Smart Grid Traffic Modeling in GSM and LTE using Multidimensional Markovian Process

Vishwajeet Singh

A Thesis Submitted to

Indian Institute of Technology Hyderabad

In Partial Fulfillment of the Requirements for

The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद

Indian Institute of Technology Hyderabad

Department of Electrical Engineering

June 2015

Declaration

I declare that this written submission represents my ideas in my own words, and where ideas or words of others have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

Vishwajeet

(Signature)

(Vishwajeet Singh)

EE13M1008

(Roll No.)

Approval Sheet

This Thesis entitled Smart Grid Traffic Modeling in GSM and LTE using Multidimensional Markovian Process by Vishwajeet Singh is approved for the degree of Master of Technology from IIT Hyderabad

(Dr. Sumohana Channappayya) Examiner
Department of Electrical Engineering
IIT, Hyderabad

(Dr. P. Rajalakshmi) Examiner
Department of Electrical Engineering
IIT Hyderabad

(Dr. Mohammed Zafar Ali Khan) Adviser
Department of Electrical Engineering
IIT Hyderabad

(Dr. G.V.V.Sharma) Chairman
Department of Electrical Engineering
IIT Hyderabad

Acknowledgements

I am grateful to my parents for their love and support throughout my life. Thank you both for giving me strength and counsel in every circumstances to achieve my goals.

Personally, I would like to thank my supervisor Associate Prof. Zafar Ali Khan for his guidance and support throughout my work, and especially for his confidence in me.

Thank you to my friends Venkatareddy, Viyyapu, Rama Krishna for their understanding, encouragement, counsel and company. Thanks are due to my VLSI group and to all those who motivates and helped me and made my stay enjoyable at IITH. Thanks again to all for their wonderful support and experience.

This thesis is only a beginning of my journey.

Dedication

Dedicated to my beloved Mother for her measureless love, support and motivation

Abstract

The traditional electrical grid has provided electricity over a decades. Since then it has been of static nature without significant update and offers limited control. But as of now with rise in demand of power the traditional grid is not capable of meeting them. Also, several blackouts have occurred which raises the serious Questions on grid reliability and efficiency. Recently smarter solution has been suggested to address the above problem. It will take the advantage of advanced Information and Communication technology (ICT) and transform the grid into Smart grid.

The advanced ICT is a highly developed and constantly evolving technology that provide access to information through communication networks. This includes Wireless networks, Internet, etc. It is promising in realizing the smart grid as it will handle large volume of information flow. The Cellular network is a good choice for providing communication among the devices of smart grid. It not only offers low cost solution but it provides secure, reliable transmission with advanced technology like GSM, LTE, etc. However, they facilitate communication services for voice and data traffic.

With smart grid new services like Advance meter reading (AMR), Utility etc. also come into picture. These services exchanges information on regular intervals of time over a cellular network. Hence, the performance of cellular network need to be evaluated when smart grid services also contends for service. The characterization determines the impact of smart grid on voice and data services of cellular network as well as the expected traffic volume.

We present a Multidimensional Markovian model to evaluate the performance of GSM and LTE network. Firs the model is dimensioned to find the crucial services required to represent the fully deployed smart grid network. These are Advance meter reading(AMR), Generation and Distributed energy resources (DER), Distribution side management (DSM), Grid Automation, Utility, Voice and Data according to us. Previous analysis using reduced markovian model has been proposed. But in this thesis we propose the exact analysis of the unreduced markovian model for GSM and LTE network.

The analysis shows the maximum number of smart grid devices that can be handled by GSM and LTE network under different utilization condition and it turns out to vary linearly with utilization which is derived from cell capacity with constraint to the technology parameters. It represents the expected traffic volume of smart grid. The most important influence is captured by blocking probability of voice and data services of GSM and LTE. It varies in exponential manner and increases significantly at high volume of traffic i.e. when more number of grid devices contends for service. Therefore, at high loads the traditional service is badly affected. These results need to ba taken into account for future network deployments.

It turns out that unreduced model provides an overestimate in number of smart grid devices served and blocking probability of voice and data services as compared to reduced model.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Overview

The conventional electrical grid is capable of meeting the requirements of last century setup. In grid the central generation plant generates the electricity which is transmitted with one-way power flow to consumers within a country or region. The generation plant burn fossil fuel like coal, oil, and natural gas to generate electricity, low in efficiency and causes greenhouse effect. The large scale increase in electricity demand make it very difficult to solely depend on the traditional power plant. The provision of Peaker plants based on non-renewable source of energy may find the solution to meet the above average demands but it will be wasteful approach if the average demand is lower than peak especially at night because electricity once produced has to be consumed as storage is expensive. Renewable energy resources characterized by their environment friendly electricity generation have become popular but they are distributed in nature with offshore farms. Also, the energy they produce is variable because of unpredictability of the sources unlike for the non renewable ones. In such situation it is attractive to use the advanced Information and Communication technology (ICT) to address the above issues.

The advanced ICT enables two way communications between the grid and the customer premises. This necessitates the flow of metering information from the customer premises to the grid to identify the demand, and control information. 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 necessary to transform the grid into Smart grid (SG) which is the future for the power industry. This identifies the need for a communications infrastructure and protocols to support the aforementioned functionalities.

1.1.1 Smart Grid

Smart grid is an intelligent electric grid compromising of controls, utility, automation, new devices and communication technology. It aims to improve the efficiency, reliability, and stability of the conventional grid by effective management and control of the grid resources [9]. Smart grid is based on advance techniques like power control, communications, signal processing, and networking. The smart grid consists of intelligent devices that can operate, communicate, and interact autonomously to monitor the grid operations and reliable power transmission to consumers. The advanced ICT enables two way communication in reliable and efficient manner between different devices of the grid. Smart grid offers the comprehensive solution to conventional grid by integrating the key components like distributed energy resources (DER), Advanced metering reading (AMR), Demand response (DR), Automation, Utility and advanced ICT [1]. ICT is responsible to provide communication infrastructure between grid and consumers for exchanging the crucial grid data. The non-availability of real time information of load may defer the operator to react upon if failure occurs. Not only this, the real time information is very important in load scheduling and efficient management of the grid. Hence, Smart grid offers massive machine to machine (M2M) data volume

1.2 Motivation

It is quite sure that a smart grid is the reformation of conventional grid in terms of energy efficiency, reliability and incorporation of wide range of non-renewable energy resources. Not only this smart grid also aims to minimize the cost of the generation and operation. So, the heterogeneous nature of the smart grid faces technical challenges at different levels such as design, control, and implementation. Therefore, Smart Grid has attracted interests from National Governments, Utility companies, Consumers, Cellular companies and communication technology firms.

The availability of real time information from grid devices is very crucial in the efficient management and control of grid. The non-availability of real time information of load may defer the operator to react upon if failure occurs and also defer proper load scheduling. That's what exactly happened in Northeast blackout 1965 [11] and it raises the serious question on the grid reliability. Thus, the exchange of real time grid data is very important in load scheduling and efficient management of grid. Hence, it is required to define the ICT communication infrastructure. The main obstacle in the deployment of Smart Grids is their high cost. Hence, it is favorable to exploit the existing communication infrastructure to meet the challenges. Therefore, detailed analysis is required to analyze the impact of smart grid devices on existing Cellular technologies. This will help in deciding How efficiently shared network will handle the smart grid traffic and its effect on background voice and data services.

1.3 Related Works and Scope of Thesis

In this we will discuss the earlier work related to smart grid communication using Wireless technologies like Wi-fi, IOT, GSM, UMTS, LTE etc. The earlier work presented the overview of machine to machine (M2M) communication in the grid in reference to the applications, standards, enabling technology and research challenges. It primarily explores the area of Advance meter infrastructure and discusses its impact on Wireless Access technology like GSM/GPRS, UMTS, LTE, IOT, Wi-fi etc. in terms of the network latency, blocking probability and traffic volume. [13][14] gives an insight of the enabling technology (communication technology) and its applicability for smart grid services and QOS requirement along with the applications and research challenges. In the related work

[15][20], traffic from smart meter and home devices is considered to show the arrival distribution and blocking probability of Random access channel(RACH), Access granted channel(AGCH) and Data storage in GSM and deals with number of smart meters deployment and shows the inverse relationship between the number of smart meters and loss probability in GSM respectively. In [16] three class model is exploited to show the mean queuing delay of each traffic in LTE and [4] discuss the traffic parameter in multi-rate system. Similarly, [17] describes the uplink latency for AMR and sensor data traffic in LTE. [18][19] discussed the delay and packet delivery fraction of sensor network in Wi-fi and Wimax and AMR traffic data over UMTS network to provide the TCP and UDP Throughput and latency respectively. In nutshell all related work discussed the M2M communication that mostly related to Advanced meter Infrastructure and does not include other crucial services like Utility, Automation, DER etc.

The main objective of this work is to envisage the crucial services in smart grid and presents the full fledged smart grid communication network. We will then investigate the impact of smart grid services on the existing cellular network (GSM and LTE) using Multidimensional markovian process [7] having seven dimensions where each dimension represents one type of service class.

Chapter 2

Smart grid Communications Pre-Analysis

This chapter presents the overview of the crucial services required in the fully deployed smart grid network and detailed analysis of the performance requirements of different communication technologies.

We will first examine the necessary components and different levels in Smart Grid, the next step is to analyze and have an overview of the communication technologies that can be used in Smart Grids. We would also discuss the latency and QOS requirement of smart grid applications. The applications will form the basis of dimensioning the underlying markovian model.

2.1 Smart grid Key Components

For better understanding of the problem in Smart grid it is important to know the key components. As we already discussed that advanced ICT is a key enabler of smart grid. [1][2] discussed the important components required in smart grid and formed the basis in identification of the different levels. Figure 1 shows the generalized architecture of smart grid with aggregation of different levels and key components.

Level 1 - Level 1 integrates the services of generation plant, DER and AMR. We will discuss each component in detail.

Generation Plant : A generation plant is responsible for the generation of electrical power in large scale. They do so by electric generators that converts mechanical power into electrical power and depend on fossil fuels such as coal, oil, natural gas and nuclear power also. They are generally located at the sub-urban areas to meet the power requirements of a regions at larger distance.

DER : DER harness renewable energy resources which are not concentrated in a region such as wind, solar, biomass etc. for the generation of electricity. DER collects energy from above mentioned resources without any burden on climatic effect. Hence, proper interface is required to manage and coordinate DER with smart grid.

AMR : AMR is responsible for transmitting the power consumption at consumer premises to Utility. It is a collection of Home area network (HAN), Neighborhood area network (NAN) and a Data concentrator(DC). The HAN is an internetwork within a home that connects smart appliances, smart meters and customer. The group of HANs is called NAN which constitutes a large number of customers and size is restricted to a colony. HAN gateway communicates with utility via NAN and exchanges information on energy consumption, billing, incentives and load scheduling if provided. The NAN send the data collected from HANs at regular intervals of time to utility via suitable communication technology. The DC act as a synchronizer between communication technology and NAN.

Level 2 - Level 2 integrates automation of grid equipment's. This part is mainly responsible for data acquisition and control of the grid. It monitors electrical waveform, relay status to check for phasor offsets, faults etc. and alerts operator to take corrective action if needed. In Northeast blackout 2003 [12] the grid couldn't respond when the increased load led the overload of power line resulted in shutdown of grid. These mechanisms increases the grid stability.

Level 3 - Level 3 is responsible for Utility center actions. It process the data received from level 1 and level 2. Its functioning is very crucial to implement the load forecasting model, load scheduling, demand response, control actions, incentives and energy trading. These functions must be regularly updated for dynamic operation of grid with assured functioning. In short, Utility is the main component to control the grid.

2.2 Prospective Communication technologies

We already discussed the importance of real-time information in smart grid for real time monitoring and operations. Hence, smart grid network must be reliable and robust to meet the challenges.

For smart grid one of the key technology enabler is communication systems. The development of more advanced technologies and applications over the conventional grid, leads to the formation and need to transmit large amounts of data from different locations, so it is critical for the utility companies to define the communication requirements[22] to ensure reliable service and functioning of the whole system. The flow of information can be achieved in two most common methods namely wired and wireless. The same method can be realized for Smart Grid networks also. Each of the mentioned channels offers certain advantages and disadvantages depending on the applications. We will discuss it in subsequent sections.

Earlier we discussed different levels in the conceptual model of smart grid. We will analyze the communication technologies for smart grid network in context to defined layers. Now, let us discuss some of the prospective technology that can serve our purpose :

2.2.1 ZigBee

Zigbee is a wireless communication technology built on IEEE 802.15.4 protocol. It is cost effective, efficient and low power technology. It can be used for device control, remote monitoring, reliable messaging etc. Hence, it is best suitable for applications like AMI, home automation in smart grid. It uses 2.4 gigahertz radio spectrum which is an ISM band. Zigbee supports 10-100 meters of transmission distance in direct line of sight, If meshed then transmission distance will be longer. It is useful in low data rate application

Zigbee is easy to deploy with low cost, utilizes free spectrum and provides secure communication using cryptographic keys. It suffers interference from other devices using the same ISM band.

2.2.2 Wi-fi

Wi-fi offers low cost local are wireless communication that uses mainly 2.4 gigahertz. Now a days many devices are equipped with Wi-fi are sold. Hence, the 802.11 Wi-fi networking need to be extended to meet the demands of the smart grid and suitable for applications like AMI, Distribution, Automation and Utility.

One of the challenges in its deployment is to provide long distance communication with few repeaters with low latency. Secondly, it should support range of frequencies to connect with variety of devices in the smart grid

2.2.3 Bluetooth

Bluetooth is a wireless technology that offers low cost and short-range communication and mainly used for personal connectivity. The bluetooth device will be able to communicate with other devices like smart meter meters, appliances etc. and useful in monitoring and control of slave devices in home. Hence, it is best suitable for Home automation. It uses ISM band for radio transmission. As it uses low power for transmission the strong noise signals using ISM band can interfere to destroy the desired signal.

2.2.4 Cellular Networks

Cellular networks is one of the most promising communication technology for smart grid and suitable for cost effective solutions. It can facilitates the communication to almost every entities in the grid ranging from HANs, NANs, Utility, DER etc. As, it has well established infrastructure, hence the network deployment costs will be less. But the requirement is to use this infrastructure for grid as well. Therefore, it will be a shared network. The technologies that can be used are GSM, UMTS and LTE and provides large scale implementation. Apart from low costs, cellular networks provides secure data transmission, hence, it will fulfill the security constraint which is very important in a shared network. Therefore, detailed analysis is required to analyze the performance of networks in Smart Grid applications scenario.

2.2.5 Power Line Communication

Power Line Communication (PLC) make use of existing power lines for transmission of data from one device to another i.e. power line carries data. It facilitate communication by adding modulated carrier to the power lines. It can be used for connecting smart meters and utility. PLC may be advantageous due to wide spread availability of electrical infrastructure and deployment cost will be less.

PLC suffers from electrical noise which is due to the harsh condition created by power line which therefore requires the use of highly complex error detection and correction techniques. That's why it will not meet the need of high data transfer requirements.

2.2.6 Optical Communication

Optical communication make use of optical fiber to transmit information in the form of light pulses from one point to another. The fiber act as a medium between points. Now a days it is widely used

Table 2.1: Advantages and Disadvantages of different Communication Technologies

Technology	**Advantages**	**Disadvantages**
Zigbee	Low cost and power; Simple network and secured; Self configurable	Interference issues; Low processing capability
Wi-fi	Easy to mesh; Convenient; Mobility; Low cost	High interference to EM waves; Interoperability issues; Short range communication
Bluetooth	Low cost and power; Low implementation	Low data rate; Short range communication; Interference issues
Cellular Netwoks	Well established infrastructure; Low deployment cost; High data rate; Robust security; High reliability	High maintenance cost; Finite spectrum and licensing; Hand-off issues
PLC	Low deployment cost; Developed infrastructure	Low bandwidth; High electrical noise
Optical Communication	Low interference from inside and outside environment; Low attenuation; High bandwidth and data rate	Huge deployment cost; Difficult installation on irregular terrain

for providing high bandwidth transmission. Also it is useful in very long transmissions which is due to low attenuation and interferences in fiber.

The biggest problem in optical communication is the high installation cost of fibers.

2.2.7 Wireless Mesh Networks

Wireless mesh networks (WMN) offers high capacity for data transmission. These days they are very popular as they provide cheap solution for wide personal area network (WPAN). The node are basically devices forms the network that routes the packets to the desired destination. The nodes function can be adjusted as per the algorithm which makes WMN's dynamic and flexible. Also WMN's are self healing and scalable which makes them ideal in smart grid scenario.

A major concern in WMN's is the interference and noises due to radio signal in environment and the security concerns at each node which therefore requires encryption, thus causing additional processing and power.

Table 2.1 shows the advantage and disadvantage of the above mentioned technologies.

2.3 Smart grid Applications

We already discussed different levels in the smart grid architecture. Continuing our discussion, here we will define the crucial applications or services that fully represents the deployed smart grid network. These services are identified from the related work of [ref1][ref2]

2.3.1 Advanced Meter Infrastructure (AMI)

AMI refers to an architecture consisting of Smart meters that facilitates the two-way communication between consumers and the utility. Smart meter is a device that communicates the information of energy consumption on regular intervals to utility in real-time. It eliminates the need of manual reading in which person has to go individual home for noting down the readings.

The objective of AMI is to provide remote metering data and process control messages from utility like load scheduling, billing, incentives etc. Thus, it provides an efficient way of load monitoring and dynamic scheduling and price in grid. But it requires high capital costs for full scale deployment and international standards need to be defined which is one of the challenging issue.

2.3.2 Distributed Energy Resources (DER)

DER defines the decentralized small scale generation of power. It is mostly owned, controlled and managed by the end consumers. Smart grid offers provision to consumers to sell the excess electricity from DER, electrical vehicles to the grid. DER capabilities meet the demand of peak consumption and improves grid utilization and efficiency.

DER often represents the renewable energy from solar, wind, geothermal sites etc. and promotes carbon free generation. Government encourages the consumer to use DER to meet short term power to lessen the load on utility and empowers green power generation. But the addition of DER adds complexity to the existing distribution in terms of its integration, balancing power of each DERs, synchronization between DERs and grid.

2.3.3 Distribution Side Management (DSM)

DSM means the alteration in the energy demand of the consumers as per the generation and load statistics, thus reducing the peak electricity demand and thereby reducing blackouts, improving grid reliability and economical system. DSM offers comprehensive solution to both utility and consumers. For utility it aims to reduce the energy demand and thus avoid the need of storage or new plants while for consumers it aims to reduce the cost of the energy. One of the method is financial incentives in which low tariff is provided to consumers so as to encourage them to use energy in off-times. Similarly, high tariff during peak loads and advised to defer the loads so as to minimize the cost and storage.

DSM was introduced publicly by Electrical Power Research Institute (EPRI) in the 1980s. Katoomba demand management project, New South Wales, Australia is one of the example. One of the problem with DSM is privacy issues of the consumers. Its implementation requires the consideration of cost to consumers, variation in prices of electricity etc.

2.3.4 Grid Automation

Grid automation is a system that monitors the substation, distribution networks, energy trading and improves the measurement visibility. It provides real time management of the grid components. It is one of the most important functionality in smart grid. Decision made relies on the information gathered from the grid components. Hence, the secure and reliable data is very crucial.

Table 2.2: Network requirements for Smart grid applications

Applications	**Data Rate**	**Latecy**	**Reliability**
AMR	Low	High	Medium
DER	Medium/Low	Low	High
DSM	Low	Low	High
Grid Automation	High	Very Low	Very High
Utility	Very High	Very Low	Very High

SCADA/EMS/GMS (Supervisory control and data acquisition/ Energy management system/ Generation management system) are used for monitoring, controlling, optimizing and management of generation and transmission systems. These systems uses the information collected from the thousands of data points deployed in network and provide real-time monitoring. These systems increase the reliability, safety, interoperability, communication capabilities of the grid.

2.3.5 Utility

Utility is one of the most complex and important part in smart grid control. As smart grid components are distributed in nature, the information must be sent to utility in reliable and secure manner where the data gathered from different grid devices is processed and analyzed and accordingly take the required control action. Hence, it is responsible in management of the grid by balancing the power generated and consumed power with better efficiency and control by efficient algorithms. It requires complex communication network to realize the smart grid. It must link the wide range of components and ensures the high degree of reliability, interoperability and security.

As discussed the Utility and Grid automation are very crucial in the management of the grid so, the network must be very highly reliable, very low latency and provide high data rate for information exchange. DER and DSM meets the gap in the generated energy. The information on generated energy is important in balancing the load, thus it requires network to be highly reliable and low latency. Similarly, AMR sends the at regular intervals of time so the requirement of data rate is low with medium reliability and high latency. These network requirements are summarized in a table. Table 2.2 shows the network requirements of smart grid applications in terms of Data rate, latency, reliability.

2.4 Delay bandwidth and QOS requirements for Smart grid Applications

A communication network infrastructure is backbone of the smart grid to make it observable, manageable and integrable. Also smart grid is distributed in nature, hence every applications have their own set of QOS requirements to meet their objectives. So, we need to address the Quality of service (QOS)T requirements of smart grid applications. The related work [22] answered the question " What is the QOS requirements in the context of smart grid. This issue is important to address

Table 2.3: Delay and bandwidth requirements for Smart grid applications

Applications	**Delay**	**Bandwidth**
AMR	2-15s	10-100k kbs
DER	400s	10-30Kbs
DSM	500s	10-30Kbs
Grid Automation	25-100ms	2-5Mbs
Utility	20-100ms	2-5Mbs

because the underlying communication infrastructure should be able to provide guarantee QOS and meet all requirements.

Table 2.3 presents the delay and bandwidth requirement for smart grid applications.

Chapter 3

ICT Architecture of Smart grid based on Cellular Network

3.1 Introduction

The Smart grid need wide range of requirements and communication infrastructure is one of them. The large volume of flow of data in a communication network makes the designing of architecture complex. Further, data with high priority like control or fault messages adds the complexity in the architecture.

There are many technologies available to meet the communication requirements in smart grid. They must be cost effective with efficient architecture to support scalability, security and reliability. Cellular network can be promising technology to provide two-way secure communication to support the grid functionality like generation, distribution, transmission etc. but they need to be studied as they were designed for voice and data communication. Cellular coverage is one of the issues in network which tends to make the system unreliable. In this we will discuss the types of network infrastructure and define the proposed cellular network architecture for smart grid.

3.2 Type of Network Infrastructure

Two types of network infrastructure are possible to realize the smart grid. These are dedicated and shared network infrastructure. We will discuss each of them.

1. Dedicated Network Infrastructure

In Dedicated network infrastructure the architecture is planned out such that it exclusively meets the demands of targeted applications. In our case it is smart grid. Dedicated network effectively meets the demand of the applications with high efficiency and reliability. These network not only provide the communication exchange but also enablers of new services and applications with required QOS. The network will provide better performance because it will handle the smart grid traffic only. While in shared network it has to handle smart grid as well as traditional traffic. Also, the load pattern of traditional traffic like voice, data etc will be different from smart grid. Hence, the network design must be scalable and reliable so that data can be transferred in regular manner.

But the initial deployment cost will be very high which put severe constraint on cost effectiveness.

2. Shared Network Infrastructure

The technological developments in Information and communication technology (ICT) has evolved the concept of convergence, meaning a single network will be able to carry different services like voice, data, video etc. By this way the network is shared among the different services. For example Internet was evolved as a Data communication network and now it has become global communication infrastructure which serves different services. Hence, sharing of infrastructure is beneficial in low cost, integration of services and efficiency. A numerous work has been done on the operational issues of shared infrastructure. For example Keon and Anandalingam (2005) study deployment of multiple service classes in telecom networks and explore the use of price discounts as a congestion avoidance scheme. Similarly, Hosanagar et al (2005, 2008) and Du et al (2008) study operational aspects of deploying multiple service classes for distributed caches on the Internet. Thus, all the related works have addressed the problem of multiple user class on a shared network. But the sharing may not always result in cost effectiveness because sharing can result in complex interactions among services, congestion, offsets etc. Hence, considerations like cost of capacity with cost of loss of demand and cost of sharing and benefits.

3.3 Network Architecture

In earlier chapters we had already discussed that advanced ICT is a key enabler of smart grid. As smart grid is a complex system with integration of different components. Hence, a reliable ICT architecture is required in successful deployment of the grid. Therefore, it is important to identify the crucial services needed that completely represents the smart grid. The presented work in [1][2] discussed about the important components required in smart grid. These components formed the basis of identification of different levels required in grid. Figure 1 shows the generalized architecture of smart grid with aggregation of different levels and key components. Level 1 integrates the services of generation plant, DER and AMR. Level 2 integrates automation of grid equipment's while Level 3 is responsible for utility center actions. In level 1 the generation plant and DER sends the information of power generated and AMR send the power consumption data to the utility. AMR consists of Home area network (HAN), Neighborhood area network (NAN) and Data concentrator (DC). The HAN is an internetwork within a home that connects the smart appliances, smart meters and customer. The group of HANs is called NAN which constitutes a large number of customers and size is restricted to a colony. HAN gateway communicates with utility via NAN and exchanges information of energy consumption, billing, incentives and load scheduling if provided. The NAN send the data collected from HANs at regular intervals of time to utility via suitable communication technology. The DC act as a synchronizer between communication technology and NAN.

The Automation part is responsible for data acquisition and control of the grid. It monitors electrical waveform, relay status to check for phasor offsets, faults etc. and alerts operator to take corrective action if needed. In Northeast blackout 2003 [12] the grid couldn't respond when the increased load led the overload of power line resulted in shutdown of grid. These mechanisms increases the grid stability.

The Utility is the main part to control the system. It process the data received from level 1 and

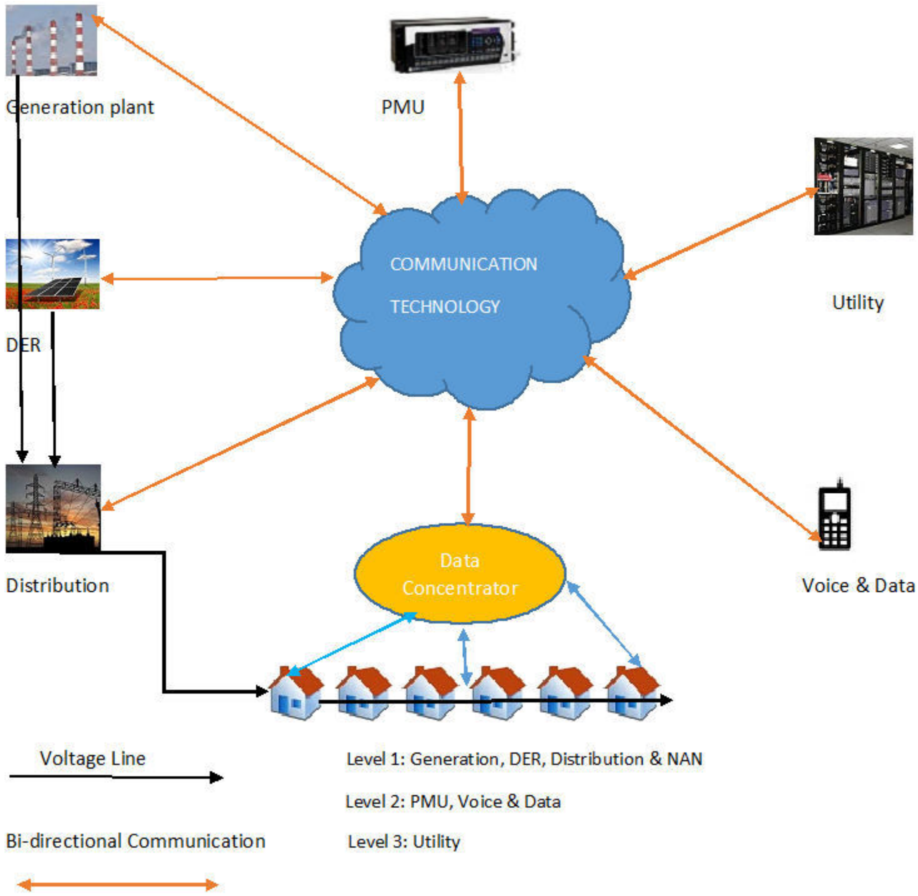

Figure 3.1: Conceptual Block Diagram of Smart Grid

level 2 and formulates and implement the load forecasting model, load scheduling, demand response, control actions, incentives and energy trading. These functions must be regularly updated for dynamic operation of grid with assured functioning.

3.4 Network Topology

The prominent technology for smart grid is Wireless technologies. Cellular technology has well established infrastructure with high reliability, availability and advanced technology like Third generation (3G) and Fourth Generation (4G). That's why it is worldwide adopted. First we will define the Cellular concept, its suitability for smart grid and then network topology is presented

The cellular concept was introduced during the development of First generation (1G) mobile technology. A cellular system consists of a network of base stations or cell that facilitates the communication. Base station has antennas and base transceiver station (BTS). Each cell has its coverage area and hand-off is provided if user moves from cell to other. Figure 3.2 shows the cellular system architecture. It has cell in hexagonal shape which denotes the coverage area of the cell. Cell site is repeated known as frequency reuse to improve the spectrum efficiency. As shown Cell 1 is repeated among other cell in such a way that interference will be minimal

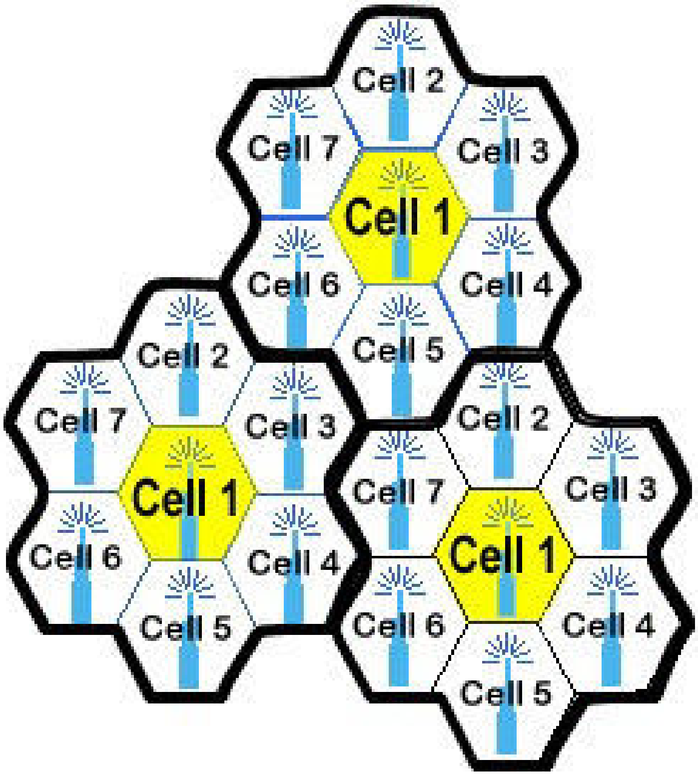

Figure 3.2: Cellular System Architecture

Cellular technology is obvious choice because of well developed and advanced infrastructure. Here is several advantages that makes the choice worthy.

1. **High Performance :** Performance of cellular network is regularly improving with advancement in technology. 4G is expected to offer data rate up to 1 Gbps for fixed speeds and 100 Mbps for mobile users.

2. **Scalability :** Cellular network offers high scalability to support fast device and traffic growth. It can support million of devices.

3. **Security :** Cellular network is built with advanced encryption techniques and authentication to ensure privacy. Additional security may be implemented at application layer to meet specific requirements.

4. **High reliability :** Cellular network availability is very high touching to 99. The frequency reuse and additional network components makes the system uniterrupteed and hence, highly reliable.

5. **Coverage Area :** Cellular network provides wide coverage of area. The hand-off procedure and cell reuse increases coverage. Now a days one can make a call from one country to other.

Figure 3.3 shows the ICT architecture of smart grid based on cellular network. It consists of Base station in a cell which process the request of smart grid applications as well as voice and

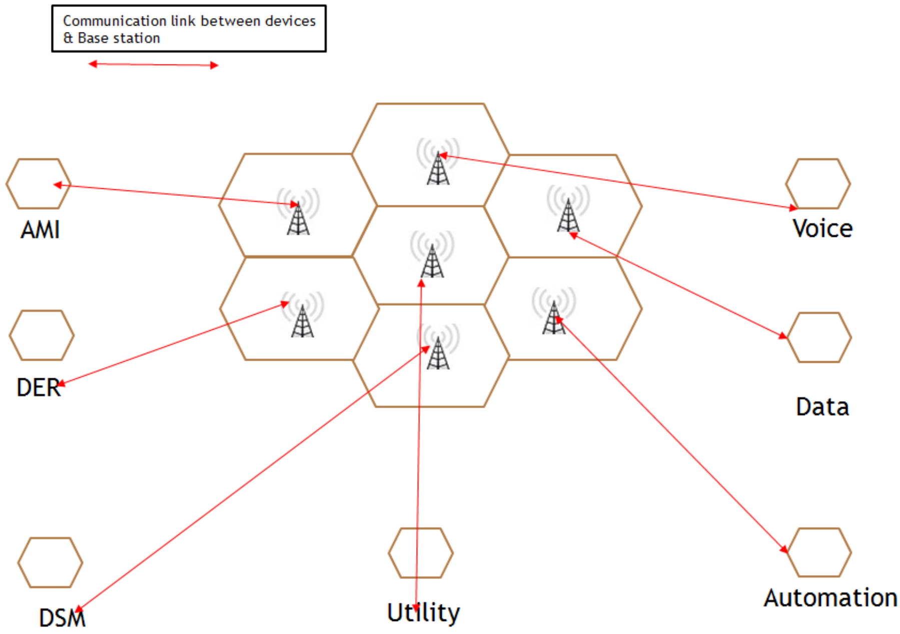

Figure 3.3: ICT Architecture of Smart Grid based on Cellular network

data applications. The applications contends for service with base station with different traffic characteristics.

Chapter 4

Problem Statement

The heterogeneous communication network have been identified to support the functionality at different levels of smart grid. There are issues like interoperability, spectrum utilization and processing in heterogeneous network. Hence, we will consider the homogeneous network of cellular technology for smart grid and evaluate its performance when smart grid applications also contends for service. Figure 3.3 describes the ICT architecture of smart grid based on cellular technology. The worked out dimensions discussed in above chapters are AMR, DER, Distribution, Automation, Utility, Voice and Data [6]. All these have different traffic characteristics with different resource requirements and altogether distinct from voice and data traffic. The architecture consists of a typical Base station at the center of cell (one cell in a cellular network) which act as processing node and enabler of communication among devices. The applications both smart grid and voice and data contends for service by base station. Each application represents one type of traffic class. Therefore, the first four class captures the Machine to machine (M2M) traffic while last two captures (H2H) traffic. The classes have distinct traffic characteristics like arrival and service rates and resource requirements. So, on receipt of request base station then allocates the available resources to the requested class [5]. If resources are not free then service is blocked. Therefore, we need to know the performance of cellular technology in smart grid environment i.e. how the voice and data services will be affected and what will be the maximum number of devices that can be services. We will deal with this problem in scope to Queuing theory [8].

The earlier work [3][8] presented the behavior of multiple class contending for service with single server having infinite buffering capacity. In this we will develop the stochastic method based on Multidimensional Markovian Model (multidimensional Erlang's B system) to evaluate the performance of cellular technology in terms of smart grid traffic volume and blocking probability of voice and data traffic. Here, the resources are completely shared without any priority to classes. We will do th exact analysis of the model without reducing the dimensions. The related work [11] described the parametrization of smart grid traffic classes in terms of arrival rates. Table 4.1 describes the arrival rates of different classes in the presented model. The description of the underlying model is described in Chapter 5.

Table 4.1: Arrival Rates of M2M and H2H Traffic

Service type	**Class**	λ**(1/s)**
Smart grid	AMR	1/15
Smart grid	DER	1/720
Smart grid	DSM	1/30
Smart grid	Grid Automation	1/20
Smart grid	Utility	1/60
Background	Voice	1
Background	Data	1/2

Chapter 5

System Model

The mathematical tools for network design are in the early stages of development. Nevertheless different methods have been employed to model the data traffic and analyze the demand of resources in communication networks. The common methods includes analytic and simulative methods. The analytical methods is based on markovian process while simulative methods are OPNET modeler, SP Netcop, SP Guru Network Planner etc. The analytical methods give reasonable putative for predefined planning of required resources. Simulative methods give more detailed abstraction on the performance of networks. Both methods have provided reasonable validation for traffic parameters of the well developed and existing technology i.e. Telephony and Internet.

A Multidimensional markovian process is presented to evaluate the performance of cellular networks (GSM and LTE) in smart grid environment. The model is dimensioned to identify the crucial services needed to represent the fully deployed smart grid. In earlier chapters we have discussed the crucial services which are AMR, DER, DSM, Grid Automation, Utility and traditional services of Voice and Data.

5.1 The Model

In this we will define the multidimensional markovian model. Figure 5.1 shows the model under consideration. The model has $\boldsymbol{k}$ dimensions and each dimension represents one type of traffic class. The total resources available in the system is $\boldsymbol{N}$ units and completely shared. The arrival (λ_i) and service rate (μ_i) of i^{th} classes are distributed as a Poisson process. Let the resource requirement of the classes is $\boldsymbol{b}$ units. A class request is accepted if at least any of $\boldsymbol{b}$ unit of resources is idle. As mentioned resources is fully accessible and completely shared. Hence, if all resources are busy

Table 5.1: Technology dependent service rates(1/s)

Cellular Tech	Resources(N)	AMR	DER	DSM	Grid Automation	Utility	Voice	Data
GPRS	76	3.4	1.41	.05	.05	2.26	70.7	.75
LTE	50	59.9	25	.91	.91	40	1250	13.3

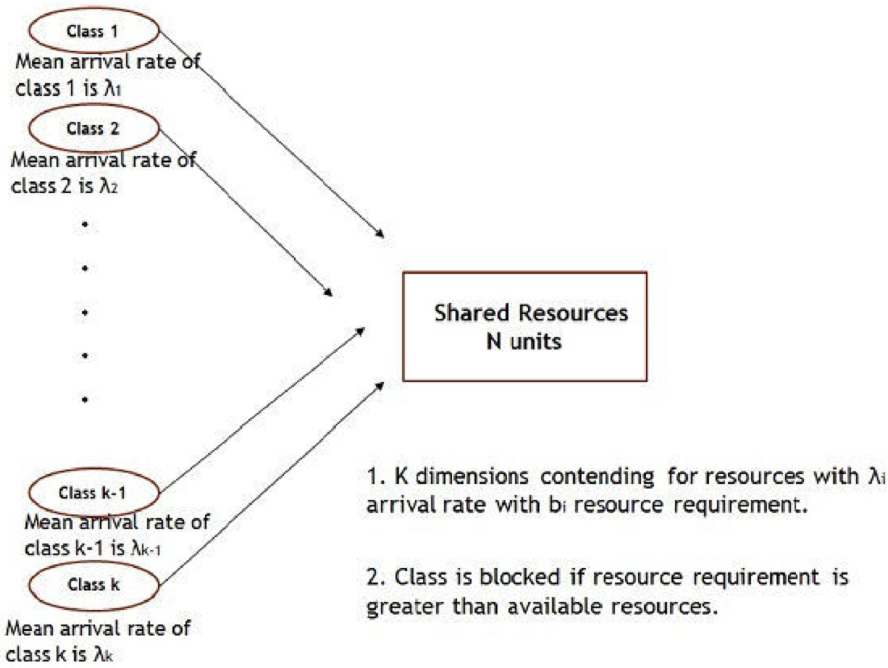

Figure 5.1: Model Description

i.e less than ***b*** unit of resource then service request is blocked. A blocked request will be dropped without affecting the system.

Table 4.1 presented the arrival rates of different classes described in the model. One thing to note that the arrival rates of the classes are technology independent. The technology dependent service rate for each seven class (AMR, DER, DSM, Grid Automation, Utility, Voice and Data) is presented in related work[10][11]. Table 5.1 describes the technology dependent service rates and available resources; for GSM it is 76 channels while for LTE it is 50 resources blocks in 10 Mhz bandwidth. The first four class represents the smart grid while last two denotes the background traffic which is voice and data.

Chapter 6

Model Analysis

A multidimensional markovian process or multidimensional Erlang's B system is a method to model the traffic characteristics with distinct resource requirements of each class. Each class denotes one dimension in model.

Traffic :

1. The arrival process of i^{th} class is a Poisson process with rate λ_i.
2. The service rate of i^{th} class is exponential distributed with mean of μ_i.
3. Offered Traffic : The offered traffic of i^{th} class with poisson process is equivalent to the ratio of average number of requests made to mean service rate.

$a_i = \lambda_i/\mu_i$.

6.1 State Description

Figure 6.1 shows the state description of the defined model. As mentioned earlier the model has $\boldsymbol{k}$ dimensions with total $\boldsymbol{N}$ number of resource units. The arrival and service rate of i^{th} class is a Poisson process with mean rate λ_i and μ_i respectively.

Let $i \in 1, 2, 3, \ldots, k$ denotes the different type of classes. The State is described by a vector n as

$$n = (n_1, n_2, \ldots, n_k)$$

where n_i is the number of resources occupied by user class i. The following restrictions are made

$$0 \leq n_i \leq N \qquad \forall i \in 1, 2, \ldots, k$$

$$0 \leq \sum_{i=1}^{k} n_i \leq N$$

The state transition diagram is shown in Figure 6.1. The system changes its state and moves to a new state when request is received from user class i for resource access. It can be described as :

$$n^+ = (n_1, n_2, \ldots, n_{i-1}, n_i + 1, n_{i+1}, \ldots, n_k)$$

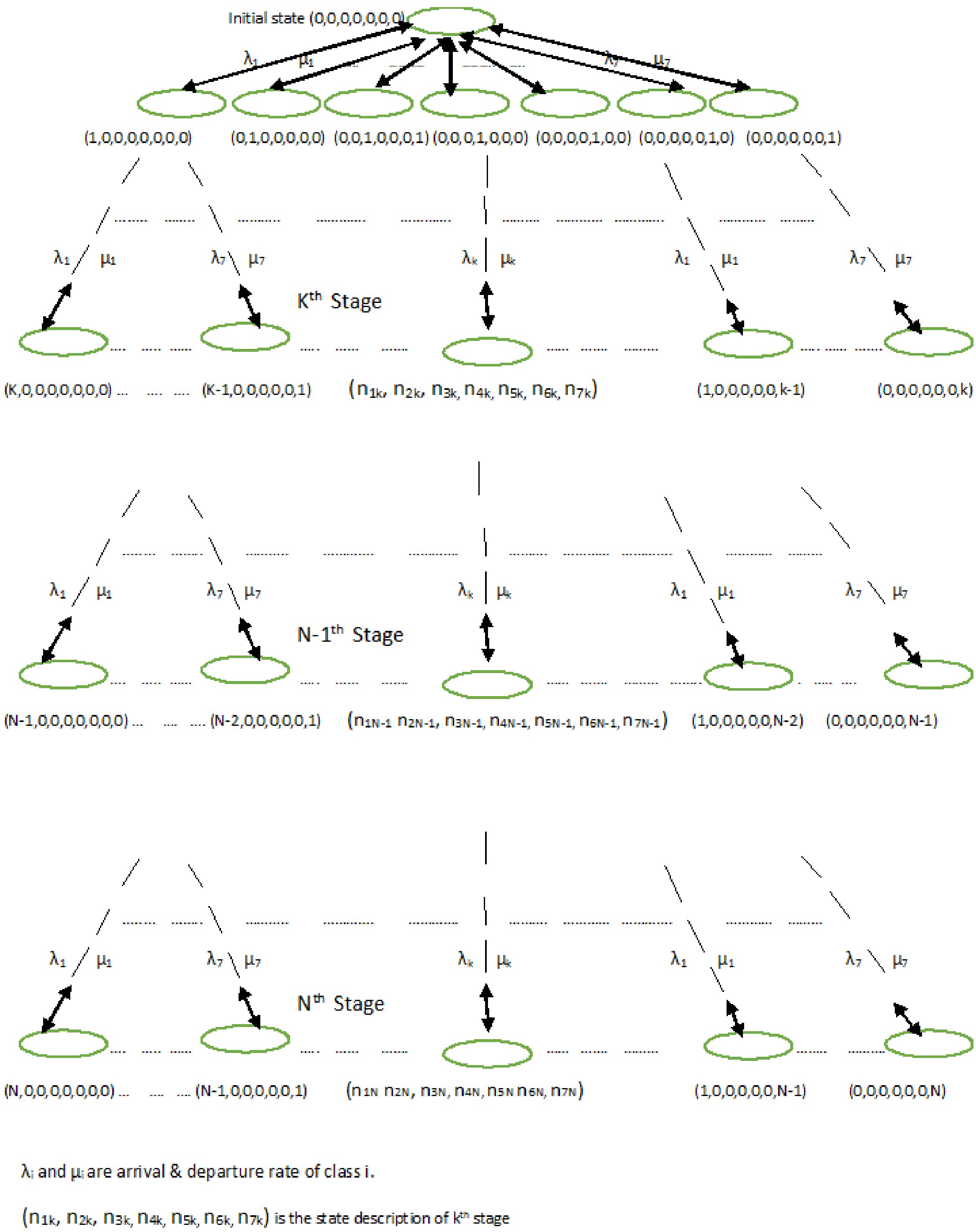

Figure 6.1: State Diagram of the Markovian Model

Similarly, on completion of service the system change its state as

$$n^{-} = (n_1, n_2, \ldots, n_{i-1}, n_i - 1, n_{i+1}, \ldots, n_k)$$

The resource sharing policy give rise to a set of S allowable states from the above mentioned restriction.

The coordinate convex schemes defines the various resource allocation schemes like complete sharing, complete partitioning etc. The **Aien** considered the most general class of policies called coordinate convex policy.

Definition: A non-empty set S is called coordinate convex if and only if it holds the following property

1. for each $n \in S \Rightarrow n_i \geq 0 \qquad i =\in 1, 2, \ldots, k$
2. for $n \in S$ and $n_i > 0 \Rightarrow n_i^{-} \in S$

The state is having coordinate convex policy[5] and also a reversible markov process. Therefore, above conditions is enough to say that state probability $P(n)$ have product form solution [5] of k times. Thus, state probability can be described as

$$P(n) = \prod_{i=1}^{k} \frac{a_i^{n_i}}{(n_i)!} P_A^{-1}(0) \qquad \forall n \in S$$

where $a_i = \lambda_i/\mu_i$ is the offered traffic of i^{th} class
$P_A^{-1}(0)$ is normalization constant.
$P_A^{(}0)$ is calculated using axiom of probability by equating sum of state probability to one i.e.

$$\sum_{n \in S} P(n) = 1$$

The resources in use is given by $C(n) = \sum_{i=1}^{k} n_i$. For simplicity we allowed each class to occupy one resource unit for GSM and LTE. The service request of class is blocked if the resource in use is greater than N i.e C(n) > N and it will be dropped from system.

Multinomial Theorem

Theorem: The multinomial theorem describes how to expand a power of a sum in terms of powers of the terms in that sum. It is the generalization of the binomial theorem to polynomials. It can be described as: For any positive integer k and nonnegative integer n the multinomial formula can be expanded as

$$(a_1 + a_2 + \ldots . a_k)^n = \sum_{n_1+n_2+\ldots . n_k = n} \binom{n}{n_1, n_2, \ldots . n_k} \bigcap_{i=1}^{k} \frac{a_i^{n_i}}{(n_i)!}$$

6.2 Mathematical Implementation

The state probability described above can be written as

$$P(n) = \prod_{i=1}^{k} \frac{a_i^{n_i}}{(n_i)!} P_A^{-1}(0) \qquad \forall n \in S$$

where $P_A^{-1}(0)$ is normalization constant.

Since, $\sum_{n \in S} P(n) = 1$

Therefore,
$\sum_{n \in S} \prod_{i=1}^{k} \frac{a_i^{n_i}}{(n_i)!} P_A^{-1}(0) = 1$

or

$P_A(0) = \sum_{n \in S} (\prod_{i=1}^{k} \frac{a_i^{n_i}}{(n_i)!})$

Hence, $P_A(0)$ can be written as
$P_A(0) = \sum_{n_1, n_2, \ldots, n_k \geq 0} \frac{a_1^{n_1}}{(n_1)!} \frac{a_2^{n_2}}{(n_2)!} \cdots \cdot \frac{a_k^{n_k}}{(n_k)!}$

The Mean number of jobs in system :

$$\begin{aligned} E[n] &= \sum_{n \in S} nP(n) \\ &= \sum_{n \in S} n \bigcap_{i=1}^{k} \frac{a_i^{n_i}}{(n_i)!} P_A^{-1}(0) \\ &= P_A^{-1}(0) \sum_{n \in S} n \frac{a_1^{n_1}}{(n_1)!} \frac{a_2^{n_2}}{(n_2)!} \cdots \cdot \frac{a_k^{n_k}}{(n_k)!} \\ &= P_A^{-1}(0) \sum_{n \in S} (n_1, n_2, n_3, \ldots, n_k) \frac{a_1^{n_1}}{(n_1)!} \frac{a_2^{n_2}}{(n_2)!} \cdots \cdot \frac{a_k^{n_k}}{(n_k)!} \end{aligned}$$

Applying Multinomial theorem. Hence,

$$E[n] = P_A^{-1}(0) \Big(\frac{a_1 A^{i-1}}{i-1!}, \frac{a_2 A^{i-1}}{i-1!}, \ldots, \frac{a_k A^{i-1}}{i-1!} \Big)$$

where i=1,2,...N

The Mean number of waiting jobs in system :

$$
\begin{aligned}
E[n-1] &= \sum_{n\in S}(n-1)P(n) \\
&= \sum_{n\in S}(n-1)\bigcap_{i=1}^{k}\frac{a_i^{n_i}}{(n_i)!}P_A^{-1}(0) \\
&= \sum_{n\in S-1}(n_1-1,n_2-1,\dots,n_k-1)\bigcap_{i=1}^{k}\frac{a_i^{n_i}}{(n_i)!}P_A^{-1}(0) \\
&= \sum_{n\in S-1}(n_1-1,\dots,n_k-1)(\frac{a_1^{n_1}}{(n_1)!},\dots,\frac{a_k^{n_k}}{(n_k)!})P_A^{-1}(0)
\end{aligned}
$$

Applying Multinomial theorem. Hence,

$$
E[n-1] = P_A^{-1}(0)\Big((\frac{a_1A^{i-1}}{i-1!}-\frac{A^i}{i!}),(\frac{a_2A^{i-1}}{i-1!}-\frac{A^i}{i!}),\dots,(\frac{a_kA^{i-1}}{i-1!}-\frac{A^i}{i!})\Big)
$$

where i=1,2,...N

Invoking Littles Law[4] for multi-class

$$
E[n] = \sum_{i=1}^{k}\lambda_i E[s]
$$

where $E[s]$ is sojourn time.

Hence,

$$
E[s_i] = \frac{E[n_i]}{\sum_{i=1}^{k}\lambda_i}
$$

Similarly

$$
E[w_i] = \frac{E[n_i-1]}{\sum_{i=1}^{k}\lambda_i}
$$

where $E[w]$ is waiting time.

Average Utilization :

$$
\begin{aligned}
U_A &= \sum_{n\in S}\frac{C(n)P(n)}{N} \\
&= \frac{\sum\limits_{n\in S}\sum\limits_{i=1}^{k}P(n)}{N} \\
&= \frac{\sum\limits_{n\in S}n_1P(n)+\cdots+n_kP(n)}{N} \\
&= \frac{E[n_1]+E[n_2]+\cdots+E[n_k]}{N}
\end{aligned}
$$

Blocking Probability : Let B be the set blocked space.

$$\begin{aligned} P_{b_i} &= \sum_{n \in B} P(n) \\ &= 1 - \sum_{n \in S} P(n) = 1 - \sum_{\sum n_i \leq N} P(n) \\ &= 1 - \frac{A^{n_i}}{(n_i)!} P_A^{-1}(0), \qquad A = \sum_{j=1}^{k} a_i \end{aligned}$$

6.3 Equivalent Reduced Model

The problem of dimension reduction is solved according to the earlier work [5]. It presented the one-dimensional recursion of the underlying multi-dimension. The state probability is calculated by recursive equation. Also in the related work [11], the analytical model presented is reduced multi-dimensional markovian model based on [5] to evaluate the performance of cellular technology. The recursive distribution to find the state probability for the n_i allocated resource is given by :

$$P_n = \frac{\tilde{P}_n}{\sum_{k=0}^{N} \tilde{P}_k}$$

$$\text{with} \qquad \tilde{P}_n = \begin{cases} 1 & n = 0 \\ \sum_{i=0}^{k} \frac{a_i n_i}{n} \tilde{P}_{n-c_s} & n > 0 \end{cases}$$

The blocking probability is given as :

$$P_{b_i} = \sum_{j=N-n_i+1}^{N} P_j$$

where N is the maximum number of available resource, a_i is the offered traffic of class i, n_i are resource of class i and k is the number of service classes.
describe the equivalent reduced model from paper.

Chapter 7

Results Analysis

The key factor that affects the performance of existing cellular network is the blocking probability of the traditional services like Voice and Data. For this we want to study the smart grid traffic volume and its effect on the voice and data services of GSM and LTE. These results need to be considered in future network infrastructure.

As mentioned in earlier chapters seven dimensions or class have identified to represent the smart grid architecture for GSM and LTE networks. These are AMR, DER, Distribution, Automation, Utility, Voice and Data. The first four characterizes the M2M traffic of smart grid while last two signifies traditional H2H traffic in GSM and LTE network. The arrival and service rates of different classes are distributed as Poisson's distribution parametrized by mean value λ. It can be shown as :

$$P(x) = \frac{e^{-\lambda}\lambda^{x}}{x!}$$

Table 4.1 shows the mean arrival rates λ_i of i_{th} class in the model and it is independent of the cellular technology. Table 5.1 shows the mean service rate μ_i in GSM and LTE network for i_{th} classes under consideration. In GSM time slots are allocated while in LTE resource blocks are allocated to the requested class. With and without dimension reduction model is evaluated in MATLAB

Figure 7.1 and 7.2 depicts the state probability distribution and blocking probability of the model described in section 6.2. Figure 7.6 and 7.10 describes the relative deviation or comparison of the state probability from the model with and without dimension reduction. The maximum relative deviation is less than 2.5% for GSM and for LTE it is less than 2%. Hence, it shows that state probability is well constrained to the assumed Poisson's distribution. Also, it is closely related to state probability distribution described in equivalent reduced model [11]. Thus, validating the model. The maximum number of smart grid devices that can be handled by the network under different utilization condition is shown in Figure 7.3 and 7.7 for GSM and LTE respectively and represents the smart grid traffic volume. It shows the number of devices served varies as a linear function of the utilization derived from cell capacity with constraint to the technology parameters. Figure 7.5 and 7.9 characterizes the average throughput offered by GSM and LTE in response to different service requirements of the classes. The throughput decreases significantly from 60% because of large amount of smart grid traffic. The most important influence captured is on the blocking probability of H2H traffic which is given by Figure 7.4 and 7.8 for GSM and LTE respectively. It

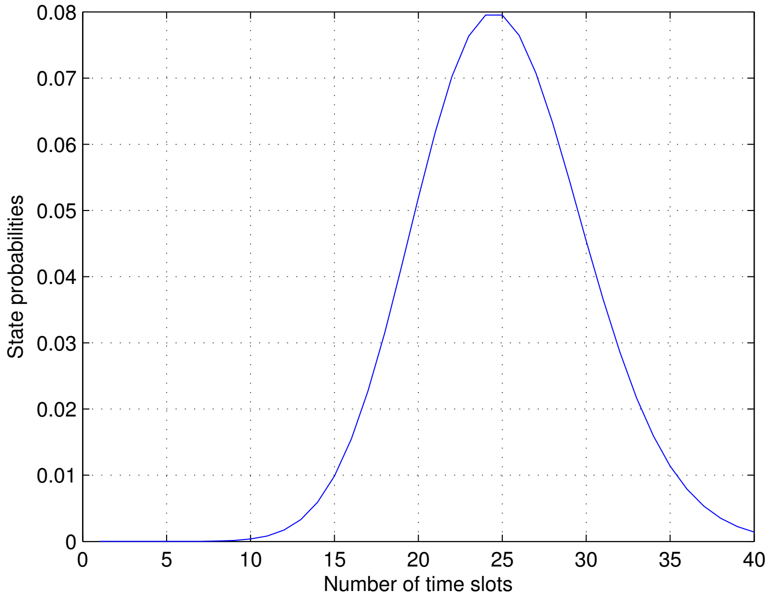

Figure 7.1: Markovian model State probability

varies in exponential manner and increases significantly at high volume of traffic i.e. when more number of grid devices contends for service. The blue line corresponds to one dimension and red line corresponds to multi-dimension respectively. In general wider the probability distribution larger will be the state probability. Hence, these results provides an insight of the behavior of GSM and LTE network when overwhelmed by the Smart grid services also. The graphs also shows that the unreduced markovian model outperforms the reduced markovian model in terms of the number of grid devices served and blocking probability of voice and data traffic.

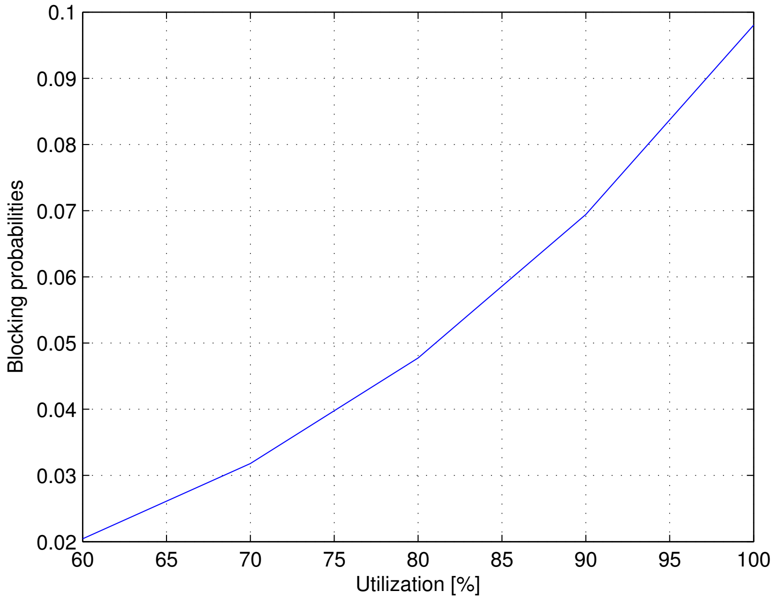

Figure 7.2: Markovian model Blocking probability

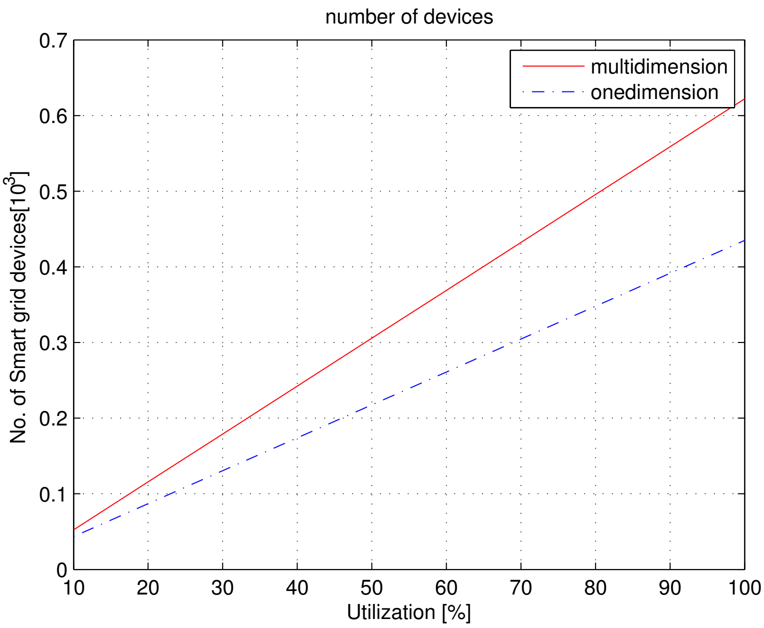

Figure 7.3: Number of smart grid devices served in GSM network

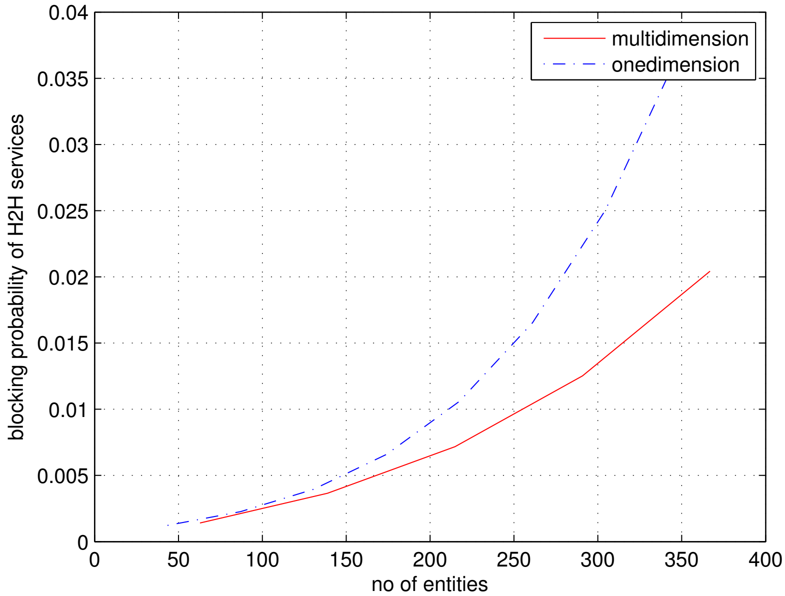

Figure 7.4: Blocking probability of H2H services in GSM network

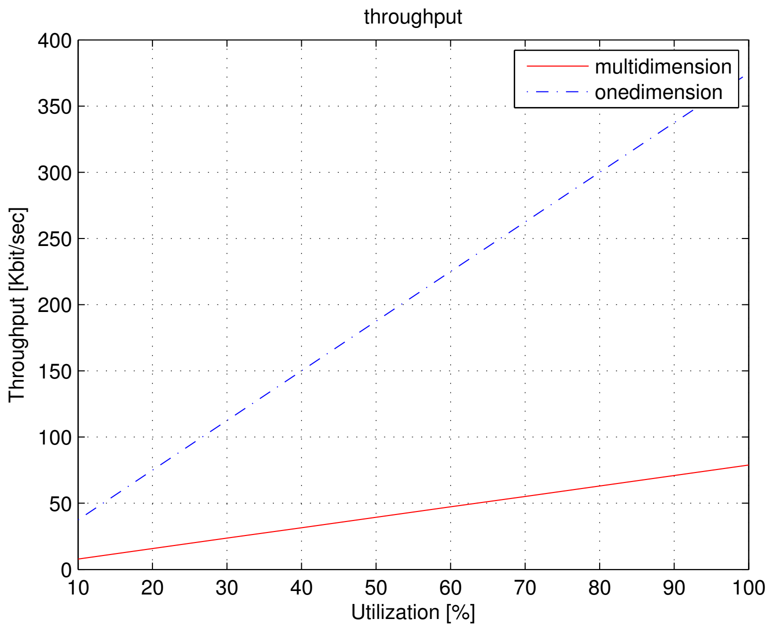

Figure 7.5: Offered Throughput in GSM network

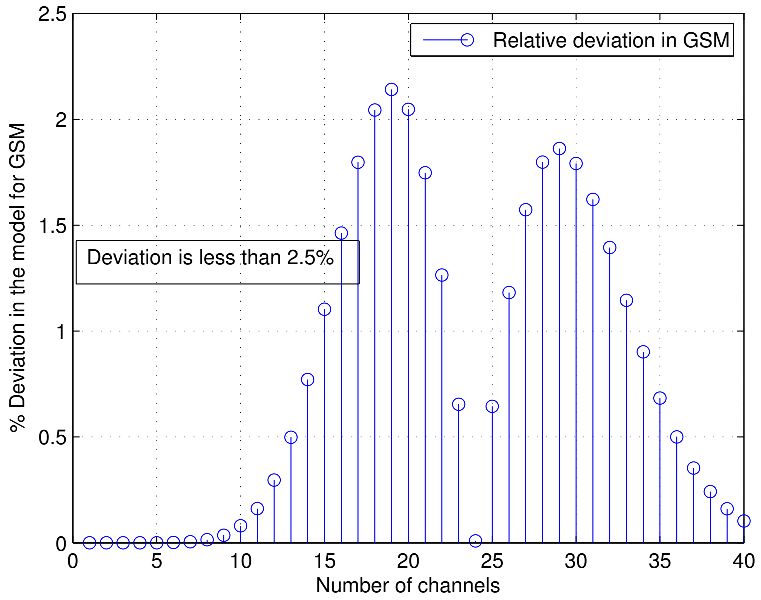

Figure 7.6: Relative deviation in model with and without dimension reductions in GSM

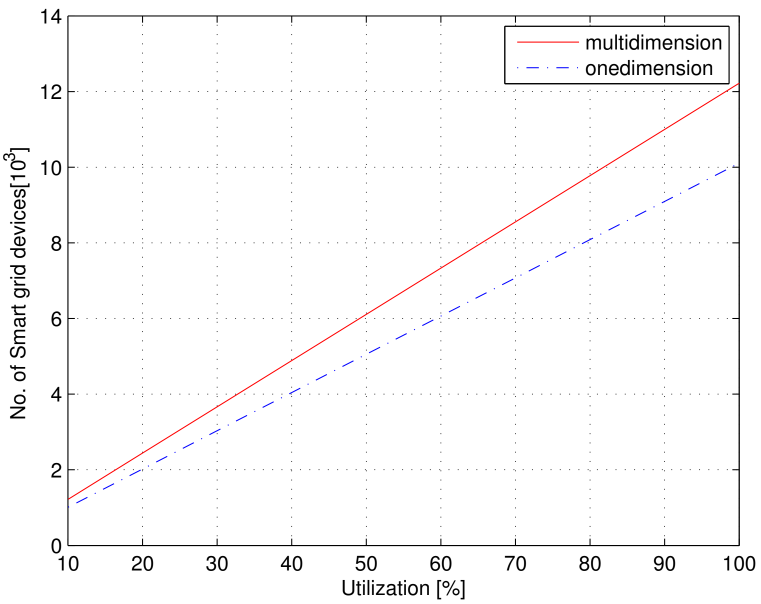

Figure 7.7: Number of smart grid devices served in LTE network

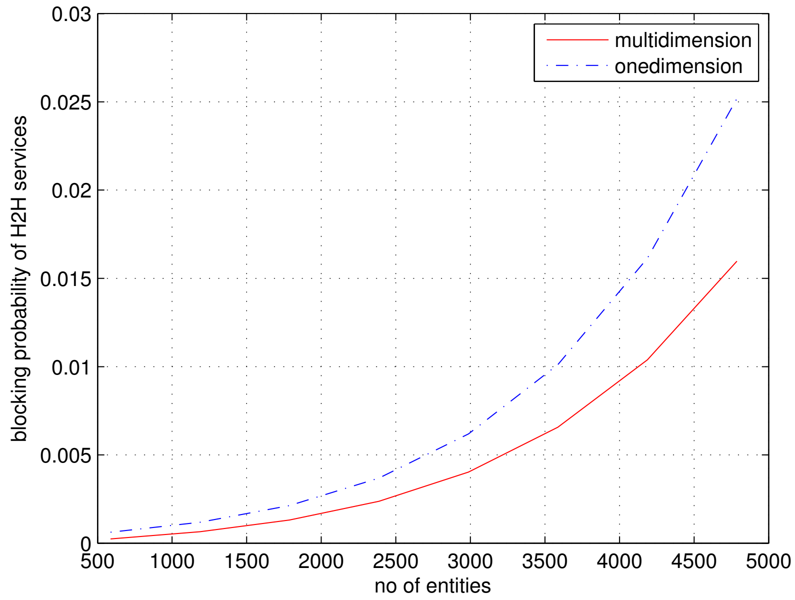

Figure 7.8: Blocking probability of H2H services in LTE network

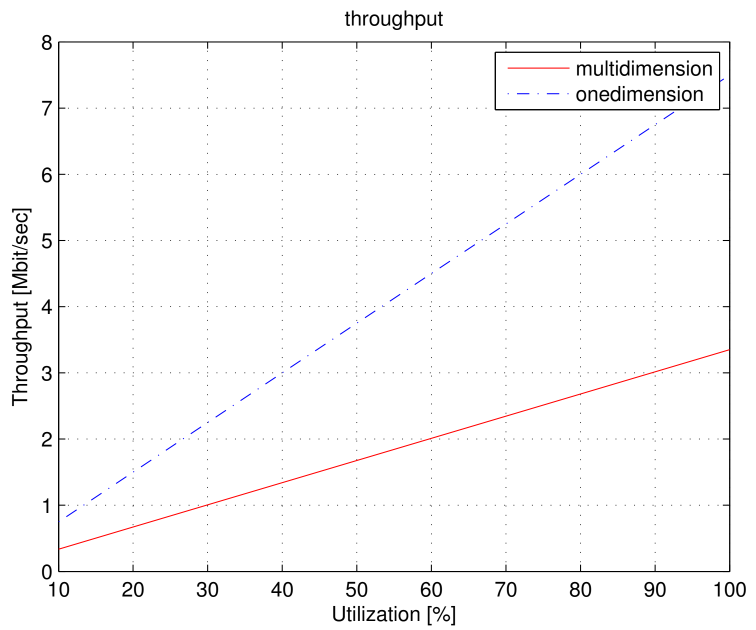

Figure 7.9: Offered Throughput in LTE network

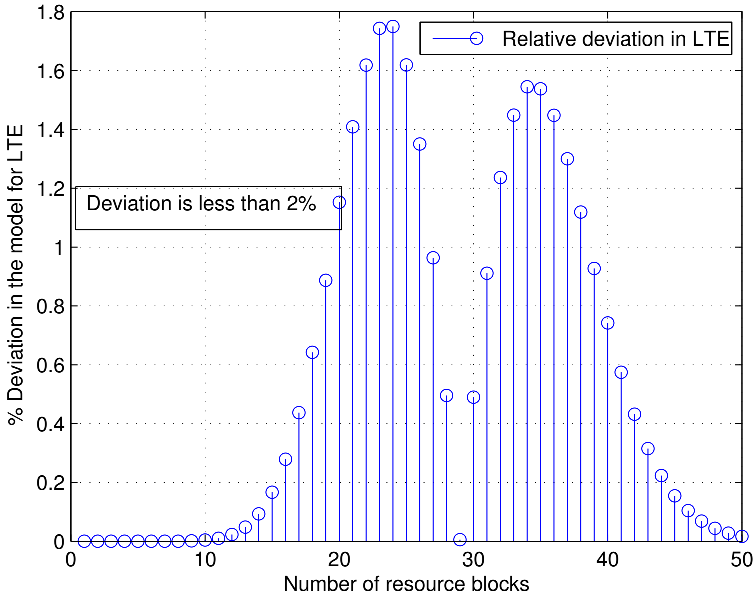

Figure 7.10: Relative deviation in model with and without dimension reductions in LTE

Chapter 8

Conclusion and Perspectives

In this thesis we identified the crucial services required to represent a fully deployed smart grid network. We presented and implemented the multidimensional markovian model in reference to the ICT architecture of smart grid. The multidimensional model is based on the Erlang's B model. This model has been successfully implemented for more than 80 years for telephone traffic. The evaluation will give the expected smart grid traffic volume.

We mathematically evaluated the model to present the maximum number of smart grid devices that can be handled by GSM and LTE network. The most important impact of smart grid is signified by the effect on traditional voice and services in GSM and LTE network. In Addition, we compared multidimensional and equivalent one-dimensional model and results shows an enhancement in serving maximum number of grid devices with less blocking probability of voice and data traffic. But compromise has to be made on throughput and it is due to serving more number of smart grid devices with less blocking probability. This is useful in the scenario where the objective is to accommodate more number of devices. Future research work focus on the performance of Cellular network when priority is assigned to the classes and also MAC modeling to improve the blocking probability of voice and data services.

References

[1] Zhong Fan, Parag Kulkarni, Sedat Gornus, Costas Efthumiou, Georgios Kalogrodis, Mahesh Sooriyabandara, Ziming Zhu, Sangarapillai Lambotharan, and Woon hau Chin, "Smart Grid communications: Overview of Research Challenges, Solutions and Standardization". IEEE COMMUNICATIONS SURVEY AND TUTORIALS Vol. 15, No.1, First Quarter 2013.

[2] Ruofei Ma, Hsiao-Hwa chen, Yu-Ren Huang and Weixiao Meng, "Smart Grid Communication: Its challenges and opportunity". IEEE Transactions on Smart Grid, Vol. 4, No.1, March 2013.

[3] Giovanni Giombene, "Queuing theory and telecommunication Networks and Applications". Springer Science+Business Media, Inc. 2005.

[4] Thomas Bonald and Jorm Virtmao, "A recursive formula for multi-rate system with elastic traffic". IEEE COMMUNICATIONS LETTER, Vol 9 No.8 August 2005.

[5] J.S Kauffman, "Blocking in a shared resource environment". IEEE Trans. Comm. Vol 29, 1981 PP(474-478).

[6] Kenneth C. Budka, Jayant G. desphande, Tenofik L. Doumi, Merk Medden and Tim Mew, "Communication Network Architecture and Design Principles for Smart Grids". Bell Labs Technical journal 15(2), 205-228(2010).

[7] Villy B. Iversen, "Teletraffic engineering and network planning". DTU course 34340, Technical University Denmark, 2010 edition.

[8] Janos Sztrik, "Queuing theory and its applications, a personal view". Proceedings of the 8th international conference on Applied informatics Eger, Hungrary, January 27-30, 2010. Vol-1.

[9] B. Hamilton and M. Summy, "Benefits of Smart Grid". IEEE Power energy mag., Vol. 9, no.1, PP-104-102, Jan-Feb 2011.

[10] C. Wietfeld, H. George, S. Groning, C. Lewandowski, C. Muller, and J. Schmutzler, "Wireless M2M Communication Network for Smart Grid Applications". European Wireless 2011, April 27-29, 2011, Vienna, Austria.

[11] Christian Muller, Markus Putzke and Christian wietfeld, "Traffic Engineering Analysis of Smart Grid Services in Cellular Networks". IEEE SmartGridComm 2012 Symposium-communication Networks for Smart grids and Smart metering.

[12] Wikipedia http://en.wikipedia.org/wiki/List of major power outages.

[13] Bernd Srries, "Communication technologies and networks for Smart Grid and Smart Metering". CDG 450 Connectivity Special Interest Group (450 SIG), Sep-2013.

[14] Siok Kheng Tan, Mahesh Sooriyabandara, and Zhong Fan, "M2M Communications in the Smart Grid: Applications, Standards, Enabling Technologies, and Research challenges". International Journal of Digital Multimedia Broadcasting, Vol. 2011, 26 May 2011.

[15] German Corrales Madueno,Cedomir Stefanovic, Petar Popovski, "Reengineering GSM/GPRS Towards a Dedicated Network for Massive Smart Metering". 2014 IEEE International Conference on Smart Grid Communications, 3-6 Nov. 2014.

[16] Al-Khatib, O., Hardjawana W. ; Vucetic B. "Queuing analysis for Smart Grid communications in wireless access networks". 2014 IEEE International Conference on Smart Grid Communications, 3-6 Nov. 2014

[17] Jason Brown and Jamil Y. Khan. "Performance Analysis of an LTE TDD Based Smart Grid Communications Network for Uplink Biased Traffic". GC'12 Workshop: Smart Grid Communications: Design for Performance, 3-7 Dec. 2012

[18] Visvakumar Aravinthan, Babak Karimi, Vinod Namboodiri, Ward Jewell "Wireless Communication for Smart Grid Applications at Distribution Level Feasibility and Requirements". Power and Energy Society General Meeting, 2011 IEEE, 24-29 July 2011.

[19] S. Abdul Salam, S.A. Mahmud, G.M. Khan and H. S. Al-Raweshidy, "M2M Communication in Smart Grids: Implementation Scenarios and Performance Analysis". WCNC 2012 Workshop on Internet of Things Enabling Technologies, Embracing Machine-to-Machine Communications and Beyond.

[20] German Corrales Madueno,Cedomir Stefanovic, Petar Popovski, "How Many Smart Meters can be Deployed in a GSM cell?". IEEE International Conference on Communications 2013: IEEE ICC'13 - Second IEEE Workshop on Telecommunication Standards: From Research to Standards.

[21] Yaling Nie, Yanchen Ma, "A First Look at AMI Traffic Patterns and Traffic Surge for Future Large Scale Smart Grid Deployments". INFOCOMP 2012 : The Second International Conference on Advanced Communications and Computation.

[22] Yoong-Hee Jeon, "QoS Requirements for the Smart Grid Communications System". IJCSNS Vol. 11 No.3, March 2011

[23] Georgeta Budura, Cornel Balint, Adrian Budura, Eugen Marza, "Traffic Models and Associated Parameters in GSM/(E)GPRS Networks". WSEAS Transactions on Communications" Vol. 8, August 2009.

[24] Anurag Kumar, "Discrete event stochastic process". Lecture notes for an Engineering Curriculum.