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Architecture design and optimization of Edge-enabled Smart Grids

Adetola B. Adeniran
University of South Florida

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Architecture Design and Optimization of Edge-enabled Smart Grids

by

Adetola B. Adeniran

A thesis submitted in partial fulfilment
of the requirements for the degree of
Master of Science in Electrical Engineering
Department of Electrical Engineering
College of Engineering
University of South Florida

Major Professor: Mahshid Rahnamay Naeini, Ph.D
Nasir Ghani, Ph.D
Ismail Uysal, Ph.D

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Dedication

This work is dedicated to God, the reason for my existence.

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First and foremost, I want to thank my advisor Dr. Mahshid Rahnamay Naeini for her advice, support, patience, and guidance throughout my graduate studies. She taught me the skills necessary for academic research that would stay with me forever. I appreciate her time, efforts, and contributions that have helped to enrich my knowledge and experience in my field. It is an honor to be one of her masters students.

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Abstract

The emergence of modern monitoring, communication, computation, and control equipment into power systems has made them evolve into smart grids that can be thought of as the electric grid of things. This evolution has enhanced the efficiency of the power systems through the availability of a large volume of system data that can help with system functions, nevertheless, it has intensified the communication and computation burden on these systems. While many of such computations were traditionally deployed in central servers, new technologies such as edge computing can provide unique opportunities to address some of the computational challenges and improve the responsiveness of the power system by processing data locally. In this thesis, first the application of edge computing technology in smart grids' applications are reviewed and discussed. These applications are ranging from functions in Advanced Metering Infrastructure to monitoring and control of transmission grids. Next, an edge enabled smart grid architecture, particularly for the support of transmission grid functions is presented. The edge layer for the smart grid is designed through optimization formulations to identify the placement of edge servers and their connectivity structure to the Phasor Measurement Units in the system. Various factors affecting the design, such as the geographical and resource constraints as well as the communication technology considerations have been incorporated in the formulations and evaluated using a power system test case, the IEEE 118 bus system. Finally, the future direction of research and challenges for the emerging field of edge-enabled smart grids are discussed.

Chapter 1: Introduction

1.1 Motivation

Power grids are large and complex systems that provide critical electricity service to communities. As such, their reliability, security, and efficiency are of utmost importance. Various communication, computation, and control technologies have been developed and adopted to enhance their efficient operation and ensure their reliability and security. Particularly, these technologies enhance the efficiency of the power systems through availability of large volume of system data that can help with various system functions such as monitoring the system, load management and forecasting, integration of renewable resources, billing, dynamic pricing and more. However, the large volume of data has intensified the communication and computation burden on these systems.

Traditionally the data generated from the smart grids are transferred to central units (utility owned servers or cloud systems) for storage and processing. Consequently, certain time-sensitive functions which requires real-time processing of data are delayed. The delay to communicate and process the overwhelming amount of data generated continuously from various components of the smart grid in a central unit may affect the critical and time-sensitive functions in power systems. This challenge has motivated researchers to identify solutions for processing data locally through distributed computing platforms and using distributed intelligence. In the recent years, the advent of edge computing has provided unique opportunities to address some of the identified

computational challenges and improve the responsiveness of the system by processing data locally. Various studies have emerged on the benefits and opportunities that edge computing can present to smart grid applications, most of which are reviewed in this thesis. Edge computing can specifically provide low latency, location awareness, support heterogeneity, and improve quality of service and real-time data analytics. Adopting edge computing technologies into smart grids provides the ability to run time sensitive applications in the grid, perform distributed machine learning approaches, improve security and privacy of various smart grid's applications, and assist local processing of data and on-demand resource management.

In this work, the application of edge computing technology in smart grids are reviewed and discussed. It is also discussed how edge computing can be a solution to processing data locally through distributed computing platforms and distributed intelligence. Moreover, an edge-enabled smart grid architecture is presented and studied. The edge layer for the smart transmission grid is designed through optimization formulations to identify the placement of edge servers and their connectivity structure to the Phasor Measurement Units in the system. Various factors affecting the design, such as the geographical and resource constraints as well as the communication technology considerations have been incorporated in the formulations. The architecture is evaluated and the effects of various factors in the design are studied using the IEEE 118 bus system.

1.2 Overview of Smart Grids

Smart grids are energy supply networks that provide electric power flow in a distributed and automated manner. They are an example of cyber-physical systems (CPS), with a large number of monitoring, communication, and computation components that generate a large volume of power and data that needs to be transferred and processed for various functions in the system. The

smart grid aims to provide information and load control for customers, distributors and grid operations during generation, transmission and distribution of electricity in order to reduce costs while increasing energy efficiency, and reliability.

The availability of data is expected to facilitate real-time monitoring, automated control operations, integration of different types of electrical components and resources, resilience to stresses, and higher reliability than the traditional power systems. Over the years, this has resulted in a wide recognition and development of smart devices, smart metering, smart home appliances, electric vehicles, and the Internet of things (IoT) to connect to smart grids. Smart grids, usually function through central processing units (e.g., the use of cloud computing), however, the new elements along with heterogeneous electrical devices connected to the grid (e.g. electric vehicles, distributed energy resources, etc.) are converting the power system into an Electric Grid of Things (EGT) [1]. The emergence of these technologies demand large computation, storage and low processing latency; however, the insufficiency of central processing units in this new era has led to the introduction of edge computing in smart grid applications.

Generally, smart grids are geographically expanded infrastructures, which can suffer from latency in the communication and processing of data in a central setting. The edge computing can provide opportunities to improve the response time for real-time monitoring and control, especially for detecting and addressing anomalies and stresses (e.g., detection of Cyber-attacks and physical stresses, monitoring voltage oscillation, etc.). Many of these functions can be designed using local measurement data with acceptable performance to, for instance, provide early warning signals for system operators. As such, edge computing seems to be a promising computational platform to achieve these requirements for modern power systems [2].

As stated earlier, smart grids are an example of CPSs, which consist of a tight combination and coordination between cyber and physical elements. By organic integration and in depth collaboration of computation, communications and control technology, smart grids can realize the real-time sensing and dynamic control of the power system [3]. The main structure of the smart grid can be classified into information system layer, physical system layer and user layer. The information system layer is responsible for the transmission and processing of the data received from the physical system layer. It also include large number of computation and communication elements, embedded systems, sensor networks, smart chips taking charge of the collection, transmission and execution of control signals. The physical system layer includes power grid components which consist of substations, generation sources, transmission lines and more. The user layer can be considered as the end users that their consumption behavior and interactions with the system affects the dynamics of the system [3].

The schematics of a smart grid and its components are depicted in Figure 1.1. In this figure, the consumption component refers to the users, (e.g electric vehicles, smart offices, and smart homes). Note that in smart grids, power generation is not solely reliant on power plants but also on other sources of renewable energy, such as solar or wind. The excess generated power can also be stored (through utility storage components).

Another key component in smart grids is the advanced metering infrastructure (AMI). In the distribution grid, large number of smart meters, which are advanced form of meters for collecting accurate readings of energy consumption are being deployed. These smart meters will serve to send data to the supplier (as well as the consumer) providing a two-way communication system between utilities and end users [4]. In addition to the smart meters, the AMI includes communication infrastructure for connecting the meters to the utility centers. The most viable

communication technologies for the AMI are wireless and power line communication (PLC) [5]. Smart meters are further discussed in Chapter 3

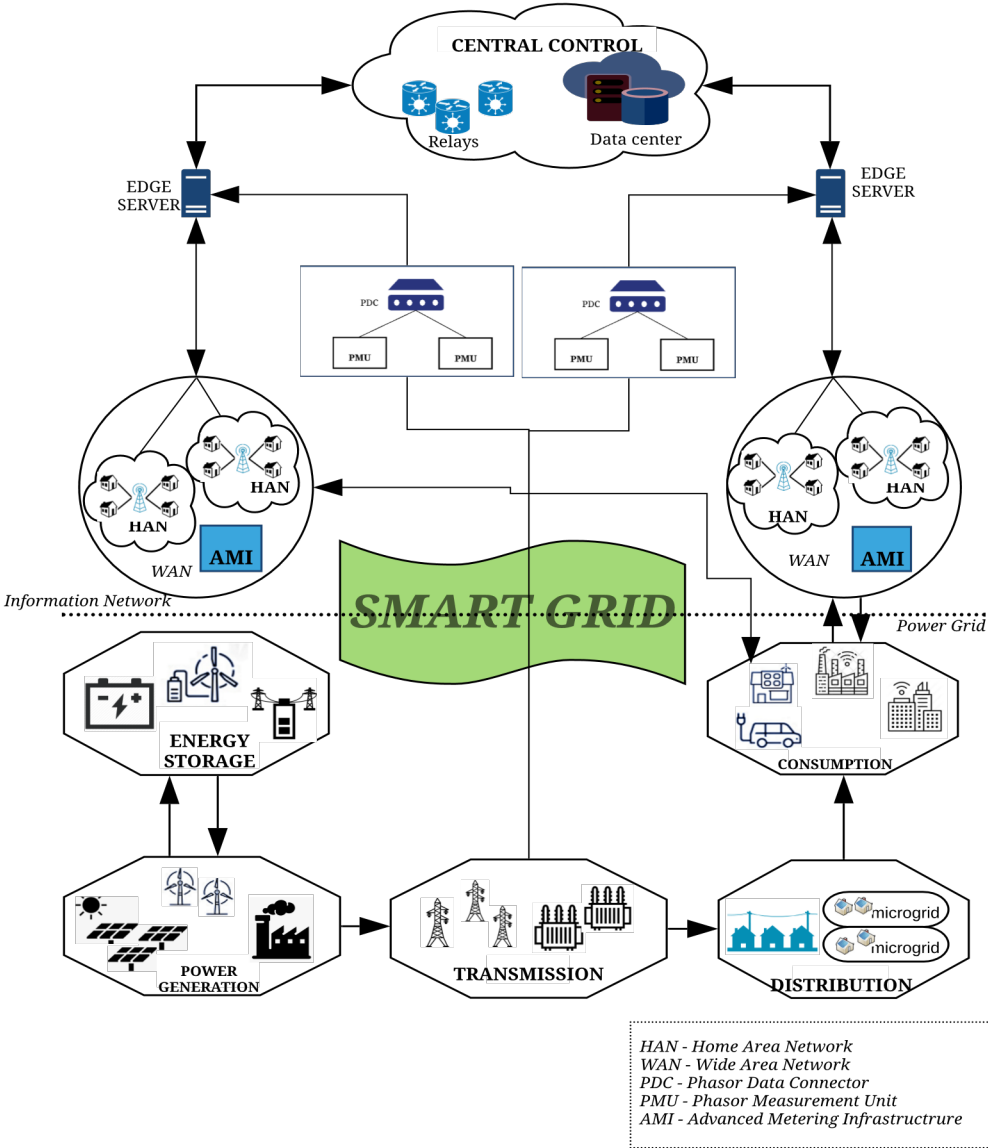


Figure 1.1: Components of the Smart grid.

1.3 Overview of Edge/Fog Computing

The natural fog made of droplets of water can be described as a low-lying cloud. When fog computing is mentioned, simply put, it suggests computation closer to the earth (end users). Fog computing, a term coined by Cisco extends the concept involved with cloud computing to the edge

of the network. A cloud with all its computing, storage, and application power settling back to the ground, away from a centralized data center [6]. In the networking world, it is a virtual extension of cloud, bringing the resources to the edge of the architecture. Cloud computing as it is, struggles with mobility and therefore results in high latency; however, fog computing allows data analysis to occur at a place, which is closer to its creation, resulting in a faster response, thereby eliminating the lag in time.

Within the research circle, the terms fog computing and edge computing are used interchangeably due to the similarity of the terms. Edge computing brings processing close to the data source, without the need to transfer it to a remote cloud or other centralized systems for processing, similar to the Fog computing. Fundamentally, fog is the standard and edge is the concept, fog enables repeatable structure in the edge computing concept, so enterprises can push computation out of the central control for a better performance [7].

Edge/Fog computing is a horizontal, system-level architecture that distributes computing, storage, control, and networking functions closer to the users (in this case closer to the EGT elements), which can result in low latency and location-aware computations for energy data. Edge/fog computing provides storage, networking, application and computation services between end devices and traditional cloud computing data centers [8]. Cisco says with edge and fog computing, we are one step closer to creating living, breathing personifications of our communities [9].

According to [10] edge/fog computing is a scenario, where a huge number of heterogeneous, ubiquitous and decentralized devices communicate and potentially cooperate among each other and the network to perform storage and processing tasks without the intervention of third parties. These tasks can be for supporting basic network functions or new services and

applications. With a large amount of data being transferred in a heterogeneous environment, the work in [8] shows the characteristics of fog computing that makes it appropriate for the computations executed in such environments. In the event that the data is sent back across a network link to be analyzed, logged and tracked, it takes much more time than if the data is processed at the edge, close to the source of the data.

There is now a wide recognition and development of smart devices in the smart grids including wide range of sensors and PMUs, smart metering devices, smart home appliances and electric vehicles that require computation and storage. Although, central processing units, such as cloud computing, was considered a solution to the limitation of these resources, smart grid applications usually require geo-distribution, location awareness and low latency [11]. The current central computing model in smart grids is not sufficient to handle these requirements, as such fog/edge computing, which provides low latency, location awareness, supports heterogeneity, and improves QoS for real time applications [12] through computation at the edge of the network architecture, has been suggested for smart grid applications. The fog computing model keeps sensitive data on premise, and reduces bandwidth consumption towards the cloud by gathering, keeping and analyzing data near devices aiding the backbone [13]. Figure 1.2 shows the layout for the technology, with the edge/fog devices placed closer to the users in between the user plane and the cloud plane. Edge devices are sensor networks with less computational capabilities [14], but capable enough to perform processing and storage activities for the physical (user) layer.

For exploiting the area of edge computing application in smart grid, it is important to design the edge layer, and the communication structures between the edge layer and the sensing and monitoring devices of smart grids. In this thesis, the focus of the work is placed on the transmission

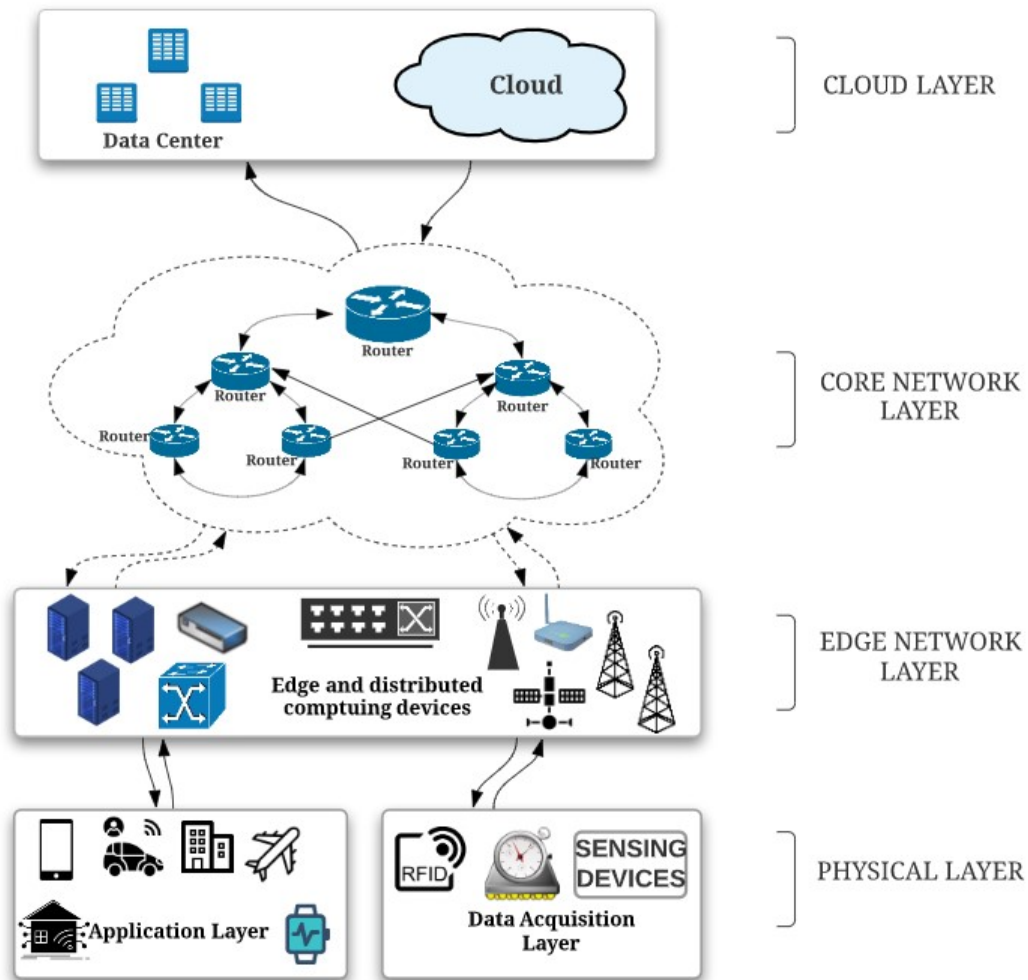


Figure 1.2: Components Edge/Fog Computing.

grid of the power systems and metering devices such as Phasor measurement units (PMU's) as a part of the EGT system. PMU's are one of the important devices deployed throughout the grid to measure time-synchronized electrical quantities, therefore, it is important to optimally design an edge layer that can collect and process data from PMUs effectively.

1.4 Contributions and Thesis Organization

The key contribution of this thesis can be summarized as following:

- Presenting a review of edge computing visions in smart grids, the possible application of edge computing in smart grids and how edge computing helps different functions in smart grids.
- Presenting an edge-computing architecture for smart grids (particularly the smart transmission grid), which comprises of the physical layer with electrical components, Industrial Internet of Things (IIoT) layer (e.g., PMUs), edge layer with the edge servers, and the central layer including cloud layer for central processing and control.
- Designing the optimal edge layer with minimum number of edge servers and optimal connectivity structure among the edge servers and PMUs with communication technology considerations.
- Evaluating and analysis of the presented edge architecture including experimental evaluation of the effect of formulation parameters on the architecture, such as the level of required reliability, on the design of the edge layer for the IEEE 118 bus system.

The key contributions of this thesis have been published in [15]. The organization of the thesis is as follows. Chapter 2 provides a comprehensive literature review of works that has been done by other researchers in the area of edge computing, edge computing for smart grids, PMU placement, edge server placement, and proposed architectures. In Chapter 3, the edge-enabled smart grid is presented and each layer of the architecture is discussed. The application of edge computing in the smart grid distribution and transmission systems is also described. Chapter 4 presents the formulation of the optimization model for each layer of the architecture, Chapter 5 shows results for the evaluation of the proposed architecture on the IEEE 118 bus system. Finally in Chapter 6, the thesis is concluded with further research suggestions.

Chapter 2: Literature Review

This section provides a review of existing research works with a focus on the application of edge computing in smart grids. Furthermore, in relevance to our edge architecture proposed in this work, the discussions include optimal PMU placement methods and review on edge server placement as well as different optimization techniques for edge architectures.

2.1 Edge Computing for Smart Grids

The technology of Edge or Fog Computing [16–19] as an extension of cloud computing has become popular in the previous decade. This technology is being used in different types of applications, especially in the context of the Internet of Things [20]. For instance, edge computing is especially suitable for geographically distributed cyber-physical systems e.g., wireless area networks [21], smart grids, smart homes [22], smart city [23], smart health monitoring systems [24], etc. A considerable amount of work has been done on the topic of Edge Computing for Smart Grids in the last few years [1, 25–29, 31–41], all aim at the introduction of edge servers to reduce the latency of data transmission in the smart grids and reduce computational and processing time in certain operation and monitoring functions of smart grids to aid awareness as opposed to the cloud-based architectures.

Edge/fog computing has been proposed for improving various functions in power transmission systems, such as state estimation, anomaly detection, power and voltage quality monitoring. Considering wide area monitoring function in smart transmission grids, the effectiveness of processing time sensitive data at the central control centers is bounded by the efficiency of the communication system. Research in this area brings an exposition to the

advantageous contributions that can be made with the use of edge computing to alleviate the shortcomings of the communication system. For wide area monitoring function, the authors in [27], proposed an anomaly detection scheme in the power grid by employing a PMU-fog architecture. To reduce the end to end delay, this work suggested the utilization of computational resources of the PMU devices for on-site anomaly detection and sending the marked anomalous data with higher priority to the cloud for further processing. Despite the challenges in moving these computationally intensive tasks to the fog, the authors showed that they can perform anomaly detection with promising accuracy, shorter detection delay, and robustness to noise. Another work demonstrating use of fog in handling measurement data is [29]. Forcan & Maksimovic in [29] proposed a fog-computing based communication system model for voltage profile monitoring and power loss estimation in the smart grid. In their work, they proposed both cloud-based and cloud-fog-based architectures and compared these two approaches based on their performance for real-time state monitoring. The authors performed simulations of voltage monitoring and power loss calculations using the proposed models and simulation of communication network between the fog servers, as well as the fog servers and the cloud, and the smart devices and fog servers. The major contribution of their work is the comparison between the cloud and cloud-fog architecture to show the advantages of the fog-based over cloud. From their simulation results, it was shown that monitoring with the fog-based architecture is more accurate with data collected in a 5 seconds frame, over the cloud-based, which collects data in a 20 seconds frame. This work is an example of studies that shows the usefulness of the fog-based architecture in time critical applications.

Edge's performance with time-sensitive environments makes it a viable technology in the smart grid to tackle real-time situational awareness and on-demand response. Hence more studies such as [1] and [30] are emerging to show the application of edge on situational awareness in smart

grids. The work in [30] implements an architectural solution using edge computing and IoT for monitoring and state estimation in smart grids with the goal of providing a low latency, bandwidth efficient, and high accuracy system. In one of our previous team's work presented in [1], we proposed an edge-computing architecture over the PMUs in a power transmission grid that is capable of detecting stresses, such as single transmission line failure in the grid locally at the edge nodes, which can help to improve the situational awareness of the smart grids. Further details on this work is discussed in Chapter 3.

The new generation of networks 5G, which holds a reputation in distributed environments, along with the edge/fog computing have shown to be important contributors in the power system. The works in [31], [42], [43], [44] suggest that using 5G with edge/fog would further bring out the best in these technologies' use in smart grid to fulfill the latency requirements. Cosovic et. al., [31] showed the possible contribution of mobile edge computing (MEC) in aiding 5G networks for distributed information processing and storage architecture, affirming the fit for low latency required services, such as state estimation and system monitoring. The work by Kumari et.al., [42] studies the communication and computing aspects in the context of 5G network infrastructure. In this work, the authors elaborate on the shortcomings of the cloud computing and further discuss the adoption of fog to aid cloud computing in smart grids. The work further suggests the use of 5G radio access technology with fog computing due to some concerns, such as risk with privacy and connectivity failure, towards a reliable service.

Barros et. al., used fog computing for calculations of the power flow in the grid, which is usually performed in real-time to avoid overloads in the system. In this model, the information about voltage of load buses are transmitted to the fog servers to calculate power flow and decide if there is a need for transmitting more power or shutdown the load affecting the transmission in

the system. This work shows the possible contribution of fog computing to uninterrupted provision of power supply and power flow analysis [28].

Fog computing has also been suggested to help with load management in the distribution grid. The work in [25] shows that transferring the processing of load demand management requests to the fog nodes, aids in reduction of response time and processing time of load management. In this work, the allocation of requests in the fog system to optimize the response and processing times of load management has been investigated. The authors in [26] proposed an edge-computing based model for smart grid that can reduce the execution time of tasks related to the operation and monitoring of the grid. They have discussed and evaluated this model using a smart home automation use case, where the operating mode of the home appliances are monitored to aid in limitation of power budget and maximization of user's satisfaction and utility. It is also discussed that the fog computing platform will help with the privacy challenges in this problem.

Data aggregation and storage is another domain in which edge computing can be effective. The authors in [32] and [33] discussed the contributions of fog computing with data collection in the AMI. Due to the high amount of data that needs to be collected and processed from the smart meters, the regular two way communication between the meters and the cloud can increase the latency. It also increases the error rate in data transfer caused by multiple hops in the traditional way. Their work discussed that the inclusion of edge devices in the grid architecture reduces the amount of data to be sent to the centralized data-storage and thereby increases the efficiency of smart meters. Okay and Ozdemir [45] described the advantages of performing data aggregation at the edge as opposed to working with the cloud servers in existing solutions for this application with a focus on enhancing privacy during data aggregation.

2.2 Edge Computing Architectures for Smart Grids

Generally, the structure for edge computing includes, the physical layer (user plane), the edge devices layer and the cloud layer (or central plane). The user plane consists of devices that require a low latency service, such as smart homes, smart offices, smart vehicles, smart factories, etc. These devices based on the functions they perform each have requirements that can be fulfilled by edge computing to provide better interactions for the users. The edge plane consist of the edge servers with computation and storage capacities. Depending on the user's requirements, such as real-time data processing or data offloading, the edge servers' resources need to be managed, and task distribution and resource allocations need to be performed for this layer. The last plane is the cloud or the central plane, which are geographically distanced from the user's plane and can help with long term data processing and storage for the overall architecture. The central layer consists of data centers and cloud devices that are capable of processing and managing large volume of data (Big Data) [46].

Currently, the studies on edge computing in the smart grid mostly take this basic architecture form [34], while some modify the architecture based on the requirements for the system [26], [37]. For example, when edge computing is applied to the IoT layer, each layer can be further classified based on the level of processing to be performed. Although the works differ in objectives and methods, in most of the works, the architecture is considered to be layered into the physical layer, the edge layer, and the central cloud layer. For example, Xun et. al., [34] propose a three-layered architecture to detect FDI (False Data Injection) attacks in the transmission line measurements by placing FDI attack detectors trained with machine learning in the edge layer.

The work in [37] proposed dividing the fog layer into sub-layers for coordination of the fog nodes in one of the sub-layers to provide low latency and faster monitoring for IoT applications

in the smart grid, with the fog layer divided into fog node and fog coordination layers, respectively. The fog node layer handles all the computations for the layer with the aim to fulfill fog computing feature to migrate processing logic to the edge of the network. The Fog coordination layer consists of fog node clusters with each cluster managed by the coordinators. They control, organize and monitor the status of the fog nodes to improve application performance and handle complex tasks. The authors in [37] tested their architecture on an electric vehicle intelligent service and experimental results indicates that for long query distance, their architecture incurs lower latency than the traditional fog due to the fog coordinating structure.

The work presented in [47] is another effort that implemented a modified edge architecture with four layers. The mobile device layer, utility layer, data collector layer and the core distributing layer. The utility layer consists of routers and gateways, which handle the communication, data collectors in the third layer capture distributed data, process it and send it to the data center for further computation.

Another aspect for edge computing architectures in the smart grid is the form of implementation. The two basic forms are the hierarchical and software implementation [46]. The hierarchical model defines the functions of each layer explicitly based on distance and resources. Most research done in edge for smart grid use this model to deploy the edge servers in the architecture. The software implementation involves the use of a software model to execute edge computing. Studies, such as [26, 40, 45], illustrate the software implementation of the layered architecture for edge in smart grids. A few study under this scope involve the use of Software Defined Networking (SDN). SDN has been suggested to ease the complexities of edge computing due its contribution to reducing management and administration cost [48, 49].

To add intelligence to the edge, various distributed data processing and analysis as well as distributed machine learning techniques have also been studied. For instance, the use of deep learning in edge for smart grid applications. An example is [40] in which Liu et. al., designed an edge computing architecture for an IoT energy management system and deep learning was used at the edge layer and the cloud layer. At the edge, it was employed to find optimal scheduling results for the edge server through deep reinforcement learning, and at the cloud servers it was aimed at reducing computation cost. In their work, Liu et. al., also implemented the software model to classify their layers as the sensing, network, cognition and application layer. Several papers have discussed the topic of edge computing architectures for smart grids with their own twist, however in this thesis, the hierarchical model is implemented.

2.3 Optimum PMU Placement Methods

Due to the nature of the smart grid, it is of high significance that these proposed layers for the smart grid are optimized to ensure efficient operation of the architecture for its desired usage. To address this issue, in this thesis, the work done in our previous team's paper [1] is extended to optimize each layer of the edge-enabled smart grid. Several optimization methods in [50] were considered to aid the problem formulation for the optimization of the two layers. In connection with the IIoT layer of our proposed architecture, the problem of PMU placement has been studied. In general, the Optimum PMU Placement Methods try to address the problem of installing the minimum number of PMUs in the power grid to facilitate the full observability of the system [50, 51]. However, since the power systems are becoming more complex day by day in terms of operation and monitoring, the optimum PMU placement frameworks are designed to focus on more specific applications. For example, Shi et. al. [52] considered the problem of optimum PMU placement from the perspective of efficient power system state estimation. In this work, the authors

proposed the placement of the PMUs to minimize the mean squared error or maximize the mutual information between the PMU measurements and the states of the power system. The observability aspects (e.g. presence of the zero injection buses, the contingency of measurement loss), as well as the limitation of the communication channels per PMU, are considered as the constraints of the optimization problem of PMU placement. In [53], the authors proposed a greedy algorithm for the optimal placement of PMUs to defend against the data integrity attack i.e., false data injection attack (FDIA) in the power grid. This method uses a technique to estimate the minimum amount of sensors that needs to be compromised for the attack to be successful, and creates the greedy algorithm to optimally place the PMU's to prevent these attacks. Kesici et. al. [54] proposed an optimum PMU placement algorithm focusing on selecting features for the early prediction of transient instability in the power grid. The algorithm is designed to maximize the performance of predicting instability after a fault in the grid using Light Gradient Boosting Machine (LightGBM) classifier. In this thesis, the IIoT layer optimization is modeled with reliability in perspective. More discussion on the optimization models is presented in Chapter 4.

2.4 Edge Server Placement

One of the key factors in designing efficient systems is provisioning and allocating the required resources, where they are needed. Based on the functions of the system, the factors considered during this process varies, so does the methods used in resource provisioning and allocation. In the edge computing environment, various forms of resource allocation problem have been considered. For instance, the work in [55] places and allocate tasks to edge servers in the edge layer for mobile edge computing using mixed-integer linear programming. In [55], Yang et. al. considered SDN in their work to deploy cloudlets. For each component in the system, the processing time for each task was reduced and the energy consumption was minimized. Another

work that focused on the placement of edge servers in the system is [56]. In this work, the authors designed an algorithm to solve the problem of deployment for edge servers while evaluating the average data traffic for each placement case to ensure a minimal and optimal selection to attain low latency. The latency aware heuristic placement algorithm helped minimizing the response time in the system.

Bahreini and Grosu [57] also deployed a heuristic algorithm to solve the edge server placement problem. Their algorithm considered user's location with respect to delay and network capabilities to also determine the best matching connection between the edge and the user devices. The solution presented in [58] for edge server placement problem focuses on energy consumption and latency reduction. The approach resulted in reduction in the energy consumption at the edge servers while maintaining low latency by employing an adjusted energy-aware Particle Swarm optimization technique. One notable point from [58] is the use of a threshold in the placement, considering an acceptable level of delay based on the Euclidean distance. In the latter work, the edge servers are placed while minimizing the energy consumption and the overall cost.

Authors in [59] proposed a technique that balances workload distribution and minimizes edge server delay. Although, in their work they described the problem as a NP-hard problem, they adopt a mixed integer programming to find the optimal placement for edge servers with access delay and resource utilization in mind. Poularakis et. al., [60] also proposed a method for the edge server placement problem by building an algorithm to balance workload on edge servers and minimize offloading to the cloud. Using a randomized technique to develop their algorithm with approximation guarantees, a dynamic algorithm was built that adapts to changes in user demand profiles.

In this thesis, the problem of edge server placement for smart grids is studied while considering the location of PMUs in the system as well as the reliability requirements through added redundancy and communication system considerations.

Chapter 3: Edge Computing Enabled Smart Grid

The edge enabled smart grid is a rejuvenation of the traditional smart grid with the inclusion of edge computing. In this new form of smart grids, the functions of devices in the physical layer, power generation, power distribution, power transmission can be enhanced. For example, monitoring the state of the power system, electric vehicles charging options and information, as well as load management and billing information can be processed and accessed through the edge platform. The edge computing platform can also enable various security and privacy solutions for the smart grid. Efficiency is boosted by computation at the edge and consumers can receive better energy services through added reliability and security. In this chapter, the architecture of the edge-enabled smart grid is discussed. Furthermore, the application of the edge computing in the transmission and distribution networks of the smart grid is also discussed.

3.1 Edge Computing Enabled Smart Grid Architecture

In this thesis, a four-layered architecture for the EGT including the physical layer, the IIoT Layer, the edge layer, and the central layer is proposed. The physical layer includes the electric infrastructure containing electrical components, such as substations, generators, storage devices, transmission lines and consumer devices. The user devices comprise of smart meters, smart cars, smart home appliances, smart offices, and smart factories. Devices in this layer of the grid usually require time critical services, which suggest the need for local computation and processing power that can be supported by the edge layer.

The IIoT layer consists of monitoring and sensing equipment for measuring electrical signals and quantities throughout the physical layer. In this work, our focus in the IIoT layer is on the PMUs, which are deployed throughout the power grid to measure the time-synchronous measurements -

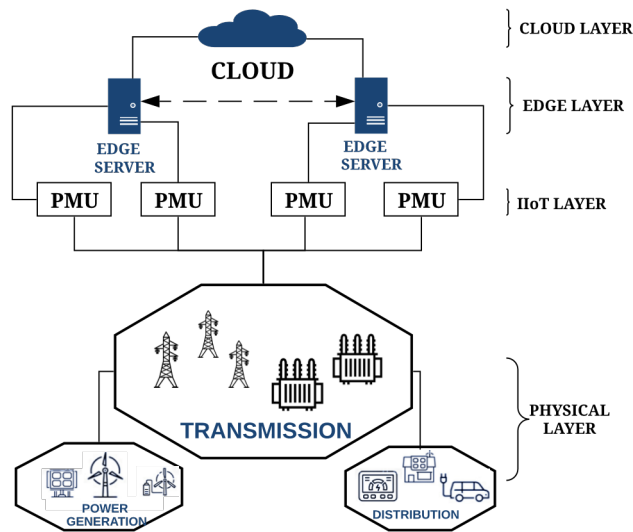


Figure 3.1: Architecture of the edge-computing enabled EGT. Flow from the physical layer to the Edge Layer.

of voltages, currents, and instantaneous frequencies. Although this layer has a limited computational capability in general, this layer collects data at a very high sampling rate and transmits data in various data-rates to the upper layers based on their priority and function.

The edge layer consists of edge servers that are equipped with data storage and data processing resources to perform certain data processing and collection tasks. Such tasks in power grids can, for example, help with time-sensitive functions and operations for monitoring the system using local data. The edge devices can also be some user components from the physical layer. Some examples of devices that can serve as edge nodes are standby computers, gateways, and smart phones.

The topmost layer is the central control layer also known as cloud layer, which performs central and heavy computations for the system that are not suitable to be performed in the edge layer. The central control consists of large data processing units, storage devices, and data centers that perform long term computations. As stated earlier in this thesis, the edge layer is not capable of taking on the task of the cloud, but it eases the load sent to the cloud for each computation and performs as the layer close to the end user for improving the response time in case of time sensitive functions or when the privacy aspects of data collection and processing is of concern. Traditionally, the computations for power grids are performed in the central layer. Figure 3.1 provides a conceptual illustration of this architecture.

3.2 Edge Computing in Smart Grid Applications

In this section, the application of edge computing in transmission and distribution networks of smart grids are discussed. In the transmission network, edge computing can enable system state estimation and system monitoring using local data processing, which can enhance the response time of the system in detection and mitigating the effects of stresses on the system. Developing early alerts for anomalies in the system using local processing of data in the edge, can improve the reliability and efficiency of smart transmission grids. To demonstrate the contribution of edge computing in the transmission network, in this chapter, specifically the application of edge computing in situational awareness in transmission grids is discussed.

The use of edge computing can also enhance the reliability and performance of distribution grid by adding processing and storage resources close to energy consumers and enabling privacy preserving solutions by avoiding the need to send all the data to the central cloud and processing units. To demonstrate this, the application of edge computing in the smart grid's AMI system is discussed.

3.2.1 Situational Awareness in Smart Transmission Grids Using Edge Computing

Power grids are critical infrastructures that provide the electricity service to the communities. The core backbone of these systems are transmission grids, which are responsible for high voltage transfer of power from generation sources to distribution networks. As such, their reliability is of critical concern and various research and technologies have been focused on enhancing the reliability of these systems. One of the critical functions towards enhancing the reliability of these systems is situational awareness and system state monitoring. As the transmission grids are geographically distributed systems, various sensors such as PMUs have been deployed in these systems to collect data on the state of the components of these systems. However, collecting these large volumes of data and processing them at a remote central location will inevitably add delays and affect the real-time observability and monitoring of these systems.

Traditionally, state estimation in power systems is performed using system models at the control centers with the aid of cloud computing. With the emergence of large number of meters, sensors and large volume of generated data, data-driven state estimations have been also considered to provide better system monitoring capabilities and to detect anomalies such as failures and cyber-attacks in the system. Moreover, the inclusion of renewable sources of energy has caused transmission networks to be more dynamic and more challenging to monitor. As such there is a need for real-time low-latency system monitoring and control for these systems, which traditional techniques and computational models may not be able to satisfy. The distributed and local processing nature of edge computing has been suggested as a promising new approach for supporting distributed state estimation and situational awareness in smart transmission grids. Note that similar discussion will also hold for power distribution network; however, due to high

sensitivity and critical requirements of the transmission network, the focus of this discussion is on transmission grids.

For instance, in the work presented in [1], edge computing platform is utilized for distributed state estimation using PMU data in the transmission grid. In this work, a data-driven technique for detection of anomalies in the system was designed to only use the local PMU data. It was shown that by implementing this distributed approach over the edge platform, where the system state estimates were generated at the edge servers, can generate early warnings for transmission line failures only using local data. In a similar approach, new distributed data-driven state estimations, particularly the multi-region ones, can be implemented using the edge platform, which will enhance the response time and real-time monitoring of the system. The situational-awareness performance and requirements can also guide the design and optimization of the edge architecture for smart grids. For instance, it can guide how to define regions and local neighborhoods over the system to be able to process their generated data locally more effectively. In the work in [1], the correlation among the PMU data streams were considered in defining the regions and the edge platform. In the latter, to test the architecture, a line failure was induced in the transmission grid and the voltage angle data of the buses were monitored. By local processing of such data in edge servers it was shown that the tripping of a line and location of failure can be identified in real-time locally by the edge nodes connected to a neighborhood or region. Similar to the work done in [1], this thesis focuses on the application of edge servers in the smart grid, furthermore, the thesis provides an answer to questions like to how many edge servers are required in the grid, on which node should the edge servers be placed, and how observable are the nodes to the edge servers in the system.

3.2.2 Edge Computing-Enabled Advanced Metering Infrastructures

The AMI involves a collection of smart meters connected over a communication network to enable two-way communication between the consumers and the energy suppliers (utilities). The installation of smart meters has enabled data collection and processing of load and demand profile of consumers. Smart meters can also control the smart appliances in a residential building, schedule their operations, and monitor their energy usage. The smart meters may receive the dynamic price information for load management from the utility supplier and send back the information about the energy usage over time. The use of advanced metering infrastructure in the electricity grid enables demand response, notification of suspicious activity or security breach, billing based on usage, power outage alert, wide area monitoring, self-damage repair and metering of energy consumption.

In terms of dynamic pricing, AMI would enable consumers manage their usage of electricity to reduce cost and also store energy for future use. This features put the consumers in control in terms of decision making for energy use. AMI along with micro-PMUs can also be used for state estimation. AMI in general allows new services, optimal asset utilization, and efficiency of operation in the grid. As stated earlier, AMI is a key system in the smart grid as it enables some of the smart functionalities of the smart grid, it consists of the smart meters, communication networks, data concentrators, and central system also known as the head-end system. The smart meters at the consumers are for collecting and communicating data. A smart meter is connected to a home area network (HAN) as shown in 1.1 for connecting, monitoring and controlling consumer devices. The head-end system is usually located inside a metering company involving the meter data management system (MDMS) which stores, manages collected data, maps it to the relevant

customer and perform analysis on the data to help with the distributed operator system actions on the grid.

The AMI has several requirements based on its specific functions; however, one of the basic requirements is security and privacy of the consumer data as data from consumers in these environments carry sensitive information that needs to be protected. Failure to provide adequate mechanism to provide privacy can lead to attacks from intruders. Also, smart meters being a part of the cyber physical systems are exposed to security threats and concerns of the cyber world (e.g. false data injection or denial of service attacks). Hence there is a need for authentication and encryption techniques to fulfill the security requirements of confidentiality, integrity, accountability and availability.

Edge computing as a technology capable of handling environments with heterogeneity and large volume of data to be collected, processed and handled, provides new opportunities to enhance the AMI functions. Edge computing can bridge the gap between the consumer and suppliers by ensuring low latency, increase in privacy, security, and reliability of data collection and processing. Due to the fact that edge does not require data to be sent to a central controller for decisions to be made, the edge-enabled AMI would be able to support privacy preserving data processing. Moreover, various data processing techniques over smart meter data, such as load disaggregation and demand prediction can be implemented using distributed data processing and machine learning methods over the edge platform.

Chapter 4: Optimization of Architecture Layers

In this chapter, the optimization formulations for the IIoT and edge layer are presented. The optimization formulations include IIoT layer optimization, edge layer optimization and edge layer optimization with communication technology considerations.

4.1 IIoT Layer Optimization

The key goals of design and optimization for this layer is to identify the least number of PMUs to place in the system while providing full observability for the smart grid. As discussed in Section II, optimal placement of PMUs have been studied extensively in the literature. The goal in this thesis is to use a simple formulation that will help with the design of the Edge layer. Any other optimization approach with other constraints such as more power specific constraints can also be used for this layer.

In this work, it is simply assumed that a bus, say i in the system is observable if a PMU is placed and associated with it or one of the directly connected buses to bus i has a PMU. However, since a single PMU providing observability for a bus can be a single point of failure, it is considered that a required number of PMUs, denoted by β , should be present in the one-hop vicinity of the buses for added reliability. For instance, $\beta = 2$ means at least two PMUs should be in one-hop distance of each bus (including on the bus itself).

Based on the above simplifying assumptions, the formulation for the PMU placement optimization as following:

$$\min_x \sum_{i=1}^N x_i,$$

such that:

$$(1) (x_i + \sum_{j=1}^N A_{i,j}x_j) \geq \beta, \text{ for all } i \text{ and } j \quad (4.1)$$

$$(2) x_i \in \{0,1\}, \text{ for all } i$$

where N is the number of buses (e.g., substations or generators) in the system and vector $X = (x_1, x_2, \dots, x_N)$ is a binary vector capturing the placement of PMUs.

Specifically, $x_i = 1$ if there is a PMU co-located with bus i and $x_i = 0$ means there is no PMU at bus i . The objective of this optimization is to identify the minimum PMUs needed while satisfying the observability condition discussed in the previous paragraph in the first constraint. Note that A_{ij} are the elements of the adjacency matrix of the power grid, where $A_{ij} = 1$ if buses i and j are connected through a transmission line and $A_{ij} = 0$, otherwise. The optimization problem can be solved using Binary Integer Linear Programming (BILP).

4.2 Edge Layer Optimization

In this subsection, the design of the edge layer is addressed by determining the optimal location of edge servers over IIoT layer considering the location of PMUs. As the PMUs sample and collect measurement data from the power system, they transmit data for processing to the processing units in the edge layer as well as the central layer. As such considering the local communication and computational constraints are important for this optimization. Therefore, as important criterion in placement of edge servers is their geographical proximity to the PMUs that they need to communicate with. Moreover, each edge server has specific communication and computation capacity that limits the number of PMUs that they can work with for communication

and data processing. Finally, redundancy in the edge layer is another important factor that will allow the system to continue its operation effectively under edge server failures. Finally, the objective in this optimization is to minimize the number of edge servers and decide the optimum connectivity among edge servers and PMUs. With these considerations in mind, the formulation of the optimization problem is as follows:

$$\operatorname{argmin}_{Y,K} \sum_{j=1}^N w y_j + \sum_{i=1}^N \sum_{j=1}^N k_{i,j} d_{i,j}$$

s. t. :

- (1) $k_{i,j} \leq x_i$, for all i
- (2) $k_{i,j} \leq y_j$, for all j (4.2)
- (3) $\sum_{i=1}^N k_{i,j} \leq C$, for all i and j
- (4) $\sum_{i=1}^N k_{i,j} \leq \alpha x_i$, for all i and j
- (5) $k_{i,j}$ and y_j are binary variables for all i and j

In the above optimization formulation, the binary vector $Y = (y_1, y_2, \dots, y_N)$ is the binary vector of edge server placement, where $y_j = 1$ means an edge server will be co-located with bus j and $y_j = 0$ means no edge server is placed at bus j . Note that the PMUs are identified based on the optimization in equation (1) in the form of vector $X = (x_1, x_2, \dots, x_N)$. As such, it is assumed that the vector X is known for this optimization. The binary variable $k_{i,j}$ (for all $i, j = \{1, \dots, N\}$) specifies the connection among edge servers and the PMUs. The $k_{i,j}$ form the elements of matrix K , which shows the overall connectivity structure between the IIoT and the Edge layer. Specifically, $k_{i,j} = 1$ refers to the case that PMU at bus i is connected to the edge server at bus j and $k_{i,j} = 0$ indicates that there is no connection between PMU at bus i and edge server at bus j . Parameter $d_{i,j}$ denotes the geographical distance between buses i and j . The parameter C represents the capacity limit of edge

servers; specifying the number of PMUs they can support. The parameter w denotes the cost of edge servers, which will help balance the weight of the two terms in the objective function. The parameter α captures the required number of redundancy (i.e., backup servers for each PMUs). Based on the above notation, the first constraints specifies that if there is no PMU at bus i (i.e., $x_i = 0$), then the element $k_{i,j}$ should be zero; otherwise, if there is a PMU at bus i , then $k_{i,j}$ could be either 1 or 0. The second constraint specifies that if there is no edge server placed at bus j then the element $k_{i,j}$ should be zero; otherwise, if there is an edge server at bus j , then $k_{i,j}$ could be either 1 or 0. The third constraint of the optimization defines the capacity limit for the edge servers, which means that an edge server placed at bus j can be connected to maximum of C PMUs. The fourth constraint implies that each placed PMU x_i needs to be connected to at α number of edge servers.

4.3 Edge Layer Optimization with Communication Technology Considerations

In designing the edge layer for the smart grid, one of the key considerations is the communication technology that can best serve the critical and time-sensitive functions and operations in the system. Specifically, certain time-sensitive functions that require local data processing, may dictate specific communication delay requirements between the PMUs and the edge servers. As such, not only the placement and geographical distance among PMU and the edge servers are important (as captured in the optimization formulation in (4.2)) but also the type of technology to support the communications (wireless or wired technologies, such as LTE, 4G, 5G and optical, power line communication) are critical. As such in this section, the optimization formulation (4.2) is extended to capture jointly the placement, connectivity and the technology selection for this layer.

For simplicity, two types of communication technologies are considered to optimize the solution (this formulation can easily be extended to any number of technology options). The problem is formulated as follows:

$$\begin{aligned}
 & \underset{Y, K^1, K^2}{\operatorname{argmin}} \sum_{j=1}^N w y_j + \sum_{i=1}^N \sum_{j=1}^N w^1 k_{i,j}^1 d_{i,j}^1 + \sum_{i=1}^N \sum_{j=1}^N w^2 k_{i,j}^2 d_{i,j}^2 \\
 & \text{s. t. :} \\
 & (1) \quad k_{i,j}^1 \leq x_i \text{ and } k_{i,j}^2 \leq x_i, \text{ for all } i \text{ and } j \\
 & (2) \quad k_{i,j}^1 \leq y_j \text{ and } k_{i,j}^2 \leq y_j, \text{ for all } i \text{ and } j \\
 & (3) \quad \sum_{i=1}^N (k_{i,j}^1 + k_{i,j}^2) \leq C, \text{ for all } i \text{ and } j \\
 & (4) \quad \sum_{j=1}^N (k_{i,j}^1 + k_{i,j}^2) \leq \alpha x_i, \text{ for all } i \text{ and } j \\
 & (5) \quad (k_{i,j}^1 + k_{i,j}^2) < 2, \text{ for all } i \text{ and } j \\
 & (6) \quad k_{i,j}^1 \cdot d_{i,j}^1 \leq D \text{ and } k_{i,j}^2 \cdot d_{i,j}^2 \leq D, \text{ for all } i \text{ and } j \\
 & (7) \quad k_{i,j}^1, k_{i,j}^2 \text{ and } y_j \text{ are binary variables for all } i \text{ and } j
 \end{aligned} \tag{4.2}$$

In this new formulation, the optimization formulation in (2) has been extended such that instead of making decision about connections among PMUs and edge servers through $k_{i,j}$, two types of binary k variables are considered, one for communication technology type 1, denoted by $k_{i,j}^1$ and one for communication technology type 2 $k_{i,j}^2$. This means that if the $k_{i,j}^1 = 1$ then for communication between PMU i and edge server at bus j , the communication technology type 1 is employed. Note that each communication technology impose certain communication throughput and delay based on geographical distance, channel properties and other factors (as discussed later), which are captured through updated $d_{i,j}$ variables, denoted by $d_{i,j}^1$ and $d_{i,j}^2$. In other words, the $d_{i,j}^1$ represents the communication link properties and specifically delay between PMU at bus i and

edge server at bus j . The constraints 1-4 in this optimization are equivalent to the 1-4 in formulation (2). The new constraint (5) ensures that only one of the k_{ij}^1 or k_{ij}^2 are claiming value 1 for each i and j . Finally, the new constraint (6) captures the acceptable communication delay between PMU at bus i with edge server at bus j , denoted by D as dictated by time-sensitive functions in smart grids. Note that w^1 and w^2 represent the cost to employ communication technology type 1 and 2, respectively.

Also, note that in this formulation, it is assumed that a single edge server can support multiple technologies. While this assumption may not be valid for all edge platforms, it can be relaxed in the extensions of this work. In this thesis, two example communication technologies are considered, specifically, a wired technology (such as fiber optic) and a wireless technology (such as 4G LTE). To characterize the values of d_{ij}^1 and d_{ij}^2 based on the communication technology, various properties of the communication technology can be considered; however, in this thesis, the propagation delay between two points based on their distance is simply considered. This also depends on the speed of the communication waves in the medium.

In addition to these two factors, in wireless technologies, packet loss needs to be considered in communication delay, while for wired technology the packet loss is negligible. As such, the packet loss effect in wireless communication delay as a function of the probability of successful packet transmission and the propagation delay of the channel is captured. In case of wired technology, the communication delay is defined as a function of just the propagation delay.

In addition, the cost of employing communication technology 1 is defined to be γ times that of technology 2, i.e., $w^1 = \gamma w^2$.

Chapter 5: Results

In this chapter, the experimental results to the optimization algorithm is discussed. IEEE 118 bus system is considered for the physical layer of the system. Next, the results for optimal placement of the PMUs and edge servers as discussed in Sections IV are displayed and further evaluated based on the parameter in the optimization. The optimizations have been solved using integer linear programming method in IBM ILOG CPLEX [61]. In each optimization, the impact of the defined parameters β , α , ω , and C on the placement decisions have been evaluated.

5.1 IIoT Layer Optimization

For the IIoT layer optimization, the results of the pmu placements for the IEEE 118 bus system in the layer gives; the minimum number of required PMUs to be 32 for redundancy factor $\beta = 1$ and 57 for redundancy factor $\beta = 2$. In Fig. 5.1, the placement of PMUs for $\beta = 2$ is represented with PMUs denoted by green squares. The total number of pmu's, x for each level of redundancy is depicted in Table 5.1.

Table 5.1: Number of PMU (x) based on Redundancy (β)

β	x
1	32
2	57
3	76
4	89
5	100

5.2 Edge Layer Optimization

For the edge layer, levels from 1 to 5 are considered for redundancy factor (α) in the edge layer. The weight w is assigned values such that both terms of the objective function in equation 2 have comparable impacts (i.e., w is set to be equal to the average distance captured in $d_{i,j}$ values). Based on these considerations, for IIoT level of redundancy, $\beta = 2$, and the number of PMU's $x = 57$, the minimum number of edge servers in the edge layer is 12 for $\alpha = 1$ and 15 for $\alpha = 2$ in the IEEE 118 bus system. In Fig. 5.1, the optimal placement of edge servers for $\alpha = 2, \beta = 2$ are marked by the circles in magenta.

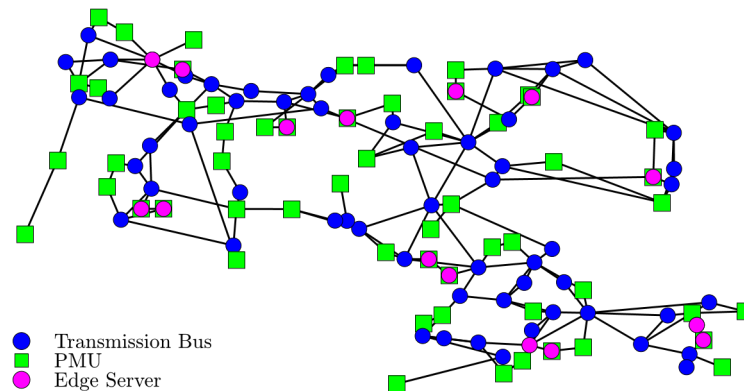


Figure 5.1: Placement of PMUs and Edge nodes for the IIoT and Edge Layer in IEEE 118 bus system.

5.3 Edge Layer Optimization with Communication Technology Considerations

Finally, in the optimization with communication technology considerations, with regards to the edge server placement, similar behavior is observed to that of the formulation without the communication factor for various parameters, such as β and C . For the optimization with communication considerations, the average delay d_i^1, j and d_i^2, j for the value of w and γ is considered to be 10. Also, $\beta = 1$, $C = 8$, and $D = 0.99\mu s$.

Table 5.2: Frequency of selection based on communication technology

α	Y	$k_{i,j}^1$	$k_{i,j}^2$
1	4	4	28
2	8	5	59
3	12	4	92
4	16	5	123
5	20	6	154

From the optimization, it was observed that the wireless technology, type 2, is selected often. For instance, when $\alpha=2$, the total connections based on wired and wireless technologies are 5 and 59, respectively. Also for $\alpha= 5$, the resulting number of times technology 1 and 2 are selected is 6 and 154 for each respective selected links. This is due to the lower cost of wireless communication with acceptable delay based on geographical distance and other discussed factors. For the cases with strict delay requirements, wired communication may be selected despite its higher cost.

5.4 Evaluation and Discussion

Table 5.3: Number of edge servers (Y) based on values of β

β, α	1	2	3	4	5
1	32	43	49	52	53
2	44	63	79	85	89
3	61	79	96	99	107
4	76	95	105	106	110
5	86	104	113	113	115

Table 5.4: Number of edge servers (Y) based on values of ω

ω, α	6000	3000	1500	750	10
1	6	8	11	17	57
2	12	15	21	36	85
3	18	23	31	50	102
4	24	30	41	66	113
5	29	37	50	78	115

Table 5.5: Number of Edge Servers (Y) based on Capacity

C	Y
3	38
4	29
5	23
8	16
10	15

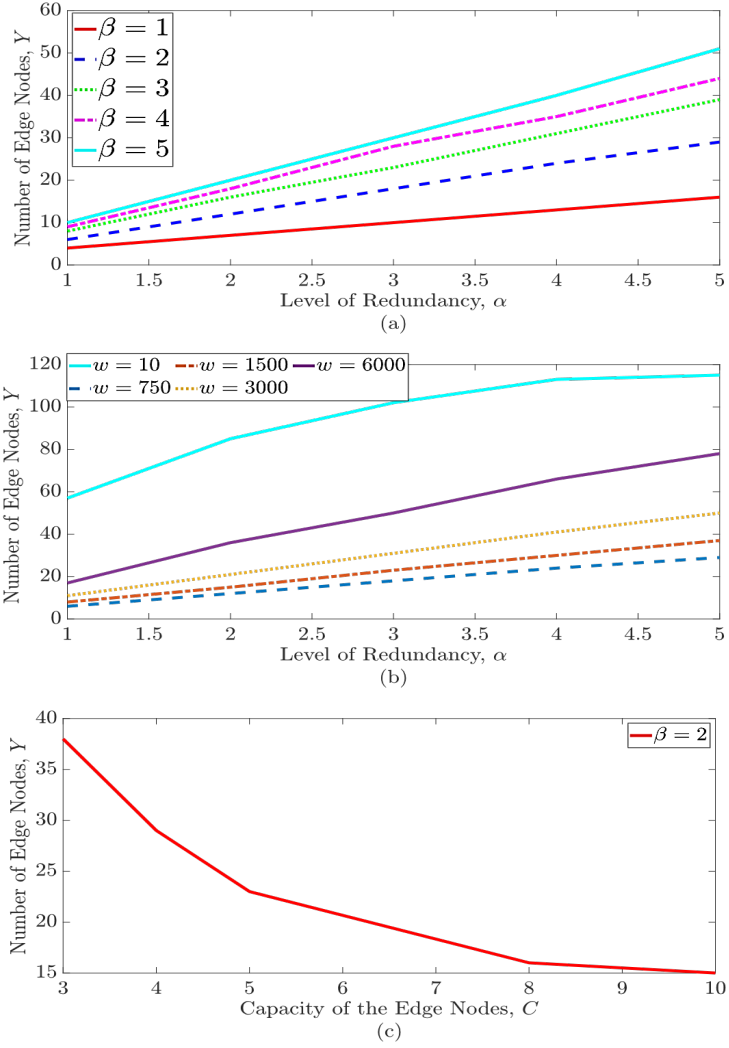


Figure 5.2: Dependency of the minimum required number of edge nodes, Y on design parameters (β , α , w): (a) effect of level of redundancy in IIoT level, β on the Y as a function of α , (b) effect of w on the Y as a function of α , (c) effect of edge node capacity, C on Y for $\beta = \alpha = 2$.

The number of edge servers as a function of other α and β values are depicted in figure 5.2- a. figure 5.2-b illustrates the number of minimum edge servers as a function of weight values w and redundancy factors. From figure 5.2-c, it is observed that the required number of edge nodes increases with the increase in redundancy in the IIoT layer, which results in larger number of PMUs.

Similarly, the number of required edge nodes increase with increase in redundancy factor for the edge layer. This means that the higher the level of redundancy, the higher the minimum required number of edge nodes for the edge layer; however, in general the redundancy factor is considered to be a small number. From figure 5.2 it can be observed that the relationship between the weight parameter and number of edge servers is of inverse proportionality (i.e., the lower the weight, the higher the number of edge servers). This indicates that with a low value for w , the algorithm places the edge nodes based on the geographical distance as a priority and the objective of minimizing the number of edge servers is not realized due to its low weight. As such, it is important to select w in the order of $d_{i,j}$ values.

Figure 5.2-c shows the inverse proportionality between the capacity value C and the number of required edge servers. For the IEEE 118 bus system, if edge nodes have higher capacities to support 10 PMUs then the total number of required edge nodes can be as low as 15. However, with low capacity edge nodes (each supporting only 3 PMUs), this number will be 38.

Chapter 6: Conclusion

In this thesis, it has been discussed that edge computing is viable to enhance the operations of the current smart grid, from its ability to provide low latency, location awareness, time critical application support, heterogeneity support, real-time data analytics and Improved quality of service, the edge computing can enable various applications in smart grids.

As such this is important to design and optimize this platform for smart grids. In this work, a literature review on edge computing for smart grids and the state of art for this new area of edge-enabled smart grids is provided. Furthermore, a four-layer computational architecture for the EGT has been proposed in this work to incorporate edge-computing in smart transmission grid. The location of the PMUs in the IIoT layer and the connection of the edge-nodes with the PMUs in the edge-layer are obtained through optimization under several constraints. Results show how the design considerations are affected by certain parameters, the capacity of the edge nodes, and the level of redundancy in the observability of the grid. Also these factors have been specifically incorporated in the optimization formulation and evaluated the results of the formulation on IEEE 118 bus system.

The edge-enabled smart grid is a new and emerging domain of research, which requires extensive investigations in various aspects to be ready to be implemented in smart grids. For instance, the edge-enabled artificial intelligence, distributed data analytics and machine learning that can be implemented on edge computing platform are important topics to investigate. Specifically, after the architecture is designed, the challenge would be how to implement the intelligence on the edge platform using its limited resources to achieve high responsiveness,

security, privacy and efficiency in analysis of energy data. While the edge computing can help with some of the smart grid functions, the central processing and control will remain to be a key platform for data analysis and processing in smart grids. As such, the co-existence and collaboration among the edge and central processing units need to be characterized and planned as well. Security of the edge platform for implementation of critical smart grid functions is another key research direction towards enabling edge computing for smart grids. Another recommendation for future research would be to investigate the use of new communication technologies such as, 5G, as the communication technology for the link between the IIoT layer and the edge layer, and also analyze the allocation of resources in such cases. Although many of the existing edge platforms can be adopted and customized for smart grids, the architecture of the edge-enabled system needs to be investigated further based on the available edge server technologies and communication technologies to identify the most effective and cost efficient implementation as the cost of these systems will be an important factor in their deployments due to the large size of smart grids.

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