis and design methods we could design the ICT system to support the power system applications and at the same time fulfill other architectural requirements such as cybersecurity, interoperability and low total cost of ownership. At the end, these methods must provide concrete guidance on the performance implications of the proposed ICT system. There are typically two basic categories of methods for conducting performance evaluation. These methods are (1) measurements of existing systems and measurements and (2) predictions of models that abstract existing or upcoming systems. These models can then be further divided into analytical modeling and simulation modeling.

Along these three development threads, a number of separate initiatives can be identified. First with regards to measurements on real systems, developments reported on in for instance [26] include development of prototype systems based on opensource platforms, e.g. OpenPDC [32]. This particular platform is being connected to PMUs spread over a large geographic area at university campuses. Using the platform it is possible to experiment with the ICT system in terms of adding security measures (e.g. firewalls) and protocol gateways and measure latencies and throughput ratios in real systems transmitting live phasor measurements. The platform can be extended to include real communcation solutions within TSO environments and therby provide real systems in which measurements of latency under differnt circumstances can be performed. This data can then be used both for system design but also for more detailed modeling of ICT systems for furhter research purposes.

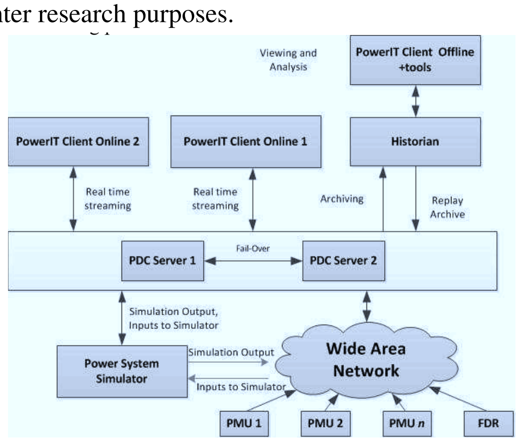

Figure 6: Overview of KTH PowerIT experimental system architecture[26]

Second, regarding simulation of ICT system's interrelation with the power system, a number of initiatives exist. One example is the EPOCHS platform, see for instance [7]. The EPOCHS platform enables concurrent simulation of power system electromagnetic phenomena and communication system dynamics. A similar approach based on hybrid systems theory and simulations using discrete events is presented in [9]. The simulators and the results presented in [9] and [7] are very comprehensive and provide good insights in to design of ICT architectures for WAMC. The limitations are however as is usually the case with simulations, the extensive modeling work required.

Finally with regards to analytical modeling of ICT systems, the approaches presented in [23] and [13] provide insights into how analytical methods could possibly be used to analyse the ICT systems. In [23], probabilistic analysis utilsing Bayesian inference is used to model and analyse the interrelation between different non-functional aspects of ICT systems. This approach may be useful for assessing the impact of qualitative aspects of ICT such as interoperability, and its impact on performance and reliability. For more rigid analysis focused on latency the methods proposed by [13] are more suitable, here however the simplifications of the ICT system to model required for applicability of the method is limiting.

5.1 Summary

We have in this paper presented an overview of the challenges facing develpoment of wide area monitoring and control systems especially the ICT system architectures necessary to support them. In the presentation we have discussed the different types of WAMC systems, and presented a generic architectural description. The paper also presents some related work within the field, addressing the challenges of ICT system design for WAMCs from different perspectives. Important for building cost-efficient, reliable and high performing ICT systems is that all non-functional aspects of the systems are considered already at design time.

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