Smart Grid Networks

Analysis of Timing Requirements for Data Aggregation and Control in Smart Grids

Masters Thesis

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Abstract:

Modern communication mechanisms are at the heart of a Smart Grid system to ensure that the required information is transmitted within various components of the Electric Grid. Throughout this Master Thesis, we have studied how communication performance and Smart Grid Controllers effects the overall Smart Grid operation with focus on time and requirements to the network.
For this we have implemented a network simulation using OMNeT++ to study smart grid network traffic and use the collected data to train a resource allocation learning algorithm implemented in Matlab. The method will enable us to have a real number evaluation of the choice of timing requirements for the communication network and the controller by taking into account the constraints present on the system.

Contents

Preface

This thesis is written as part of a work done for fulfillment of Master of Science degree in Network and Distributed Systems at department of Electronic Systems, Aalborg University. The main theme of the project being Smart Grid Networks, It is a work done at spring semester 2014.

The report has nine chapters, with the first two chapters giving an overview of the problem at hand and a better understanding of Smart Grid environment. For the introductory chapters We would like to mention that, we got inspiration from [1] which is the previous work of the same author for this work. Proper citations will be put if the materials used for this sections are from a different source other than [1].

Chapter 3 and Chapter 4 will show us how the problem is modeled by fixing the parameter space and give us an overview of the methods implemented. Chapters 5 6 7 will analyze the methods used and the process we have gone through to use them for our specific use cases.

The next two chapters are used to discuss and elaborate test scenarios and the results we got from test simulations and implemented algorithms. The last part of the report are sections for conclusion and achievement where we have explained the great lesson taught and achieved during the course of the work. We have also put some interesting recommendations for future expansion and modification of this work.

The external references will be shown as numbers, which are interactive and can jump to the reference when using the digital version. The report also has a list of figures and tables.

The attached CD contains a PDF version of this report(NDS1026-SmartGrid Networks.pdf), OMNeT++ code(omnetpp.rar) and Matlb code (matlab.rar) with each folder having the result and test data within it.

Aalborg University, June 3, 2014

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Chapter 1

Introduction

1.1 Historical Overview

Different studies show that there is a causality between the increase of Gross Domestic Product (GDP), and the consumption of energy especially electricity [10]. After the second world war, most of the now developed Europe has undertaken fast economic growth and made huge reconstruction. This has led to increasing demand in electricity because of the demand from industries and the resulted new way of life with more electrical appliances and in-home devices. Not only Europe, the worldwide consumption of electric power has doubled since the year 1965 [11].

The large scale increase in electricity demand has led to constructions of huge electric generation stations and a web of interconnected transmission grid. But after this era, the grid remained unchanged for long period of time. This has occurred due to various reasons like that it is expensive cost wise, time consuming, and in some cases controversies related to construction locations and policy makers. This reasons has played a part for the grid to remain 'ancient' compared to advancements in other areas.

The old grid is centralized in nature with the power plants placed at strategic locations close to their energy sources to produce large amounts of power needed by the grid. But in recent decades there are very fast advancements in production of power from non renewable energy sources like wind, solar, hydroelectric and geothermal. This non renewable energy sources are very distributed in nature with offshore farms and more. Another aspects of this sources is the energy they produce is variable because of unpredictability of the sources unlike for the non renewable ones.

The unpredictable nature(variability) of non renewable energy sources is a challenge in order to balance the consumption of energy with generation

of power. This has created a large demand in having real time and efficient communication infrastructure coupled with the power grid. It is also very critical to automate the system from what was manual based grid to avoid failures and make the system reliable. An example fault is a blackout in 2006 where a planned power cut in Northern Germany introduced a blackout for more than 15 Million people for up to 40 minutes, and introduced disturbances in electric lines (e.g frequency shift) in Europe for a time span of close to 2 hours[12]. Due to the above mentioned reasons and experiences it is crystal clear that Smart Grid is the future for the power industry.

1.2 Motivation

Its not questionable that a smarter grid over the traditional grid is the driving factor for energy efficiency and in incorporating wide range of non renewable energy generation units. The fact that implementation of Smart Grid promotes green technologies while minimizing cost of energy generation and operation has enabled it to get the support of major parties involved including policy makers. Smart Grid has attracted interests from National Governments, Utility companies, Consumers, Prosumers to Researchers ,Cellular companies and communication technology firms.

Energy system is becoming dependent on distributed non renewable generating units. There will also be an increase in energy demand with the growth in popularity of electric vehicles and other high power devices. For this a Smart Grid will enable the power system to collect, exchange and take action to ensure that the reliability, security and efficiency coefficients are maximized and to ensure sustainability of the system and the services it provides. [13]

Energy companies are competing to make most of the opportunities created with increased demand in electric demand. Since different governments and policy makers are tightening the rules regarding construction of non renewable energy generation units, the companies are investing more in constructing more non renewable energy generators. For the growing non renewable plants, to integrate it to the main grid, Smart Grids are playing a big rule. The major obstacle on the faster growth of Smart Grids is their cost of deployment but countries like UK and Denmark are mandating plans for the implementation. In 2011, the smart grid network set up by the Danish Ministry for Climate and Energy, published a report that points to 35 recommendations which contribute to establishing a Smart Grid in Denmark. [14]

Location Intelligence [15]and proper delivery of information are equally important for each of the technologies used in smart grids such as Power Line Communication, wireless technologies, access networks and others. In this thesis work, our aim is to examine, study and propose time allocation method for fulfilling Smart Grid communication timing requirements, focusing on Data collection by the aggregators using DSL access networks and how it affects the way electric grid is controlled.

1.3 Problem introduction and formulation

The Smart Grid concept has widely been used in recent years in different contexts and with different definitions [16]. In this project, Smart Grid is viewed as a network of electric generation units, transmission lines, distribution substations and consumers with sensors and communication devices as part of the communication infrastructure.

It is apparent that over the past century, significant improvements are seen in communication technologies. This has opened the door for resolving restrictions on electrical grids due to communication constraints. Non renewable energy sources such as solar energy and wind energy are significantly variable demanding highly sophisticated control mechanisms requiring a communication system capable of meeting the task of facilitating connection of distributed sources to consumers.

Modern communication mechanisms are at the heart of smart grid system to ensure that the required information is transmitted within various components of the grid. For this, the communication system should be resilient, self healing, reliable, low cost and secure. The choice of communication technologies between cellular technologies and building a dedicated infrastructure is mostly influenced by availability and the aforementioned factors. To give an example, choice of technologies in Denmark focuses mostly on cost since multiple technologies are already available. While for the case of my home country Ethiopia, availability becomes critical due to less coverage area as compared to the large size of the country.

For complex controllers deployed on Smart Grid, the communication infrastructure must have the capacity to route the information within an optimal time frame. This is affected mostly by delays caused by the control operation and the communication infrastructure. The main motive for this work is the need for a method to optimize the delays in-terms of minimizing the total time for the operation and maximizing the capacity of the system.

1.3.1 High Level Objectives

Throughout this Master Thesis, we will study how communication performance and Smart Grid Controllers affects the overall Smart Grid operation with focus on time delay and requirements to the network. For this we will propose a method, make analysis and implement simulation of predefined scenarios with Further comparisons and testing of the performances.

The main objectives of this work are:

- To model the problem in a proper simplified method by fixing the parameter space.
- To design a method which takes the delay requirements of the communication infrastructure and control server.
- To analyze performance delay requirements for Smart Grid control server.
- Acquire experience in using OMNeT++ for network traffic delay analysis through simulations.
- To propose resource allocation algorithm which can be used to allocate proper amounts of processing time for the control server and the network.
- Compare and evaluate proposed method by making implementation prototype and analyze it by using proper tools like Matalb .

1.4 Related Works

In this section we will asses papers related to Smart Grid timing requirements, network delay analysis using Gaussian mixture model and Smart Grid simulations. Although We didn't find a paper that is dedicated for resource allocation problems in Smart Grids specifically dealing with timing requirements, we will see related works which use part of the methods that we are using like delay estimations using Gaussian mixture models and Smart Grid network simulations.

[8] states the communication delivery times for different applications in smart grids. It has described a standard defining communication delivery times of information to be exchanged within and external to substation integrated protection, control, and data acquisition systems. Communication capabilities and system capabilities to deliver data on time are also specified[8]. The delivery time for different information types ranging from text strings, data files to streaming for grid applications are standardized.

The idea of using mixture models is a common practice in studying delay distributions of a communication infrastructure. [17], [18], [19] all use Gaussian mixture distribution with maximum likelihood expectation maximization to model the distributions of communication network delay measurements. It is mostly used for intrusion detection algorithms in the area of network security.

[20] Proposes penalized maximum likelihood expectation maximization (PML-EM) algorithm applied on additive Gaussian mixture model. We used related method for our algorithm which is maximum likelihood expectation maximization (ML-EM) and the chosen distribution is Gaussian mixture model.

while [21] is a paper to simulate both the communication side and the control aspects of a smart grid scenario. OMNeT++ is used to simulate the communication infrastructure by using Power line communication as a communication technology. On this work, they have used hierarchical control mechanism for market controller. The main goal of this work is to adapt the controller on the occurrence of network imperfection such as packet loss and delays[21].

Chapter 2

Pre-Analysis

Our goal in this chapter is to analyze and have a good overview of Smart Grid environment with detailed focus on the communication infrastructure, performance requirements and Smart Grid Controller.

We will first start by making analysis of the power components for Smart Grid, the next step is to analyze and have an overview of the communication technologies that can be used in Smart Grids with introduction to Smart Grid control making the final part. We would also like to mention that to write this section, we got inspiration from [1] which is the previous work of the same author for this work. Proper citations will be put if the materials used for the section are from a different source other than [1].

2.1 Smart Grid Power components

Let us start by introducing components of the power grid to have a better understanding of the problem at hand. The power grid is a system of electrical systems working jointly to generate and transfer electrical power from the sources to households, industries, and storage stations. figure 2.1 shows components of a modern power system. Next we will discuss the main components of the power system :

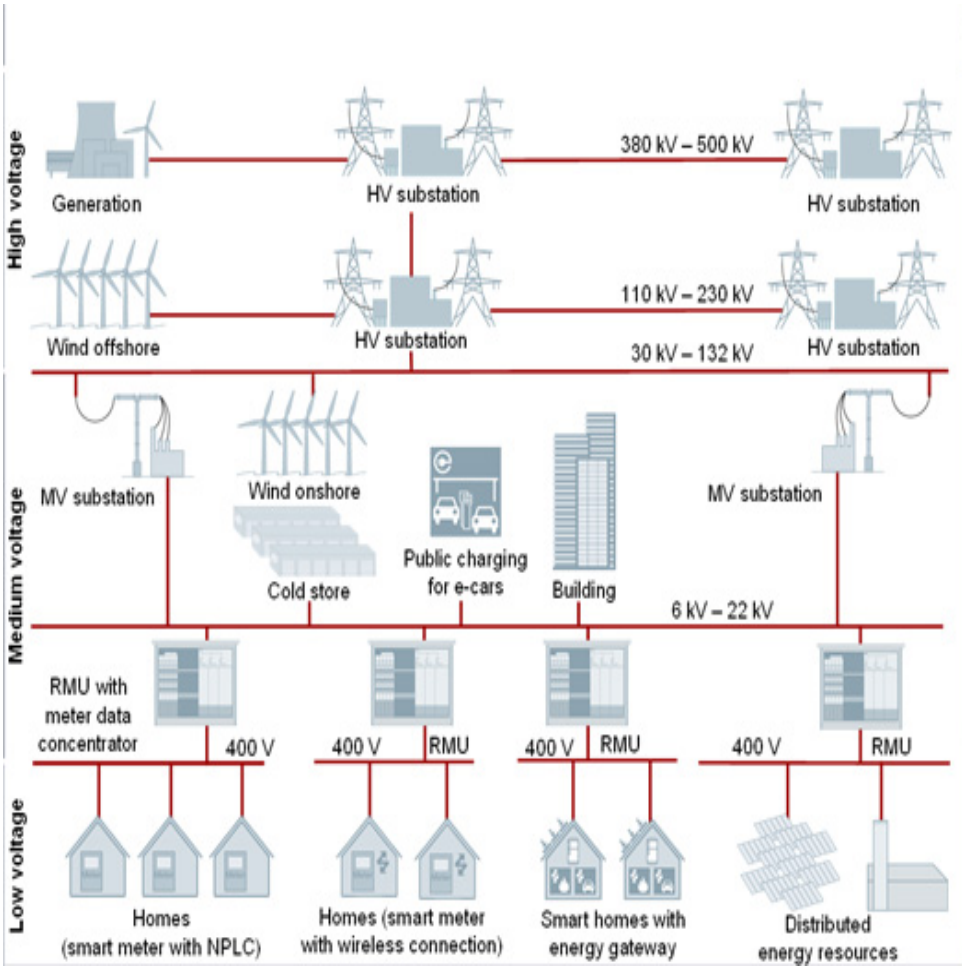

Figure 2.1: *Electricity grid schematic and components[2]*

Power Plant -A power plant is where electric energy is generated by means of conversion from other types of energy sources such as mechanical energy (from hydroelectric turbines and wind farms), heat energy (from Solar cells), and more. The main component of a power plant is electric generator built to convert mechanical energy to electrical energy by using a rotating conductor and magnetic fields.

Electrical energy sources can be categorized as renewable energy sources and non-renewable energy sources. Non renewable energy sources produce electrical energy by means of fuel sources. Some of widely used fuel sources for non renewable energy generation are coal, oil, natural gas, and nuclear energy. Renewable energy(Green energy) sources instead use solar energy, wind energy, geothermal energy, biomass and hydro electric power as a source of energy.

Figure 2.2: *Offshore wind farm [3]*

Currently, there are increasing number of initiatives to promote renewable energy sources also know as clean energy sources. For example the Danish government has set a target which states that 50% of the electricity consumption should be supplied by wind power by 2020. As shown on the chart in figure 2.3, the major sources used currently are non-renewable energy generation plants that use coal.

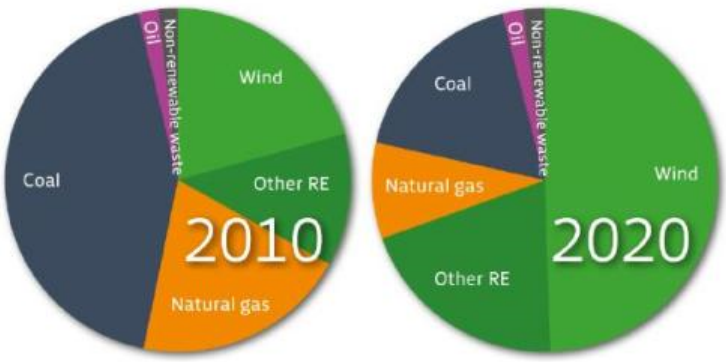

Figure 2.3: *Danish Energy generation[4]*

Transmission line -Seen widely as the most important sub component of the grid, the main task of transmission lines is to transfer the electrical energy from the source to different geographical areas where demand centers are located. Practically, transmission lines are interconnected to form a web of networks known as a transmission network.

Substations - This are familiar sites in highways and urban settlements and they are responsible to step down high voltage power from transmission lines to lower voltage. Another main task of substations is to make sure that the distribution network is working as expected or not. Inside substations we find main components like power transformers, Control devices, switching devices, and safety devices(circuit breakers to cut power on the occurrence of outages). Distribution substations are type of substations which use step down transformers to reduce the voltage to 200v or 400v which are supply voltages for usage at homes.

Transformers - It is a component used int the power grid to transform the power to the desired level. During generation, electric power has low voltage due to the fact that it is much cheaper to generate it at low voltages. To transmit this voltage, the cost effective way is to step up the voltage level to high voltage values and transmit it using high voltage transmission lines. The current for high voltage transmissions reduces significantly causing a low I^2R loss which in-turn requires a low cross-sectional area conductor. The voltage at distributed circuits is stepped down again using step down transformers.

2.2 Communication technologies used in Smart Grid

In a robust and reliable Smart Grid network, the importance of real-time and reliable information becomes paramount and can be considered a key factor in the delivery of power to end-users[22]. Real time monitoring can be used to minimize and control the impact of down times caused by natural accidents, equipment failures, and constraints due to capacity.

For Smart Grid, One of the main infrastructures is the communication system. [23] The introduction and use of more advanced technologies and applications over the electric grid, leads to the creation and need to transport large amounts of data from different locations, so it is critical for the utility companies to define the communication requirements[22] which can insure reliable service and functioning of the whole system.

In Smart Grid networks, We can categorize Smart Grid communication technologies with the two most commonly used data transmission methods namely wired and wireless communications. Each of the mentioned mediums have advantages and disadvantages depending on the scenarios they are used for which we will discuss thoroughly on the next sections.

When analyzing Smart Grid communication network, we use three types of network layers [5]. As shown on figure 2.4 The layers are Home Area Network(HAN), Neighborhood Area Network(NAN) and Wide Area Network(WAN). HAN is the first layer which has a direct access to consumers. It has metering module(MM) which records energy consumption, service module(SM) providing cost and consumption data to the consumers and meter controlling system(MCS) which takes care of information to be transmitted from SM and MM to upper layers.

The next layer above HAN is Neighborhood Area Network(NAN) with large amounts of networked meters. On this layer we find Central Access Controller (CAC) and a Smart Meter Data Collector(SMDC) which is used to collect information from the meters. SMDC is also known by the widely used term as an Aggregator.

The top layer is Wide Area Network(WAN) with the task of facilitating communication between NAN, Distribution lines and Substations. It has a component for taking care of the distribution of metering data called Energy distribution System(EDS). Supervisory control and data acquisition controller(SCADA) is dedicated for managing and controlling the components.

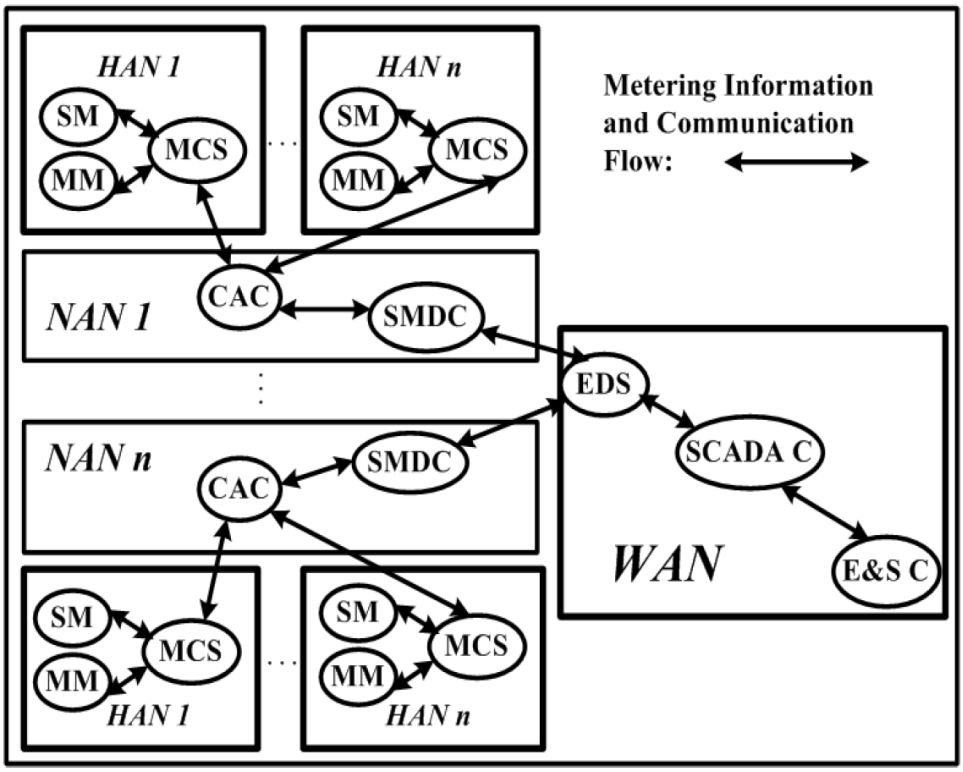

Figure 2.4: *Layer architecture of the SG Communication Network[5]*

[24] states that the two most important infrastructures needed for efficient information transmission in SG are the ones from appliance sensors to smart meters and from the metering devices to the data centers. There are multiple communication technologies used for the transfer of information through the stated infrastructures. Let us see some of the technologies which can be used for this purpose :

2.2.1 ZigBee

Zigbee is a wireless communication technology primarily built to be simple in-terms of being less complex, low power and cost effective. It is considered to be an ideal alternative for use in automatic meter reading(AMI), smart lighting, energy monitoring and home automation[25]. It is a standardized protocol and is considered most suitable for residential domain by U.S National Institute for Standards and Technology (NIST)[25]. It uses IEEE 802.15.4 standard used at 2.4GHZ which is an unlicensed band. Theoretical coverage is between 10 and 1600 meters, and of course depends on the environment around[25].

ZigBee is advantageous in that it is costs less to deploy and implement. The fact that it uses an unlicensed spectrum and the protocol it uses IEEE 802.15.4 is self configuring makes it very flexible and easy[25]. The major disadvantage of Zigbee is its low processing capability and memory size which is a constraint for large scale implementations. It is also prone to interference from WLANs, WiFi and Bluetooth devices[24].

2.2.2 Cellular Networks

These are fixed infrastructures built by cellular companies which can be used in neighborhood area networks to enable communication between the meters and data centers. Since it is an already implemented infrastructure, it reduces deployment costs and allows for faster installations for utility companies. The technologies used are 2G, 2.5G, 3G, WiMAX and LTE which can be used in large scale wide area implementations[22]. Another advantage of cellular network is its security for safe data transmissions.

As mentioned earlier, even though it is cost effective and more secure, the fact that it is a shared medium which is not a dedicated network for only Smart Grid applications may degrade the performance of the network. It is more apparent for applications that use real time and large data transfers needed for continuous monitoring where availability plays important role.

2.2.3 Digital Subscriber Lines

Digital Subscriber Lines is a communication technology which uses the telephone network for data transfer. It is high-speed point to point transmission technology that can offer secure , high bandwidth and low latency infrastructure. Another advantage of DSL communication is that it can significantly decrease installation and implementation costs due to its prior existence[22].

For low density area, it might be very costly for initial implementation and operation due to sparse location of individual houses. Another issue for low density areas is the distance issue, As the distance between the components increases the performance will degrade accordingly. This is the communication infrastructure analyzed and tested in this work because the controller chosen for this work, Smart Grid market controllers are focused in urban areas and its very much feasible for this cases.

2.2.4 Power Line Communication

Power Line Communication (PLC) is a transmission technique that makes use of the existing power lines to transmit data from one device to another[22].

It can facilitate a direct connection between the metering devices and data collection centers. PLC is advantageous in that almost every household rural or urban areas is connected to the grid.

A big disadvantage of PLC is that it is susceptible to noise due to the harsh environment created by the power line. Due to this reason, it is not able to fulfill high data transfer bandwidth requirements.

2.2.5 Cable connections

By cable connection we mean that a transmission method that uses television lines. It uses a modem that transmits digital data using TV channel space connected by coaxial cable and offers a high bandwidth. It is also advantageous because its performance is less dependent with distance.

A disadvantage for cable connections is its inconsistency in-terms of providing fixed bandwidth. This is because bandwidth depends on the number of clients using the shared network. It also has flaws because of the high deployment costs needed for remote areas which are isolated from the stations. The cost is incurred because of cable deployment, equipment installation etc.

2.2.6 Fiber-optic communication

Fiber-optic communication uses light pulses to transmit information from one point to another. It uses optical fiber as a medium and is widely used by telecom companies for data communication. One advantage of optical fiber is that for very long transmissions, it has low attenuation and interference compared to copper-wire mediums. It has one of the highest bandwidth for the communication technologies discussed here.

The biggest drawback of optical fibers is the high cost incurred for deployment. It is very costly to dig a trench and install the fiber lines specially in urban areas.

2.2.7 Wireless Mesh Networks

Wireless mesh networks are gaining popularity in SG deployment because of the increase in capacity of WMN's and the decrease in price for the components used for installation. WMN's are dynamic and flexible in that each node on the network can be seen as a router [26] that can route the packets to the desired destinations. Another behavior which makes them suitable for SG environment is, it is self healing and scalable which nowadays is seen as a very critical issue since the number of connected devices is increasing.

A disadvantage for WMN's is that its prone to interference and noises in urban environments caused by the existing radio signals. The security flaw is still a concern with [27] stating, because each node is used as data access point and the encryption added for security reason could cause loop problems which can effect a decrease in bandwidth of the system.

An overview of all the pros and cons of the technologies is stated in the following table.

Technology	Advantages	Disadvantages
ZigBee	Low deployment and implementation cost; Simple network implementation; Self configuring	Low processing capability; Small memory size; Prone to interference
Wireless Mesh Networks	Cost-effective implementation; Highly scalable; Self-healing	In an urban environment, interferences can affect the QoS offered; Possible loop problems
Cellular Networks	High level of security; Low to zero deployment cost (already existent)	Shared resources; High cost of maintenance; Low bandwidth
DSL	Low implementation and deployment costs; Low latency; Secure	Distance dependent; In remote areas, deployment costs may be high.
PLC	Low deployment costs; Already available	Noisy environment; Low bandwidth
Cable	Large bandwidth; Low latency	High cost of deployment in remote areas
Fiber-optic	Low interference; Low attenuation; High bandwidth	Potentially large deployment costs

Table 2.1: *Pros and cons of Smart Grid communication Technologies[1]*

2.3 Performance indicators and QOS parameters for Smart Grids

The realization of SG vision will be apparent when the infrastructure is able to guarantee QOS and fulfill all performance requirements. This section is focused in having a better understanding of the requirements for SG. The first part will discuss about data delivery time between the devices on SG, while the later section focuses more on QOS parameters.

2.3.1 Data delivery time between intelligent electronic devices

To describe the data delivery times between the devices on SG, we have used the state of the art IEEE 1646 standard. It has some drawbacks in that it does not specify an underlying protocol nor a data model which is used to exchange the information[8]. Table 2.2 shows the delay requirements for different information types, as stated by IEEE 1646.

Information Types	**Internal to Substation**	**External to Substation**
Protection Information , high-speed	1/4 cycle	8-12 ms
Monitoring and Control Information, medium speed	16 ms	1 s
Operations and Maintenance Information, low-speed	1s	10 s
Text Strings	2s	10 s
Processed Data Files	10s	30 s
Program Files	60 s	10 min
Image Files	10 s	60s
Audio and Video Data Streams	1 s	1 s

Table 2.2: *Typical data delivery time between intelligent SG devices[1][8]*

2.3.2 QOS Delay and bandwidth requirements of different applications on smart grids

As stated earlier, a smart grid is a distributed system where interoperable and communicable sub systems can be used for multiple applications. Different applications have their own QOS metrics to function according to the desired objectives. Table 2.3 elaborates the delay and bandwidth requirements for different applications on SG.

Information Types	Delay	Bandwidth
In-Home Communications	2-15s	10-100kbs
Meter Reading	2-15s	10-100kbs
Connects and Disconnections	9ms	-
Text Strings	2s	10 s
Demand Response (DR)	500s	-
Synchrophasor	20-200ms	600-1500kbs
Substation Supervisory Control and Data Acquisition — SCADA	2-4s	10-30kbs
Inter-Substation Communications	12-20ms	-
Fault Location, Isolation, and Restoration for Distribution Grids — FLIR	-	10-30kbs
Distribution Automation	25-100ms	2-5MBS
Workforce Access for Distribution Grids	150ms	250kbs

Table 2.3: *QOS Delay and bandwidth requirements of different applications on smart grids[1][9]*

2.3.3 Dependability

In this section we will illustrate attributes that are widely used to parametrize the performance of any communication system with focus on SG. Dependability is first introduced as a global concept that assumes the usual attributes of reliability, availability, safety, integrity, maintainability [28].

- Availability: It is a critical attribute for SG applications where it shows readiness of the system to provide the expected service. Being a system of systems, SG sub components depend on each other for proper functioning. for example a fault on data collectors will have an effect on the connected meters and the layers above such as market controllers which may lead to failure. The simplest representation of availability is expected value of up time to sum of expected value of up and down time.

$$A = \frac{E[\text{Uptime}]}{E[\text{Uptime}] + E[\text{Downtime}]} \tag{2.1}$$

- Reliability: is as an attribute that is used to show the continuity of the system performance within the expected specifications. Its only ideal to have an error free system because all systems are susceptible to failure. Reliability is mostly expressed as failure rate which is expressed in percentages. For most SG applications(e.g. in-home, meter reading, demand response), the required level of reliability may fall into the 99–99.99 percent range but Synchrophasor may require a much more stringent reliability of approximately 99.99995 percent, which equates to being out of service for 16 seconds in one year[9].

- Maintainability: System break downs are apparent on any distributed system. Maintainability deals with how the system reacts during break ups for restoring the normal process. In another word, it shows how the system remains available for continuous upgrade and modification.

- Integrity and Resilience: A SG system should be resilient in that it should be able to sustain acceptable service. It should also not be prone to possible alterations. It is a challenging task to keep resiliency for a widely distributed system like the power grid but this is one of the main reasons SG is envisioned for.

- Safety and Security: One of the major challenges of SG is protecting the safety and security of the whole system. There should be a mechanism of controlling confidential information and making sure that unauthorized access to the system is not granted. Another important attribute for SG

is safety, since SG components are located on distributed geographical locations, the system should be able to protect them on the occurrence of catastrophic natural disasters and other treats.

2.4 Smart Grid Applications

Continuing from our earlier observations, the next step is to elaborate more on applications used on SG. Some of the application areas will be illustrated on the next sections.

2.4.1 Automatic meter reading

Normal electricity meters are only used to measure the amount of electricity consumed by individual homes and providing monthly/daily/hourly consumptions. Smart meters instead can do more by facilitating continuous communication with the distribution plant. Automatic meter reading ensures information's like demand from the users, metering data, and controller messages are exchanged between the user and the upper layers.

2.4.2 Home Energy Management Systems

It is used to monitor and manage energy consumption of users with the help of a device installed at households. It is intended to make energy usage more efficient and prevent wastage of power when there is no need for it.

Home energy management systems use intelligent meters which can gather information that tells time of energy usage with the amount of power utilized which in turn will be used to monitor undesired consumptions.

2.4.3 SCADA

Increase in demand for electrical energy may gradually lead to strain on transmission lines. Supervisory control and data acquisition systems(SCADA) are used for monitoring and controlling of the power grid. SCADA systems use information's collected from sensors and synchrophasors positioned at strategic locations.

Before the invention of synchrophasors, power control centers were relying on the estimate of current states by learning from the past experiences. Developed in 1893 by Charles Proteus Steinmetz[29], Synchrophasors are devices

which can measure the state of the grid at different locations and using mechanisms to synchronize the clock. It has enabled the control centers to use real time measurements to monitor the state of the grid.

2.4.4 Demand Response

[29] states that Demand response as Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.

Demand response can simply be defined as an action by the customer to adjust his/her energy usage by checking the price of electricity at any moment of time. It can play a significant rule in decreasing energy consumption which in turn leads to less strain on the production of electricity.

2.5 Smart Grid Control

One of the greatest concerns for the power grid is voltage instability caused by wind turbine, generators and other devices connected to the grid. To tackle the issues caused due to this fluctuations, efficient Control System is very critical. The control system is tasked with balancing electric power production and consumption within the grid. In addition, it makes active use of flexibility of large number of power producing and/or power consuming units[7]. Both producers and consumers play a significant role for unwanted presence of load variations on the grid.

Smart Grid is composed of subsystems which are distributed in nature from the older domains of power generation, transmission, distribution, and consumers to the recent advancements of renewable energy sources, electric vehicles and demand response compatible loads. The concept of smart grids paves way for interaction and intercommunication within these components at specified instants of time and in a specified manner and location. To achieve this goal, its desirable to have proper control of the whole system assisted by a communication mechanism. Throughout this work, out of different control mechanisms proposed for Smart Grid implementation, we opted to use the case of Hierarchical models because of availability of detailed relevant research from Control and Automation section of Aalborg University.

2.5.1 Hierarchical Models

The concept of hierarchical control is solving complex problems by subdividing them to smaller sub problems and assembling the solutions in functional hierarchical structure.

To show an example of Hierarchical model implementation proposed by [6], Modeled after the hierarchical control architecture of power transmission systems, a layering of primary, secondary, and tertiary control has become the standard operation paradigm for Microgrids. With varying control objectives for each layer, they should allow the whole system capability for plug and play and by giving maximum flexibility for the Microgrid. Figure 2.5 shows graphic description of hierarchical method deployed for the model.

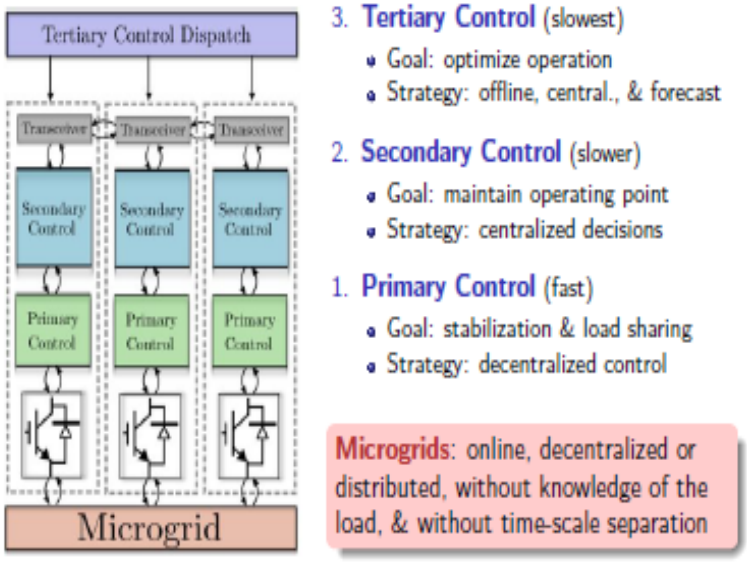

Figure 2.5: *Hierarchical Model[6]*

Chapter 3

System Model

Initially designed in the early 1900s, today's power grid has evolved to become a large network that connects thousands of generating stations and load centers through a system of power transmission lines[30]. As mentioned on chapter 2, it is very necessary to have a control system coupled with efficient communication mechanism.

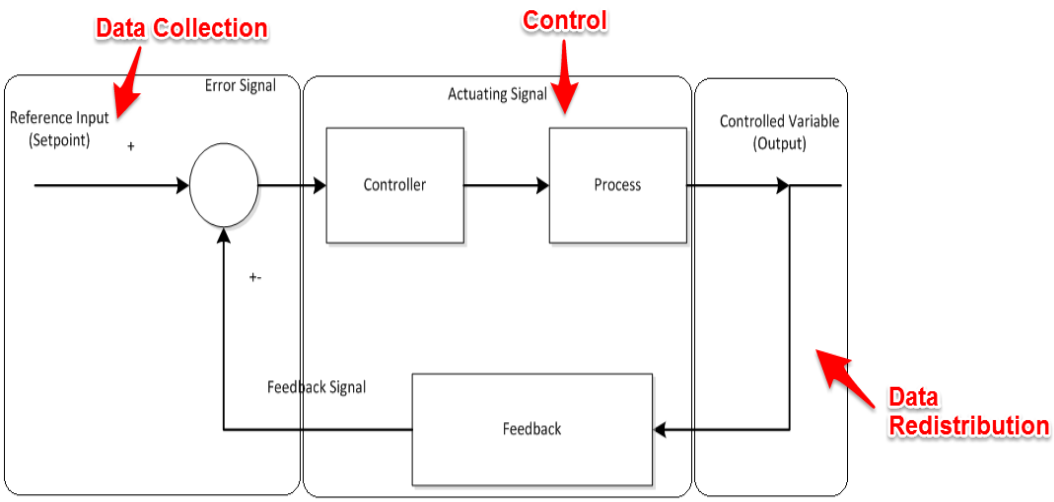

Figure 3.1: *Feedback Loop For Smart Grid Controller*

Figure 3.1 shows a simple feedback loop for Smart Grid controller, which depicts where the communication infrastructure comes in to play for Smart Grid Control. Let us first describe how we modeled the communication network and

the control loop. In this work the two major communication interfaces used by the controller(MPC) are Data collection and Data redistribution as shown on figure 3.1.

3.1 Control Algorithm

For a Smart Grid scenario, Since the location of loads is distributed geographically, It makes the computation much easier for the controller if the information for these distributed systems is collected and processed in a centralized manner. Due to this, a communication infrastructure which is reliable, resilient, easily extendable and able to heal break ups(Self healing) is a necessity.

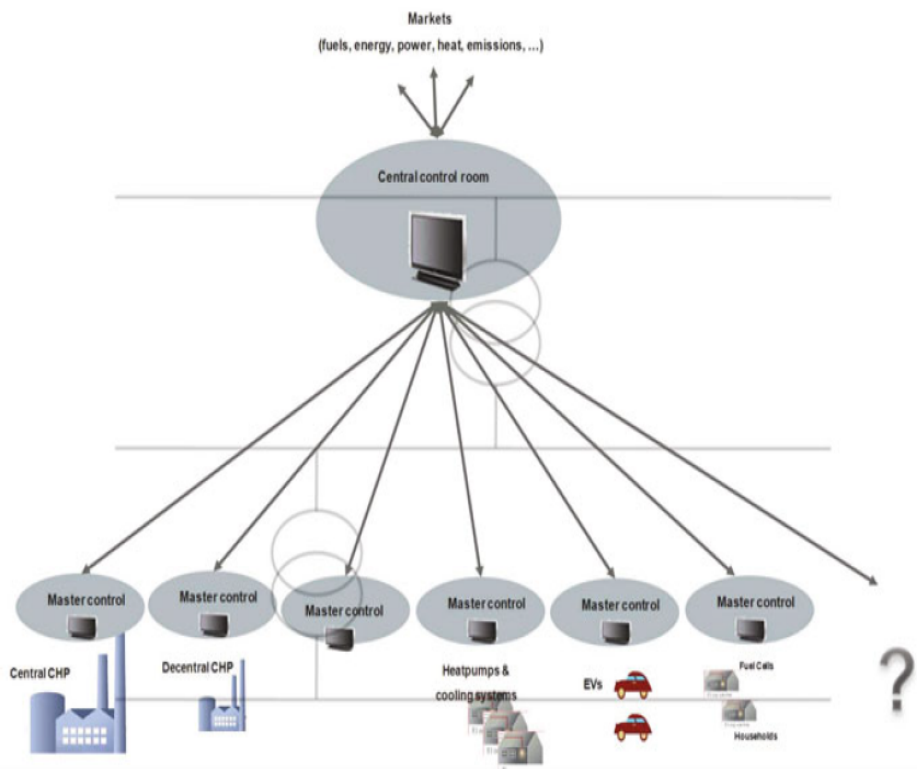

Figure 3.2: *Hierarchical Model Predictive Control[7]*

[7], Hierarchical model predictive control is used as a use case for the analysis part and the rest of this work. It is chosen because of the prior work done to study computational burdens in relation to traffic caused by the consumers and other loads which presents a tested model to be used in relation to our study. It is proposed for resource distribution to be deployed on Smart Grids.

A simplified multi-layer control model for smart grid is shown on figure 3.2 and for the model shown, the lower layer is comprising of autonomous consumers. Above this layer is found the Aggregator, giving the system computational efficiency. The upper layer containing MPC(model predictive controller) is the main controller.

3.2 Network Topology

Digital Subscriber Lines(DSL) are known to provide high-speed, low latency and secure infrastructure to be used for Smart Grid applications. For our implementation as shown on figure 3.3, It is assumed that there is point to point connection from Smart Meters to the aggregator and distribution server.

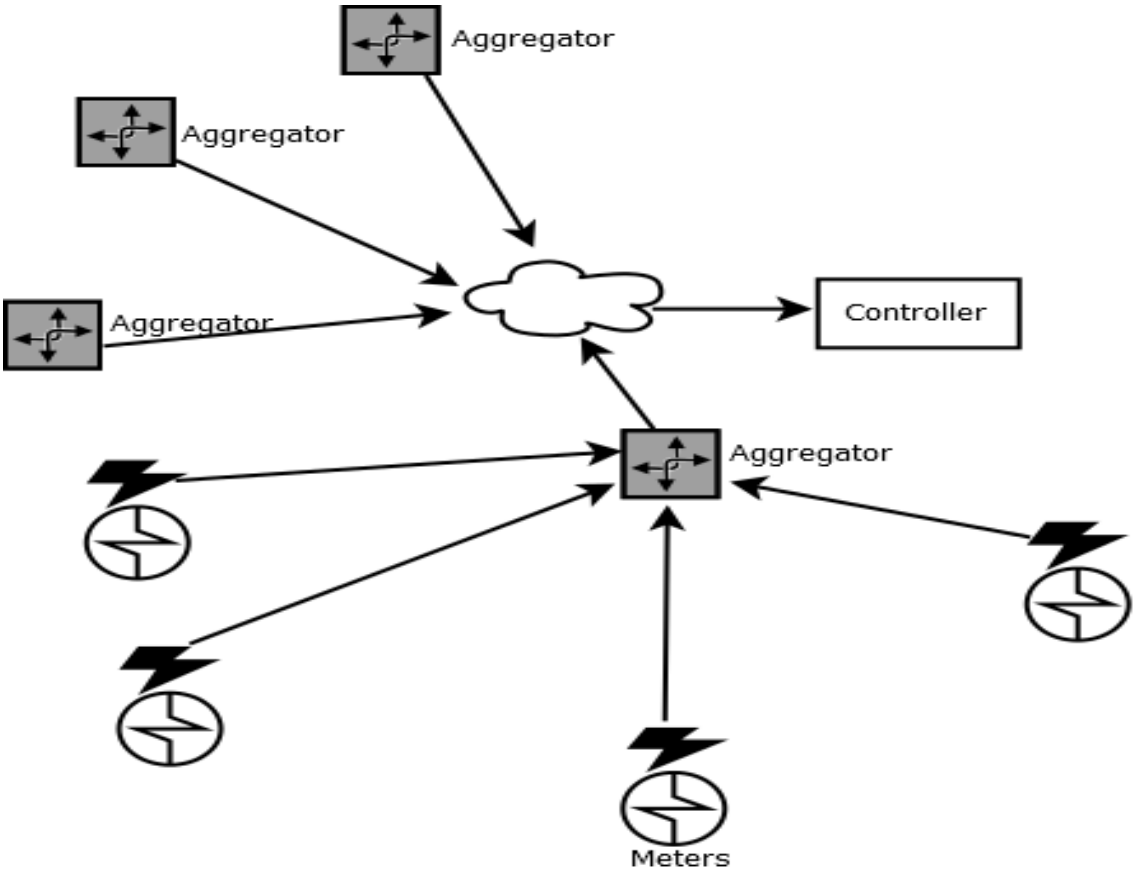

Figure 3.3: *Network Toplogy Used*

An aggregator located at central station will be used for collecting the data and forward it to the controller and redistribution is done in the same manner in which controller signals are sent back to the meters by using the same communication channel.

3.3 Timing Requirement

For the topology described on figure 3.3, The timing requirement(Control loop back time) is dependent not only due to communication delays but also time elapsed by the control operation. This scenario is depicted on the chart shown by figure 3.4.

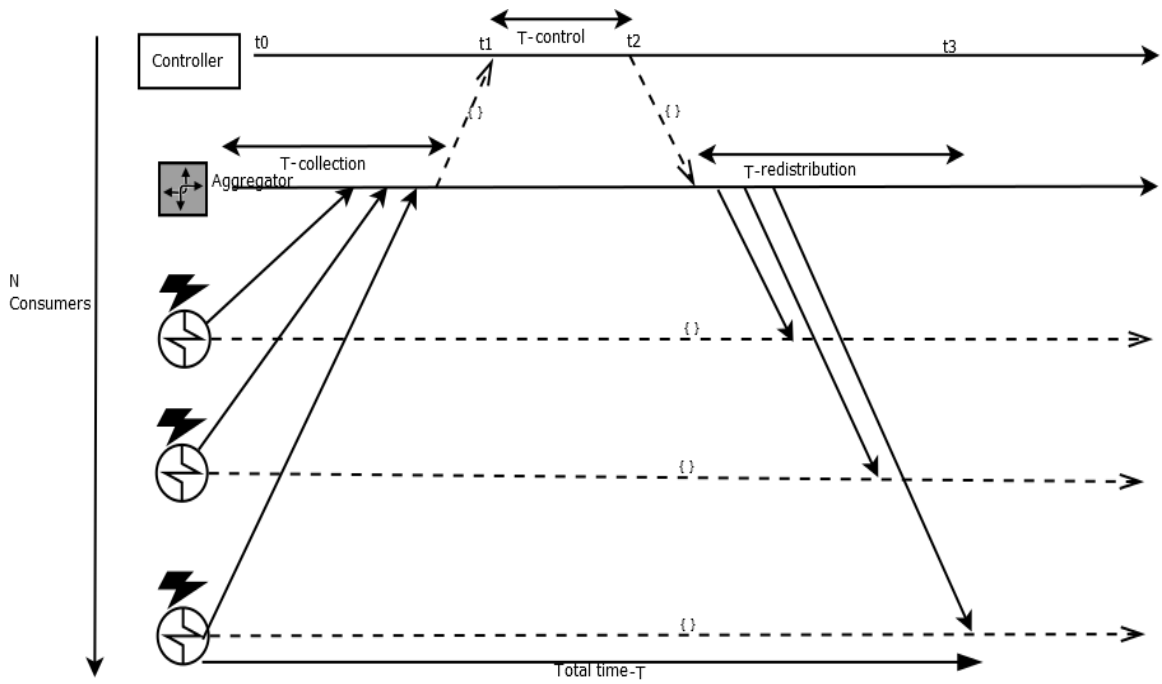

Figure 3.4: *Timing requirment*

The control loop back time is constrained by

- N_c number of consumers
- N_a number of aggregators;
- d distance;

- B bandwidth;
- β aggregation server capacity;
- ξ Control complexity;

T-collection is the time elapsed for collection operation will be denoted as :

$$\text{T-collection} = \delta_c(n) \tag{3.1}$$

T-control the time elapsed for control operation will be denoted by:

$$\text{T-control} = \xi_c(n) \tag{3.2}$$

T-redistribution time elapsed for redistribution of controller decision :

$$\text{T-redistribution} = \delta_r(n) \tag{3.3}$$

Throughout this work a case is chosen where total control loop back time T_t as shown on figure 3.4, satisfies a relationship:

$$T_t = \delta_c(n) + \xi_c(n) + \delta_r(n) \tag{3.4}$$

Chapter 4

Implementation overview

4.1 Method Overview

In this section we will give an overview of the method used and steps taken for the implementation. To illustrate this in detail, let us start by describing the next flowchart. As you can see in figure 4.1 below, multiple steps and considerations are taken for the implementation.

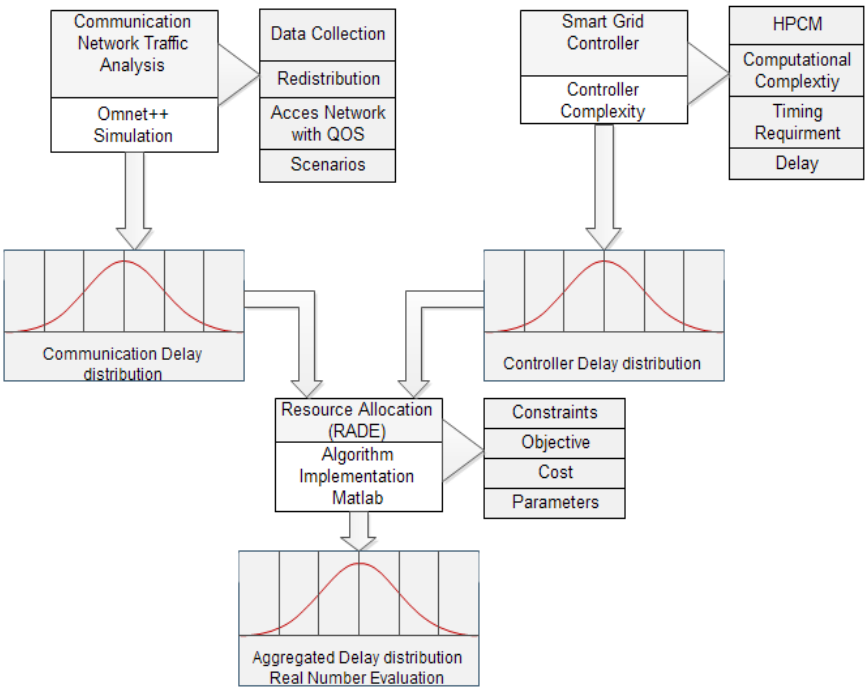

Figure 4.1: *Implementation Method Overview*

The main focus and contribution of this work is Implementation of Smart Grid resource allocation algorithm using density estimation(RADE) by proposing a method which includes traffic analysis of a Smart Grid Network. As is shown on figure 4.1, there are three main parts of the implementation namely, Communication Network, Smart Grid Controller and RADE.

Smart Grid Controller and the relationship with computational complexity is discussed on chapter 5 while the resource allocation algorithm is illustrated on chapter 6. Chapter 7 goes through OMNeT++ implementation of Smart Grid network simulation while the tested scenarios and the results is elaborated in chapter 8.

Chapter 5

Controller Time Requirement

One of the major factors which affects the control loop back time is the delay at the control server. For this we wanted to study timing requirements of the controller and how it is affected under varying control complexities. First we will start by making analysis of the chosen control algorithm used by the control server which is a Hierarchical Control Predictive model[7] and how computational burden of the system is related to number of consumers.

5.1 Computational Complexity

In Smart Grid Control, Consumers or Energy consuming units like heat pumps, car batteries, refrigerators and others, require power in a limited value within a specific span of time. This and other constraints add to the complexity of the control system. The high level controller has to deal with the aggregated value of the constraints mentioned. Hierarchical Control Predictive model(HCPM) by[7] presents a novel method for computing the aggregated constraints without approximation, yielding better utilization of the units when the load variations are large. According to this model all distributed loads are seen as one big consumer by aggregating the constraints within.

In addition to the constraints caused by the consumers, another challenge is the introduction of new renewable energy sources which use wind, sun light, geothermal and ocean wave as a source of energy. This renewable Energy sources are unpredictable in nature. Managing and controlling the load variation caused by this distributed energy generation adds to the complexity of the task for the controller.

To deal with the issues mentioned which is to control the power consumption to the desired level, various Smart Grid applications which give the consumers and producers control capability are proposed. Some of state of the art appli-

cations are Using energy storage devices[31], Voluntary load side Management [32], Demand Response and more....

5.2 Case HCPM

According to Hierarchical Control Predictive Model(HCPM)[7], depicted on figure 5.1, The main computational burdens are the vertex generation, the top level distribution and the aggregator level distribution. All of which must be performed at each time step. Vertex generation is generation of a vertex vector representing minimum or maximum power consumption rate at a specific moment for each consumer. It is stated that the complexity of the quadratic programming of a distribution task increases approximately with the square of the number of receivers and approximately doubles with an increase in the horizon length.

N_d the number of associated consumers or aggregators in the layer directly below where β_o is dependent on the computational power of computer and horizon length N_h is the amount representing the prediction length in-terms of number of prediction time steps.

$$\text{Distribution Complexity}(N_d) = \beta_d 2^{N_h} {N_d}^2 + \beta_o \tag{5.1}$$

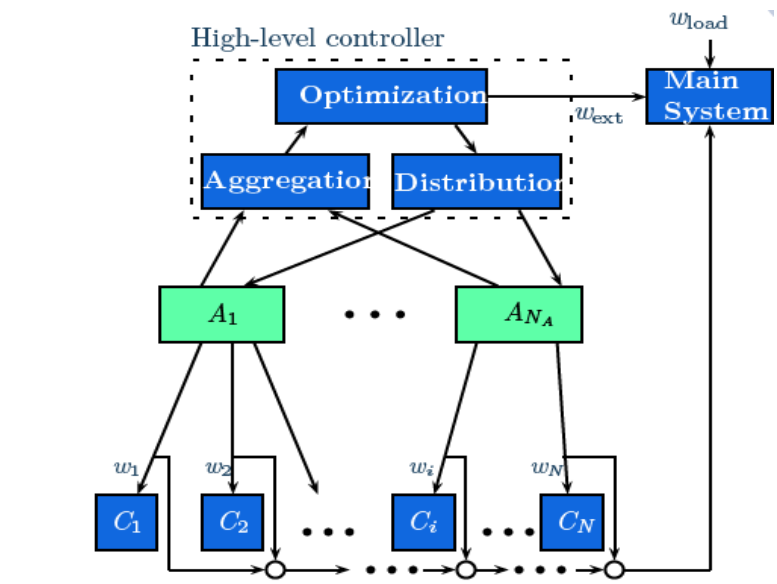

Figure 5.1: *Hierarchical Model Predictive Control[7]*

It is also argued on the paper that the vertex computation burden is linear with the number of consumers and number of vertices.

$$\text{Vertex Complexity}(N_d) = \beta_v N_h! 2^{N_h} N_d \tag{5.2}$$

Figures 5.2, 5.3 and 5.4 show the relationships for complexities generated by the distribution, vertex generations and top level controllers. The three plots show complexity relationships by increasing the Horizon Length, and it is test taken for 100 ICs(Intelligent Consumers) by varying the number of aggregators.

On this work,Total complexity is considered as the sum of Distribution Complexity and Vertex Complexity.

$$\text{Total Complexity}(N_d) = \text{Vertex Complexity}(N_d) + \text{Distribution Complexity}(N_d) \tag{5.3}$$

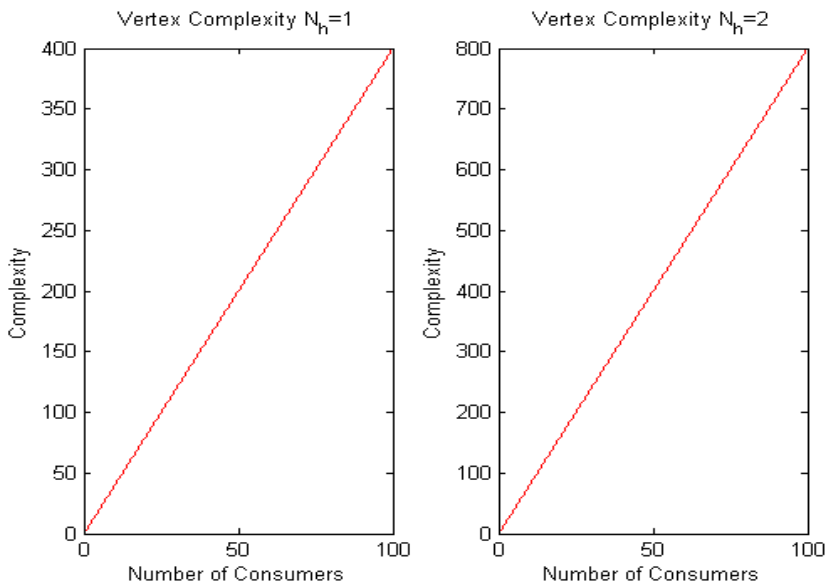

Figure 5.2: *Vertex Computational Complexity*

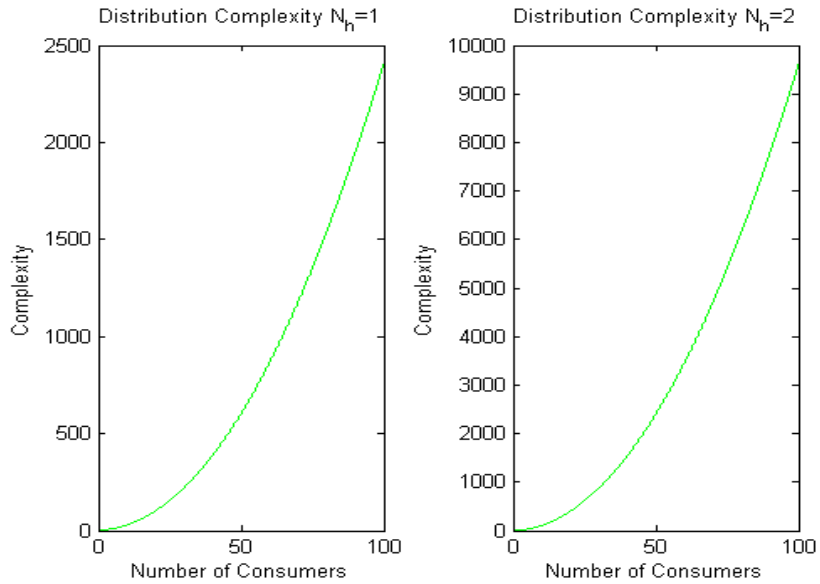

Figure 5.3: *Distribution Computational Complexity*

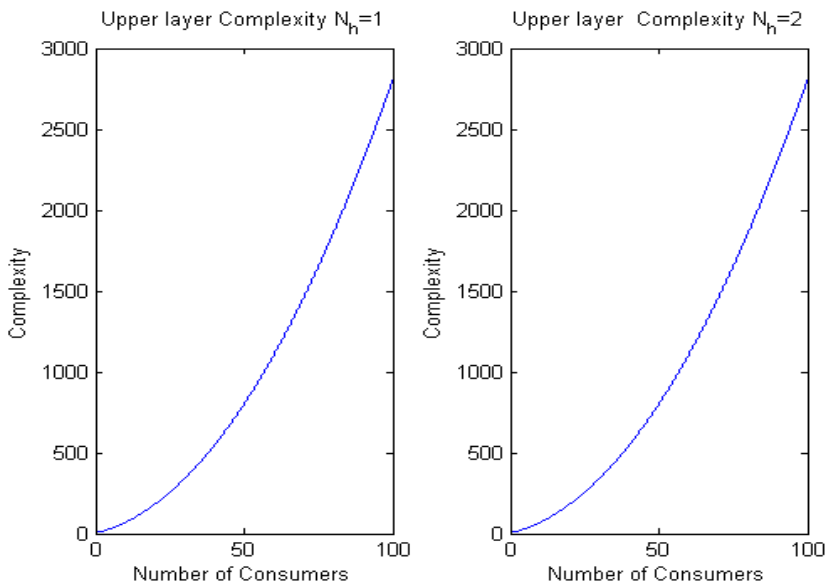

Figure 5.4: *Total Computational Complexity*

When we considered the delay distributions for the control server, it is assumed that there is a linear relationship between the complexity shown here

and the control server time required to run the algorithm. The relationship is shown on figure 5.5.

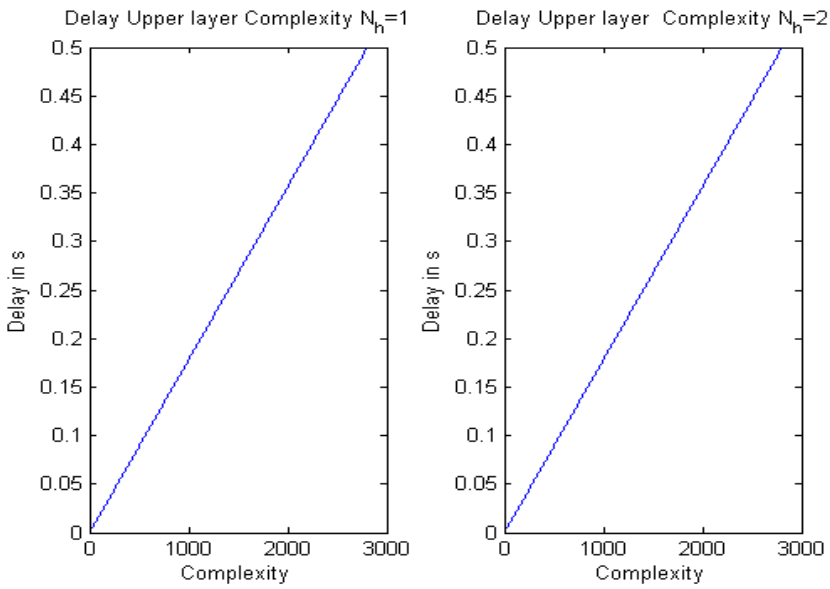

Figure 5.5: *Delay and Total Computational Complexity*

Chapter 6

Resource Allocation using Gaussian Mixture Model

As mentioned on the implementation overview, We are using a learning algorithm with two training data's as inputs. The first feature is the one we gathered from the communication network simulation(chapter 7) and the second one from the controller showing the relationship between controller and computational complexity. The first step in our algorithm is to parametrize the raw data to one of the known text book distributions.

Studies done for network traffic QOS estimation show that, it is desirable to use Gaussian Mixture Model. [20] Proposes penalized maximum likelihood expectation maximization(PML-EM) algorithm applied on additive Gaussian mixture model. We used related method for our algorithm which is maximum likelihood expectation maximization(ML-EM) and the chosen distribution is Gaussian mixture model.

A mixture distribution is a probability distribution in which it is an aggregate of random variables with values taken from one of the known distributions. Gaussian mixture model is one type of mixture distribution derived from Gaussian distributions as shown :

$$\xi \sim \sum_{i=1}^{K} \tau_k \mathcal{N}(\boldsymbol{\mu_i}, \boldsymbol{\Sigma_i}) \tag{6.1}$$

Gaussian is also known as normal distribution. It is parametrized by using two parameters μ which is the mean and σ^2 which is the variance of the distribution. The uni-variate Gaussian distribution for a data set x has the form:

$$P(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2} \tag{6.2}$$

where:

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{6.3}$$

$$\sigma^2 = \frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2. \tag{6.4}$$

The proposed algorithm for parametrization of the delay distribution gathered from the simulation is maximum likelihood expectation maximization(ML-EM) algorithm applied on Gaussian mixture model. Let us define the algorithm on the next section.

6.1 Maximum Likelihood Expectation Maximization Model(ML−EM)

Let $\mathbf{x} = (\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_n)$ is delay distribution collected from the simulation. Let us assume this sample originates from a mixture of two Gaussian distributions and let $\mathbf{z} = (z_1, z_2, \ldots, z_n)$ be the latent or hidden variable where the distribution originates.

$$X_i|(Z_i = 1) \sim \mathcal{N}_d(\boldsymbol{\mu}_1, \sigma_1) \text{ and } X_i|(Z_i = 2) \sim \mathcal{N}_d(\boldsymbol{\mu}_2, \sigma_2) \tag{6.5}$$

where

$$\mathrm{P}(Z_i = 1) = \tau_1 \,\text{and}\, \mathrm{P}(Z_i = 2) = \tau_2 = 1 - \tau_1 \tag{6.6}$$

what we want is to parametrize the corresponding individual Gaussian parameters, means and variances.

$$\theta = \Big(\boldsymbol{\tau}, \boldsymbol{\mu}_1, \boldsymbol{\mu}_2, \sigma_1, \sigma_2\Big) \tag{6.7}$$

where the likelihood is

$$L(\theta; \mathbf{x}, \mathbf{z}) = P(\mathbf{x}, \mathbf{z}|\theta) = \prod_{i=1}^{n} P(Z_i = j)\ f(\mathbf{x}_i|\mu_j, \sigma_j) \tag{6.8}$$

$$L(\theta; \mathbf{x}, \mathbf{z}) = P(\mathbf{x}, \mathbf{z}|\theta) = \prod_{i=1}^{n}\sum_{j=1}^{2} \mathbb{I}(z_i = j)\ \tau_j\ f(\mathbf{x}_i; \boldsymbol{\mu}_j, \sigma_j) \tag{6.9}$$

$\mathbb{I}$ is an indicator function, we can rewrite the above equation in exponential form

$$L(\theta;\mathbf{x},\mathbf{z}) = \exp\left\{\sum_{i=1}^{n}\sum_{j=1}^{2}\mathbb{I}(z_i=j)\Big[\log\tau_j - \tfrac{1}{2}\log|\sigma_j| - \tfrac{1}{2}(\mathbf{x}_i-\boldsymbol{\mu}_j)^\top\sigma_j^{-1}(\mathbf{x}_i-\boldsymbol{\mu}_j) - \tfrac{d}{2}\log(2\pi)\Big]\right\}. \tag{6.10}$$

(ML−EM) has two steps, Estimation(E step) and Maximization step(M step).

E step

The current estimate of parameters is θ^t, by using Bayes theorem the conditional probability of Z_i is,

$$T_{j,i}^{(t)} := \mathrm{P}(Z_i=j|X_i=\mathbf{x}_i;\theta^{(t)}) = \frac{\tau_j^{(t)}\ f(\mathbf{x}_i;\boldsymbol{\mu}_j^{(t)},\sigma_j^{(t)})}{\tau_1^{(t)}\ f(\mathbf{x}_i;\boldsymbol{\mu}_1^{(t)},\sigma_1^{(t)}) + \tau_2^{(t)}\ f(\mathbf{x}_i;\boldsymbol{\mu}_2^{(t)},\sigma_2^{(t)})} \tag{6.11}$$

this results in a cost function

$$\begin{aligned}
Q(\theta|\theta^{(t)}) &= \mathrm{E}[\log L(\theta;\mathbf{x},\mathbf{Z})] && (6.13)\\
&= \mathrm{E}[\log\prod_{i=1}^{n} L(\theta;\mathbf{x}_i,\mathbf{z}_i)] && (6.14)\\
&= \mathrm{E}[\sum_{i=1}^{n}\log L(\theta;\mathbf{x}_i,\mathbf{z}_i)] && (6.15)\\
&= \sum_{i=1}^{n}\mathrm{E}[\log L(\theta;\mathbf{x}_i,\mathbf{z}_i)] && (6.16)\\
&= \sum_{i=1}^{n}\sum_{j=1}^{2}T_{j,i}^{(t)}\Big[\log\tau_j - \tfrac{1}{2}\log|\sigma_j| - \tfrac{1}{2}(\mathbf{x}_i-\boldsymbol{\mu}_j)^\top\sigma_j^{-1}(\mathbf{x}_i-\boldsymbol{\mu}_j) - \tfrac{d}{2}\log(2\pi)\Big] && (6.17)
\end{aligned}$$

(6.17)

M step

This step is maximization step for $\theta = \Big(\boldsymbol{\tau},\boldsymbol{\mu}_1,\boldsymbol{\mu}_2,\sigma_1,\sigma_2\Big)$

$$\begin{aligned}
\boldsymbol{\tau}^{(t+1)} &= \arg\max_{\boldsymbol{\tau}}\ Q(\theta|\theta^{(t)})\\
&= \arg\max_{\boldsymbol{\tau}}\ \left\{\left[\sum_{i=1}^{n}T_{1,i}^{(t)}\right]\log\tau_1 + \left[\sum_{i=1}^{n}T_{2,i}^{(t)}\right]\log\tau_2\right\}
\end{aligned} \tag{6.18}$$

$$\tau_j^{(t+1)} = \frac{\sum_{i=1}^{n} T_{j,i}^{(t)}}{\sum_{i=1}^{n}(T_{1,i}^{(t)} + T_{2,i}^{(t)})} = \frac{1}{n}\sum_{i=1}^{n} T_{j,i}^{(t)} \tag{6.19}$$

for $\left(\boldsymbol{\mu}_1, \boldsymbol{\mu}_2, \sigma_1, \sigma_2\right)$

$$\boldsymbol{\mu}_1^{(t+1)} = \frac{\sum_{i=1}^{n} T_{1,i}^{(t)} \mathbf{x}_i}{\sum_{i=1}^{n} T_{1,i}^{(t)}} \tag{6.20}$$

$$\sigma_1^{(t+1)} = \frac{\sum_{i=1}^{n} T_{1,i}^{(t)} (\mathbf{x}_i - \boldsymbol{\mu}_1^{(t+1)})(\mathbf{x}_i - \boldsymbol{\mu}_1^{(t+1)})^\top}{\sum_{i=1}^{n} T_{1,i}^{(t)}} \tag{6.21}$$

and similarly

$$\boldsymbol{\mu}_2^{(t+1)} = \frac{\sum_{i=1}^{n} T_{2,i}^{(t)} \mathbf{x}_i}{\sum_{i=1}^{n} T_{2,i}^{(t)}} \tag{6.22}$$

$$\sigma_2^{(t+1)} = \frac{\sum_{i=1}^{n} T_{2,i}^{(t)} (\mathbf{x}_i - \boldsymbol{\mu}_2^{(t+1)})(\mathbf{x}_i - \boldsymbol{\mu}_2^{(t+1)})^\top}{\sum_{i=1}^{n} T_{2,i}^{(t)}} \tag{6.23}$$

We terminate the iteration when $\log L(\theta^t; \mathbf{x}, \mathbf{Z})$ and $\log L(\theta^{(t-1)}; \mathbf{x}, \mathbf{Z})$ are below the thresh hold level. The step shown above can be generalized for Gaussian mixture models with more than two component distributions.

6.2 Resource Allocation using Density Estimation(RADE)

Here we propose a resource allocation algorithm RADE to allocate available resource to the control server and communication mechanism used for data collection and redistribution. In this particular implementation the resource in focus is time and how it is allocated to the components on the system for proper synchronization. Here are the steps used for this algorithm.

- Collection of data sets : $\{\xi_c(n), \delta_r(n), \delta_c(n)\}$, where $\xi_c(n)$ is collected from the control algorithm, while $\delta_r(n)$and$\delta_c(n)$ are collected from the communication network.

- Estimate the distribution of the training data by using parametric density estimation, the method used for this work as mentioned on the previous section is EM-ML for Gaussian mixture model.

$$\xi_c(n) \sim \sum_{i=1}^{K} \mathcal{N}(\boldsymbol{\mu_i}, \boldsymbol{\Sigma_i}) \tag{6.24}$$

$$\delta_r(n) \sim \sum_{i=1}^{K} \mathcal{N}(\boldsymbol{\mu_i}, \boldsymbol{\Sigma_i}) \tag{6.25}$$

$$\delta_c(n) \sim \sum_{i=1}^{K} \mathcal{N}(\boldsymbol{\mu_i}, \boldsymbol{\Sigma_i}) \tag{6.26}$$

- Compute the density function $P(x)$for each

$$P_{\xi_c}(\xi_c) = \sum_{i=1}^{K} \phi_i \mathcal{N}(\boldsymbol{\mu_i}, \boldsymbol{\Sigma_i}) \tag{6.27}$$

$$P_{\delta_r}(\delta_r) = \sum_{i=1}^{K} \phi_i \mathcal{N}(\boldsymbol{\mu_i}, \boldsymbol{\Sigma_i}) \tag{6.28}$$

$$P_{\delta_c}(\delta_c) = \sum_{i=1}^{K} \phi_i \mathcal{N}(\boldsymbol{\mu_i}, \boldsymbol{\Sigma_i}) \tag{6.29}$$

- The joint probability of the features

$$\mathbf{P} = \prod_{i=1}^{n} P^i(x) = P_{\xi_c}(\xi_c) * P_{\delta_r}(\delta_r) * P_{\delta_c}(\delta_c) \tag{6.30}$$

- Get the joint cumulative density function(CDF), $F_X(x)$ of the features which is integral of probability density function $\mathbf{P}$.
- for test data : $\{x; {\xi_c}^t, {\delta_d}^t, \delta_c^t\}$, calculate

$$F_X(x) = \mathrm{P}(X \leq x) \tag{6.31}$$

- check if $F_X(x) > \varepsilon$, where ε threshold or confidence bound acceptable for the algorithm.

Chapter 7

Communication Network Implementation

7.1 OMNeT++ Network Simulation

OMNeT++ stands for Objective Modular Network Testbed in C++. It's a component-based simulation library written in C++ designed to simulate communication networks[33]. OMNeT++ is not basically a network simulator but is a framework built to create network simulations.

The framework used for implementing the network model is INET which is an open source package built for OMNeT++. It has models that can be used for implementing wired and wireless communication networking technologies. Some of the implementations that are used as part of this work are protocols UDP, TCP, IP, PPP, and more. The first phase for building the communication network is defining the appropriate network topology which is illustrated in the next subsection.

7.2 Network Definition

In OMNeT++ the first step for making a communication network is defining the network using the .ned file. The network topology mentioned on chapter 3.2 is used for building this network. It has Five main components as shown on fig 7.1 namely, a client, a router, a server(control server), Channels and FlatNetworkConfigurator. Let us describe the appropriate methods used for making this components. It is created by using the .ini file shown on figue 7.2.

- StandardHost module is used for implementing the client and the server. The client is a representation of intelligent consumers while the server in this case depicts the aggregator.
- FlatNetworkConfigurator sub-module is used to configure the corresponding IP addresses.
- The Router is implemented using Router sub module and it is used as a central station where information coming from each intelligent consumers passes through it.
- Channels are modeled by setting proper bandwidth and propagation losses to represent the conditions at access network

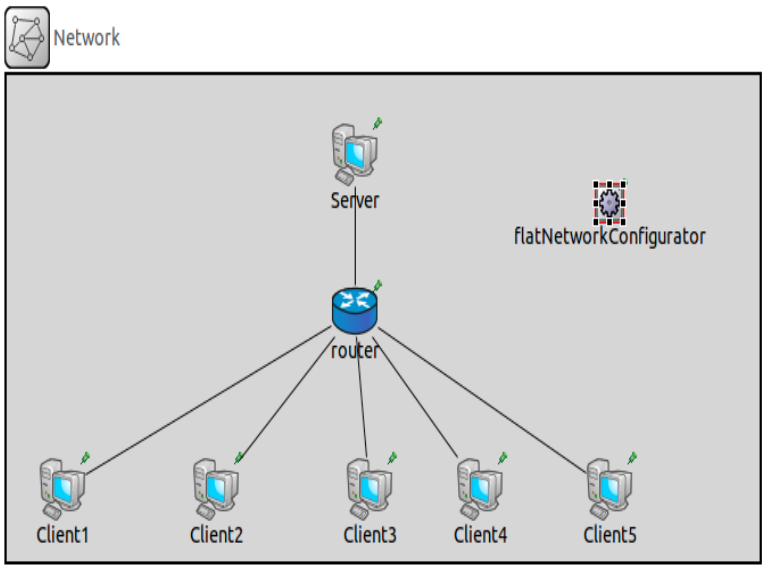

Figure 7.1: *Network Definition*

```
network Smartgrid
{
    parameters:
        int numRouters;
        int hostsPerRouter;
    types:
        channel ethernetline2 extends DatarateChannel
        {
            delay = 20ms;
            datarate = 12Mbps;
        }
        channel gigabitline2 extends DatarateChannel
        {
            delay = 10ms;
            datarate =100Mbps;
        }
    submodules:
        configurator: IPv4NetworkConfigurator;
        r[numRouters]: Router;
        cli[numRouters*hostsPerRouter]: StandardHost {
            parameters:
                @display("i=device/laptop_vs");
        }
        srv: StandardHost {
            parameters:
                @display("i=device/server_l");
        }
```

Figure 7.2: *Snippet of the ned file*

7.3 Network Configuration

In OMNeT++ once the network is defined and proper .ned file is created, The next step is configuring this components to enable communication with each other and setting the traffic generators. This is achieved by choosing appropriate protocols and setting the corresponding parameters for components on the network. Initialization method is built in OMNeT++ for this purposes and saved by the .ini file(figure 7.3). To create the scenarios in which the model is tasted, Configuration files are created for each scenarios which will be discussed on the next subsections.

```
[Config Scenario_two]
description = "Scenario two -50% metering traffic ,25%http ,25%FTP"
# setting TCP stack implementation
**.srv*.tcpType = "TCP"
**.cli*.tcpType = "TCP"
**.srv.numPcapRecorders = 1
**.srv.pcapRecorder[0].pcapFile = "results/inet_srv_scen2.pcap"

**.cli[*].numTcpApps = 2
**.cli[*].tcpApp[0].typename = "TCPBasicClientApp"
**.cli[*].tcpApp[1].typename = "TCPBasicClientApp"
#**.cli[*].tcpApp[1].typename = "TelnetApp"

**.cli[*].tcpApp[0].localAddress = ""
**.cli[*].tcpApp[0].localPort = -1
**.cli[*].tcpApp[0].connectAddress = "srv"
**.cli[*].tcpApp[0].connectPort = 80

**.cli[*].tcpApp[1].localAddress = ""
**.cli[*].tcpApp[1].localPort = 3
**.cli[*].tcpApp[1].connectAddress = "srv"
**.cli[*].tcpApp[1].connectPort = 1000
```

Figure 7.3: *Snippet of the ini file*

7.4 Traffic Generation

The internet layer protocol used for this work is IP and there are two types of upper layer packets TCP and UDP. Fig 7.4 shows how the protocols are assigned for each layer on the implementation. Let us see how different types of traffic are generated.

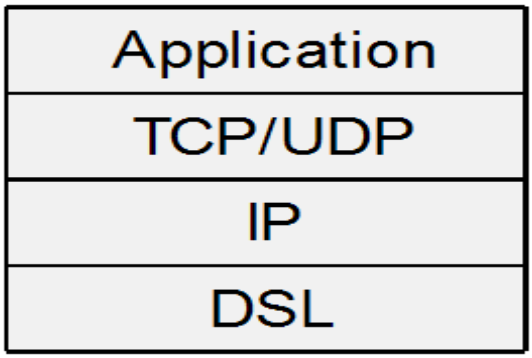

Figure 7.4: *Protocol Definition*

- Smart Grid traffic is generated by using normal TCP app on the client

side and TCPGenericSrvApp on the server side.

- HTTP and FTP traffics are generated by using TCPBasicCientAPP of the application layer on the client side and TCPGenericSrvApp on the server side.
- Video streaming is implemented by using UDPVideoStreamCli app on the client side and UDPVideoStreamSvr app on the server side
- Burst data is generated by using UDPBasicBurst app.

7.5 Network Monitoring

Network monitoring is done within the application layer modules on both the client and server side. It is chosen in a way that it will enable QOS parameters to be collected. The major area of interest out of the QOS parameters is the delay incurred on the packet sent from the intelligent consumers to the aggregator. The delay is measured by putting a time stamp on each packet sent by the traffic generator and checking the time stamp on receipt at the client side.

Different scenarios will be created in order to see how the delay on metering packets will be affected by additional traffics since the communication channel is not a dedicated one for only Smart Grid purposes. The scenarios will be discussed in detail in the next chapter.

Chapter 8

Network Analysis Scenarios

In this chapter we will discuss how we set parameters for the simulation to create multiple scenarios and see the results by plotting the recorded delay distributions. Since the DSL channel that we are using is a shared medium, We have generated four types of traffics to see how it affects the end to end delay caused by the AMI traffic.

HTTP and FTP traffics use TCP packets in which they are sent to a specific TCP port on the server where the server listens to those traffics on the specified ports. A normal scenario is tested by using Droptail queuing policy in which the last packets are randomly dropped during buffer overflow.

To implement video streaming and burst data generation, UDP ports are set for each traffic on the server and intelligent consumer. QOS with queuing and priority scheduling policy is implemented by using differentiated services(diffserv) implementation in Inet.

8.1 Scenario One- SG traffic unshared medium

The first scenario is tested in which 100% utilization capability is given to AMI traffic. The message from intelligent consumers is a 200B TCP packet transmitted with an idle interval of every 10 minutes. The full set of parameter is shown in table 8.1.

The DSL channel from each meter to the central station is set at 10Mbps where as the back-end BW from the router on the station to the upper layer aggregator is 100Mbps.

figure 8.1 is a histogram plot of minimum and maximum of variance measurements of the delay distribution data collected from 100 intelligent meters where 100 samples of delay data is collected from each meter in which the total data collected is 10000 samples. The green bar showing the highest variance

Parameter	**Value**
TCPapps	1
UDPapps	0
AMI packet size	200B
AMI packet Idle interval	3600s
AMI resource utilization	100%
Number of client	100
QOS	Droptail queue
DSL BW	10Mbps
DSL propagation delay	20ms
Back-end BW	100Mbps
Back-end Propagation delay	10ms

Table 8.1: *Scenario One- SG traffic unshared medium*

and the red bars showing the one with minimum variance. It is clear from the figure that most of the packets take between 80ms and 105ms. The maximum delay incurred is around 190ms.

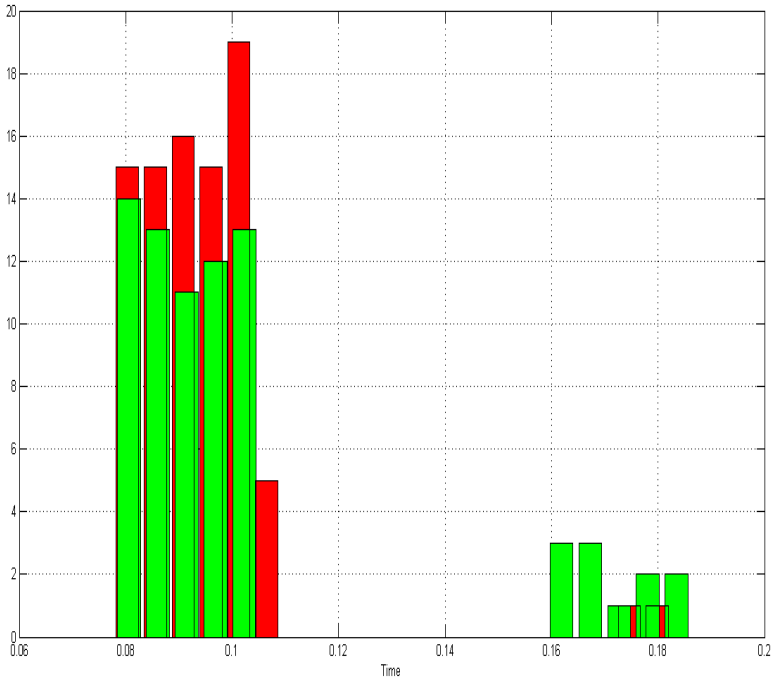

Figure 8.1: *Scenario one delay distribution*

8.2 Scenario Two-SG, HTTP and FTP traffic

The second scenario is tested where 50% utilization capability is given to AMI traffic, 25% for HTTP and FTP 25% . The message from intelligent consumers is a 200B TCP packet transmitted with an idle interval of every 10 minutes. The full set of parameter is shown in table 8.2.

Parameter	**Value**
TCPapps	3
UDPapps	0
AMI packet size	200B
AMI packet Idle interval	3600s
AMI resource utilization	50%
HTTP resource utilization	25%
FTP resource utilization	25%
Number of client	100
QOS	Droptail queue
DSL BW	10Mbps
DSL propagation delay	20ms
Back-end BW	100Mbps
Back-end propagation delay	10ms

Table 8.2: *Scenario Two-SG, HTTP and FTP traffic*

Figure 8.2 is a histogram plot of the delay distribution with maximum and minimum variances where the green bars have larger values compared to the red bars. The data collected from 100 intelligent meters where 100 samples of delay data is collected from each meter in which the total data collected is 10000 samples. It is clear from the figure that the delays vary in small amount compared to scenario one since the added traffic doesn't have much of an impact in comparison to channel capacity.

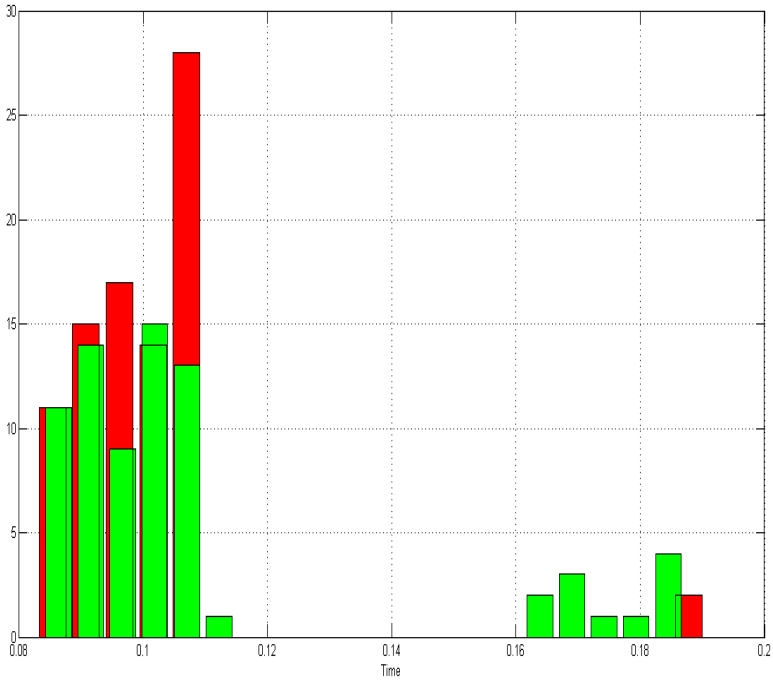

Figure 8.2: *Scenario two delay distribution*

8.3 Scenario Three- SG, HTTP , FTP and Video Streaming

The third scenario is tested in which video streaming traffic is added on the previous scenario. The message from intelligent consumers is a 200B TCP packet transmitted with an idle interval of every 10 minutes. The full set of parameter is shown in table 8.3. Here we see introduction of UDP traffic for transmitting the video stream.

Figure 8.3 is a histogram plot of the delay distribution data collected from 100 intelligent meters where 100 samples of delay data is collected from each meter in which the total data collected is 10000 samples. UDP video streaming effect is seen on the distribution on the chart with the distributions sliding by at least 20ms. We can also see from the chart the delays are distributed sparsely compared to the previous scenarios.

Parameter	Value
TCPapps	3
UDPapps	1
AMI packet size	200B
AMI packet Idle interval	3600s
AMI resource utilization	50%
HTTP resource utilization	25%
FTP resource utilization	25%
Video streaming resource utilization	25%
Number of client	100
QOS	Droptail queue
DSL BW	10Mbps
DSL delay	20ms
Backend BW	100Mbps
Backend delay	10ms

Table 8.3: *Scenario Three- SG, HTTP , FTP and Video Streaming*

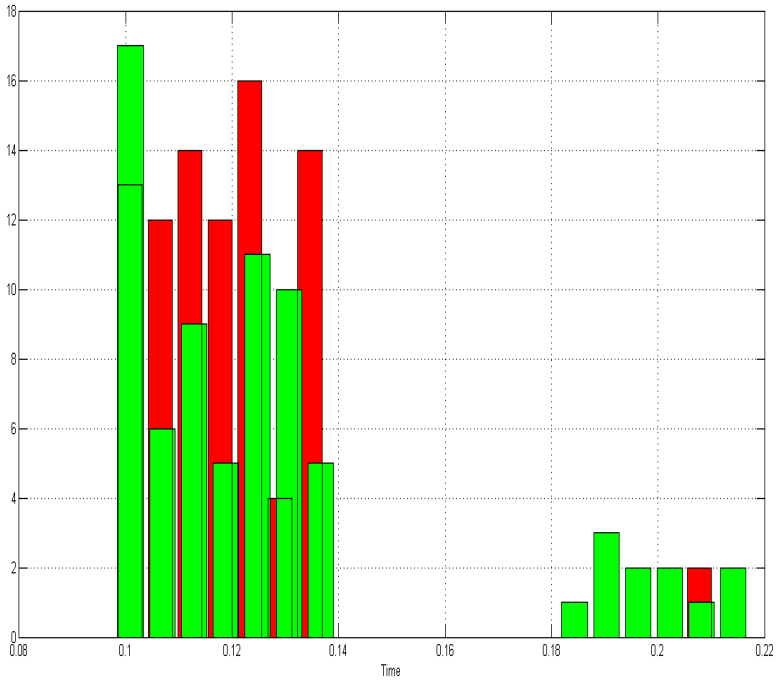

Figure 8.3: *Scenario three delay distribution*

8.4 Scenario Four with QOS

The fourth scenario is tested in which QOS parameter with priority queuing policy is implemented on scenario Three. The message from intelligent consumers is a 200B TCP packet transmitted with an idle interval of every 10 minutes. The full set of parameter is shown in table 8.4. We can see from the table the introduction of Priority queuing in which the video streaming packets are given priority at any moment of time on the queue.

Parameter	**Value**
TCPapps	3
UDPapps	1
AMI packet size	200B
AMI packet Idle interval	3600s
AMI resource utilization	50%
HTTP resource utilization	25%
FTP resource utilization	25%
Video streaming resource utilization	25%
Number of client	100
QOS	Diff Server Queuing policy
DSL BW	10Mbps
DSL propagation delay	20ms
Back-end BW	100Mbps
Back-end propagation delay	10ms

Table 8.4: *Scenario Four with QOS*

We can see from the histogram plot that the delay distributions has a significant degree of randomness because of the queue on the buffer.

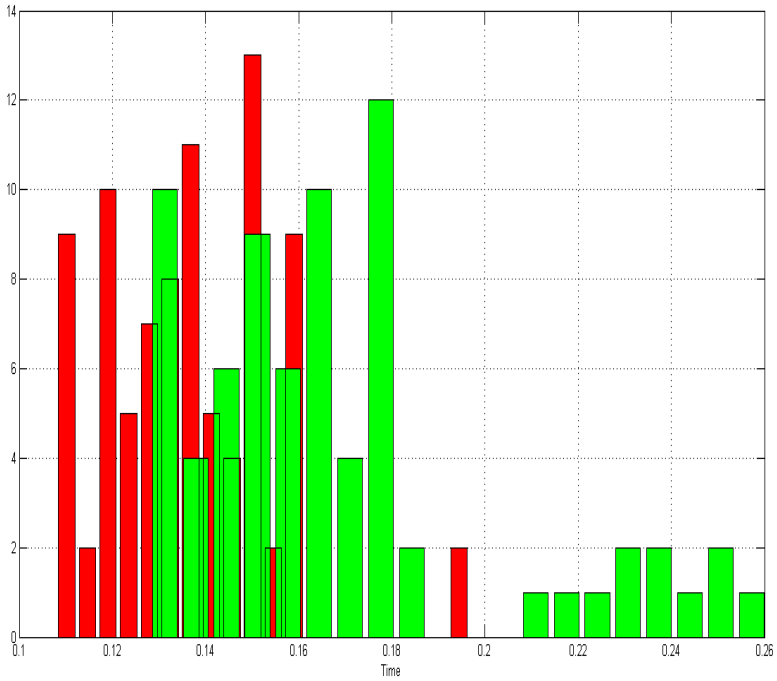

Figure 8.4: *Scenario four delay distribution*

Chapter 9

RADE Implementation and Results

The primary goal of RADE is to tell us if our allocation of Smart Grid resources for the communication infrastructure and control server are appropriate. For this we have designed a system that will give us a real number evaluation of the choice. In this work we focused on time allocation problem where RADE is used to test if our allocation satisfies delay requirements for the communication network and the controller given N number of intelligent consumers connected to the system.

On the previous sections we have analyzed how we collect the features that will be used for RADE algorithm. The two features used are the delay distributions collected from the network simulation done on OMNeT++ and the distribution for the controller. Let us discuss the data preparation phase where the collected distributions are trained to model the best fit for the algorithm.

9.1 Data Preparation and Training

We collected 100 samples from each intelligent consumers(meters) in total 10000 samples. The same amount of data is generated from the controller distribution by assuming a mixture of Gaussian distribution. The data is divided in to three Training Data, Validation Data, and Test Data.

The training data is used for RADE as input features which is used to train the learning algorithm. The first step is using the method Expectation Maximization and Maximum Likelihood method to parametrize the training data with Gaussian mixture parameters.

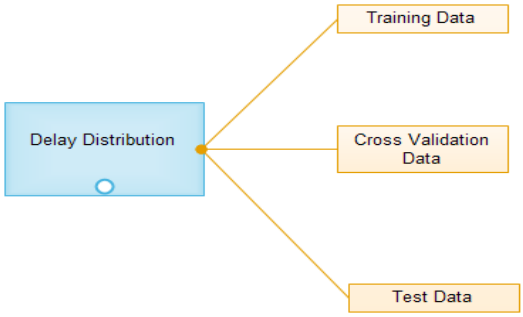

Figure 9.1: *Data Preparation*

An example fit is shown on the figure 9.2 which shows the fitting of delay distribution of the tested fourth scenario which was shown figure 8.4. The corresponding CDF plot for the distribution is shown on figure 9.3.

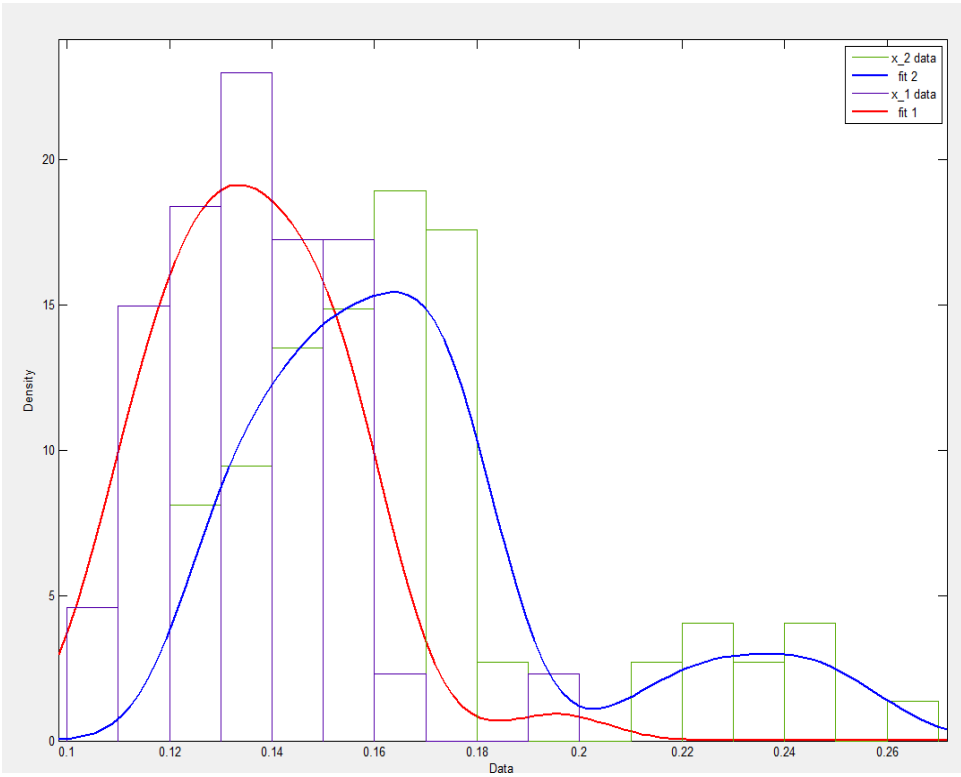

Figure 9.2: *Fitting the distribution*

The Cross validation data is used to make the learning algorithm work efficiently and if it satisfies the confidence level that we want our fit to have. The confidence level is the percentage of coverage of the distribution that our fit is able to cover. For this work we used confidence level of above 90%.

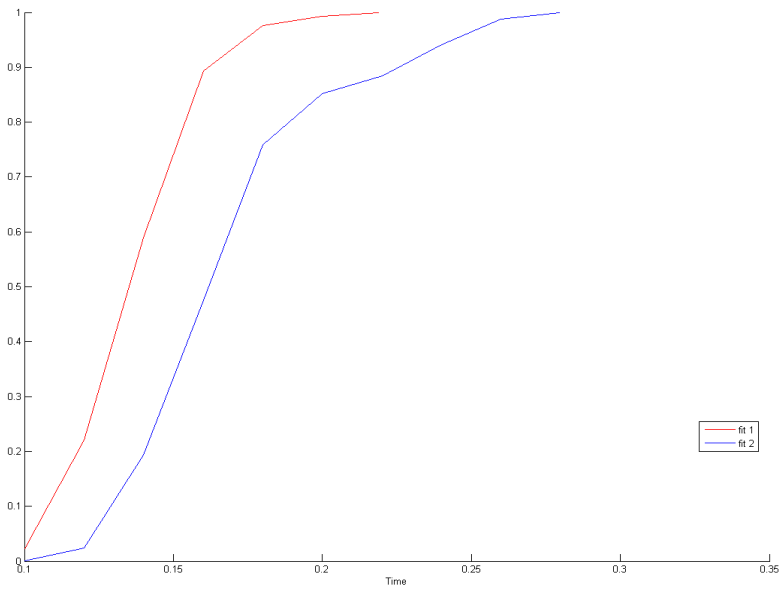

Figure 9.3: *CDF Fit of the distribution*

The same procedure is taken to divided the delay distribution of the controller. Assumption is taken that the controller delay distribution can be modeled by using Gaussian mixture model.

The test data is used to test the algorithm and see how it performs in making proper evaluation of the distributions. The main goal of dividing the data to training, cross validation and test data is to fit the model using the training data first then we improve the fit by using the cross validation data and checking if it satisfies the confidence level. finally we make a confirmation if the fit works perfect by making another test using the test data. It is widely used machine learning practice specially for density estimation problems.

9.2 RADE Test

In this section we will talk about the test results done for RADE algorithm. On previous sections we discussed what input datas we used for the model and how we prepared the data by fitting them to a Gaussian mixture model using EM-ML.

Figure 9.4 shows the scatter plots drawn for the input datas , the x-axis showing the delay for the communication network and the y-axis showing for the controller.

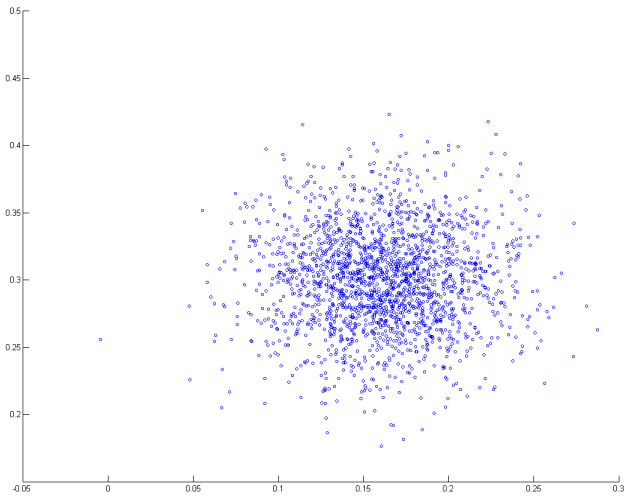

Figure 9.4: *Scatter plot of the Joint distribution*

By using the method mentioned by RADE algorithm we get the joint distribution of the input features. Figure 9.5 shows the multivariate distribution function $\mathbf{P(x)}$ of the data. The delay distribution for the communication network has a bigger peak value around 150ms and a smaller peak value at 220ms. While the controller delay distribution is concentrated at around 300ms.

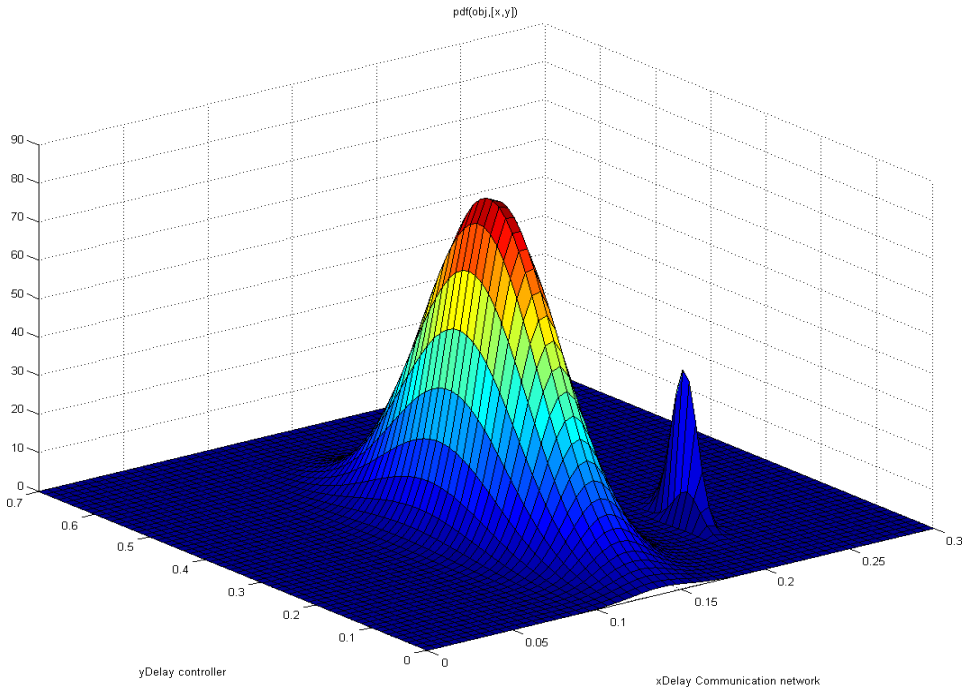

Figure 9.5: *PDF plot of the Joint distribution*

The multivariate CDF($F_X(x)$) of the distributions is shown on Figure 9.6. It is clear from the plot that we can get 100% coverage if we set 220ms for the communication network and 600ms for the controller.

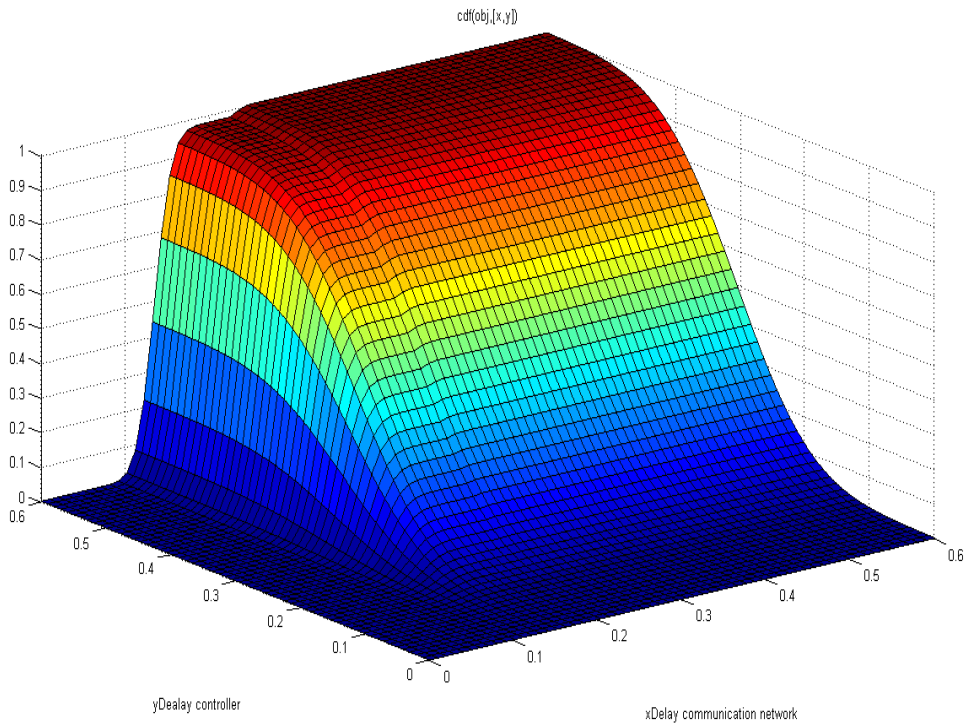

Figure 9.6: *CDF plot of the Joint distribution*

Another test taken is to relate communication network mean delay with total processing time given the control distribution is fixed and taking different confidence bounds on the CDF($F_X(x)$). As shown on figure 9.7, The test is taken for three confidence bounds 75% , 85% and 95%. The mean for the Gaussian mixture distribution is varied by sliding the whole Gaussian components by its value.

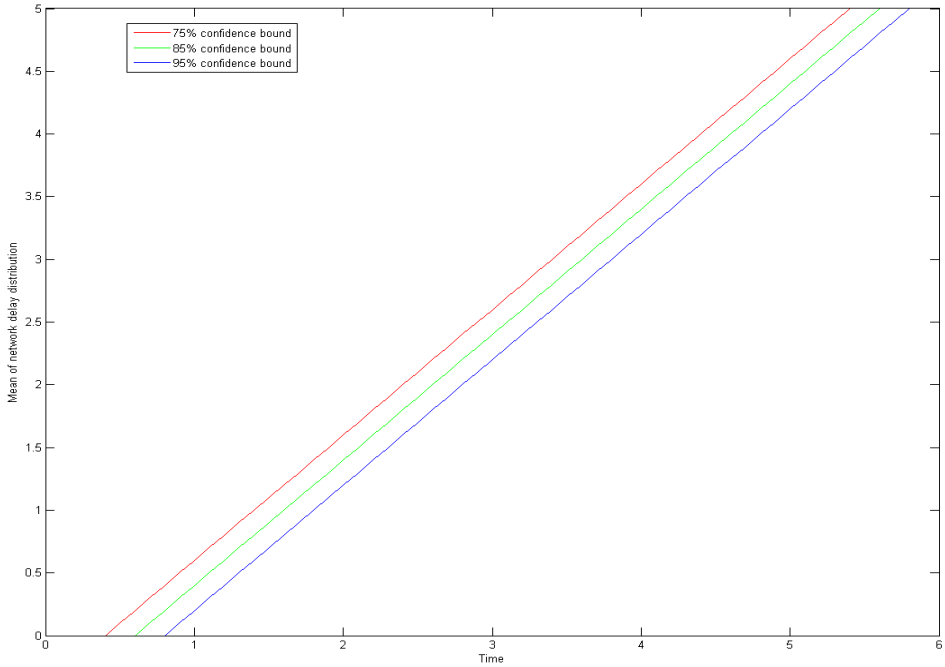

Figure 9.7: *Confidence bound and Mean Communication Network*

The same procedure is taken to see the impact of varying the control mean delay with the total processing time given the communication network delay distribution stays constant and for the same confidence bounds mentioned earlier.

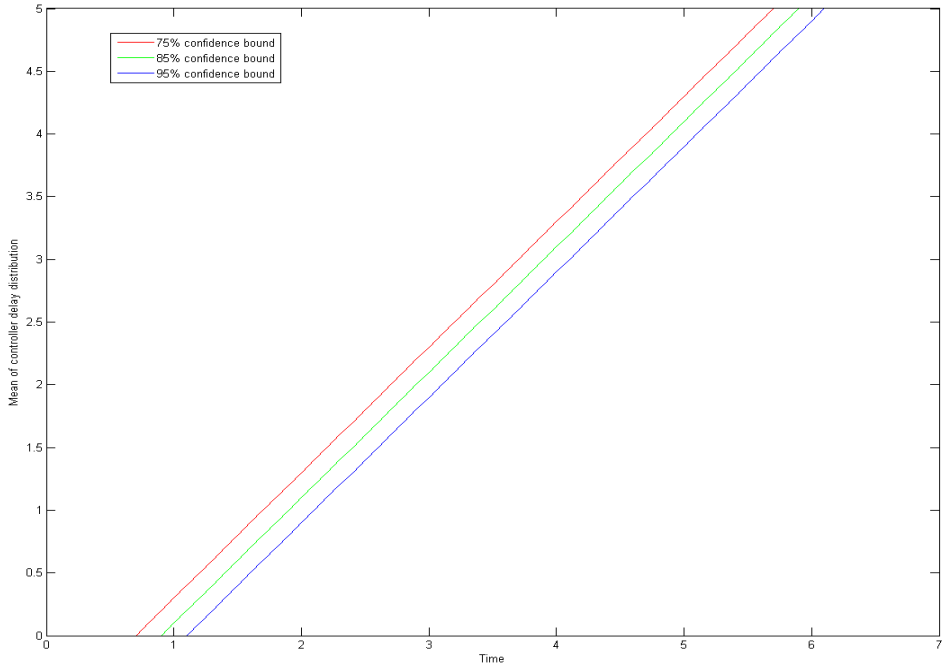

Figure 9.8: *Confidence bound and Mean Control*

Conclusions

Throughout the course of this project, We proposed and implemented Resource allocation algorithm(RADE) specifically for Smart Grid timing requirements. Resource allocation using density estimation(RADE) is a method that uses a learning algorithm to train the model and use this for providing real number evaluation of allocation of resources. The evaluation will enable us to check fulfillment of confidence bounds by allocating the proper processing time for Smart Grid communication network and controller. We learned that real number evaluation will give us a quick and powerful technique to make sure that our allocation fulfills the desired requirements.

The training datas used for this model are communication network delay distribution and controller delay distribution. Hierarchical predictive control model(HCPM) is chosen for this work for estimating controller delay distributions because it has put a good mathematical relationship between computational complexity and controller load. We took this relationship from this model and mapped computational complexity to control server delay distribution. Since multiple distributions can be used to denote controller delay distribution based on server capacity and other factors, We needed to fix to one of the possible distributions in terms of Gaussian mixture model.

The second feature used for the algorithm is communication network delay distribution. To get a realistic distribution we implemented a simulation network for DSL access network using OMNeT++. Since access network is a shared medium, To understand the impact of other traffics on the network, we tested different scenarios. For these scenarios, we generated different traffics in terms of HTTP, FTP , Video streaming and QOS parameters. We showed the relationships between the scenarios by plotting the delay distributions of Smart Grid network.

We analyzed the mathematical algorithm behind RADE which is Expectation maximization and maximum likelihood used to estimate the delay distribution of the communication network to Gaussian mixture model. Gaussian mixture model is a common model used for estimating delay distribution of a communication network. RADE is implemented in Matlab by using statistical

toolbox. Implementation is tested and got results to support our argument that this method can be used for resource allocation problems on Smart Grids.

We consider that the method we proposed(RADE) which takes in to account communication network timing requirements and the control server timing requirements is feasible method for resource allocation problems and should be used for related implementations. We would also like to mention that, because the problem is versatile, we did not cover every scenario and considerations. We made assumption to fix the parameter space and simplify the problem keeping it realistic.

Achievements

- Resource allocation problem is complicated in nature with various considerations and possibilities for the parameters. for this, we modeled the problem in a proper simplified way by fixing the parameter space.
- We design a method which takes the delay requirements of the communication infrastructure by implementing a simulation method and the control server by analyzing state of the art method in-terms of HPCM.
- Through HPCM method we analyzed the performance delay requirements for Smart Grid control server.
- Acquired experience in using OMNeT++ for network traffic delay analysis through simulations.
- We proposed a Resource allocation algorithm(RADE) which can be used to allocate proper amounts of processing time for the control server and the network
- Implemented and tested the proposed method by using Matlab and analyzed the result.

Future-work

We consider that this work could be used for further studies and implementations, Some of the improvements we propose for future implementation are:

- The control algorithm used for this work is HPCM which is modeled for a specific Smart Grid use cases, It would be more interesting to see how the model behaves for different control algorithm models.
- Further, The control model used here is through analytical method. A more realistic relationship would be gathered through practical field test or by using a testbed.
- To fix the parametric space, this work used Gaussian mixture modeling of the delay distributions. Testing other distributions would be useful for other use cases.
- The method used for parametric estimation of Gaussian mixture mode is Expectation maximization maximum likelihood. For this we have to set the number of Gaussian components through observations. A more powerful method which automatically identifies the number of Gaussian components is variational Bayesian inference for Gaussian mixture model. It would make the algorithm much efficient if this method is used.
- Similarly, The communication network delay distribution is collected from a simulation network. It would make the method much acceptable if a realistic field test is done to collect the data.
- The two protocols implemented are UDP and TCP, testing other powerful protocols could be very useful.
- The testes undertaken are limited to specific scenarios, looking at different scenarios in terms of network traffic and topology would be useful.

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