WiMAX Models for the Smart Grid

WIMAX MODELS FOR THE SMART GRID

by
Ban Abdul Elah Al-Omar

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To my beloved daughter, Maryam…

Abstract

The smart grid is the integration of the 21st century information and communications technologies with the 20th century traditional power grid. Such integration empowers the electricity utilities and their consumers to play an interactive role to better manage and operate their power consumptions and integrates their renewable energy resources to the grid. As wireless communication is evolving, it is expected that WiMAX will play a major role in the data and commands exchange between generation, transmission, distribution and consumption control and dispatch centers. This thesis proposes the design of two WiMAX network topologies to serve as a wireless communication network for the smart grid. Based on the smart grid applications' quality of service requirements, network parameters and scheduling, simulation models were developed. The traffic was classified into five priority classes. Three scheduling algorithms namely; class-based weighted fair, class-based deficit weighted round-robin and class-based strict priority scheduling were used to simulate and assess the performance of the proposed models. Simulation results showed that the class-based strict priority queuing is better for the highest priority classes and the class-based weighted fair queuing preserved the quality of service requirements for all classes.

Search Terms— Smart Grid, Traffic Classification, WiMAX, Queuing, QoS

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List of Abbreviations

NIST	-	National Institute of Standards and Technology
CPN	-	Consumers Premises Networks
DSN	-	Distribution Substation Networks
WAN	-	Wide Area Networks
SMG	-	Smart Microgrid
ADR	-	Automated Demand Response
NAN	-	Neighborhood Area Network
IAN	-	Industrial Area Network
BAN	-	Building Area Network
HAN	-	Home Area Network
DSM	-	Demand Side Management
WASA	-	Wide area situational awareness
WBN	-	Wireless Broadband Network
ertPS	-	Extended Real-Time Polling Service
rtPS	-	Real-Time Polling Service
nrtPS	-	Non Real-Time Polling Service
BE	-	Best Effort
ICT	-	Information and Communication Technologies
MRTR	-	Minimum Reserved Traffic Rate
MSTR	-	Maximum Sustainable Traffic Rate
MTU	-	Maximum Traffic Unit
PUSC	-	Partial Usage Sub-Channel
QoS	-	Quality of Service

QPSK	-	Quadrature Phase Shift Keying
SCADA	-	Supervisory Control And Data Acquisition
SDU	-	Service Data Unit
TCP	-	Transport Control Protocol
TDD	-	Time Division Duplexing
ToS	-	Type of Service

Chapter 1

Introduction

1.1 Background and Literature Review

The 20th century power grid was designed and implemented to deliver electricity from remote power generation stations to consumer premises in one way direction. Consumers have a very limited role in managing their power consumptions as well as integrating their local renewable energy resources to the grid. The status of the current electrical power transmission and distribution systems is not as efficient as it should be. Power outages and losses are costing utilities and their clients billions of dollars. Increased demands and shortages in power supplies are some of the primary concerns of policy makers and industrial communities. The need for efficient demand response and demand side management programs is becoming a necessity to ensure a sustainable and reliable power delivery system.

It is no longer that the electrical power grid development and management are the sole responsibility of the electrical engineers. With the recent developments in information and communications technologies (ICT), power and energy service providers are teaming up with their ICT counterparts to renovate the aging electrical power grid to enhance the power delivery system as well as securing the grid from cyber-attacks.

The framework for smart grid interoperability standards, release 1.0, was introduced in 2010 by the National Institute of Standards and Technology (NIST) [1]. The framework proposed a smart grid conceptual model that divides the grid into seven domains; namely, bulk generations, transmission, distribution, consumption, service providers, operations and market domains.

One of the greatest advantages of smart grid is the integration of a two-way communication networks between suppliers and their customers. This allows the smart grid to be considered as the power grid that has integrated data communication networks for data collection in near real-time. The real-time communication ability of the smart grid enables utilities to optimize and modernize the aging power grids in order to realize its full potential. Likewise, it empowers the consumers to play a role in the power consumption management.

In addition, this communication networks will provide a number of new services such as real-time metering and pricing, intelligent load shedding, consumption control, cost savings from peak load reduction, energy efficiency and self-healing. Also, it facilitates the integration of plug-in hybrid electric vehicles for energy storage and the integration of alternative and distributed mix generation sources including photovoltaic and wind turbines. Such communication networks integration into the smart grid is implemented using different communication media including wired and wireless technologies [2, 3].

1.2 Thesis Objective

As the smart grid evolves, scalability, reliability, quality of service and cyber security are becoming major issues. This is due to the large number of utilities, consumers and eco-systems participants.

The smart grid conceptual model is divided into three layers; power and energy, communication and information layers. Consecutively, the communication layer is divided into three sub-layers; namely, Consumers Premises Networks (CPN), Distribution Substation Networks (DSN) and Wide Area Networks (WAN).

This thesis proposes the design of a single hop and multiple hops WiMAX network topologies to be used as the smart grid communication media. A simulation model is developed based on the smart grid applications requirements and the WiMAX network parameters. Bandwidth, latency, priority, and some other quality of service parameters are used to categorize the smart grid applications into five different priority classes. These classes are mapped with the differentiated service code points (DSCP), and WiMAX service flows such as real-time, non real-time and best effort. Aggregated data are queued and scheduled using three different scheduling algorithms; namely, class-based weighted fair queuing, class-based deficit weighted round-robin, and class-based strict priority queuing. The expected thesis outcome is to find out which WiMAX network topology and scheduling algorithm should be used to better manage and operate the smart grid applications.

Multi-level network architectures for the smart grid using WiMAX technology are proposed. These communication networks allow the integration of all applicable components in the smart grid. Furthermore, they allow appropriate communication scenarios among various stakeholders to better operate and manage the multiple components that build the smart grid at large. Simulation models are developed and tested to evaluate the network performance based on pre-defined QoS requirements in order to explore the possible solutions for the grid.

1.3 Thesis Organization

This thesis is organized as follows: the rest of Chapter 1 provides an overview of background information on smart grid communication network, WiMAX and the existing work in the literature. Chapter 2 focuses on WiMAX properties including the physical and MAC layer characteristics. Chapter 3 discusses the implementation of the proposed system. WiMAX communication network models and the simulation algorithm are described in detail. Chapter 4 presents analysis and discussion of the simulation results. Chapter 5 concludes the thesis and recommends some future research directions.

1.4 Introduction to Smart Grids

As best described by General Electric, the smart grid is the integration of the 21^{st} century technology and renewable energy resources with the 20^{th} century traditional power grid. The current electric power systems have been serving us for more than five decades. Power generations rely heavily on the fossil fuels, including fuel, coal, nuclear energy and natural gas [4]. As the demand for power is increasing, the call for global attention on finding alternative energy resources and optimizing the current power grids is to sustain long-term economic development. The identified renewable energy resources include wind, small hydro, solar, tidal, geothermal, and waste.

These renewable resources do not release carbon dioxide (CO_2) into the atmosphere during the generation of the electric energy [1, 5]; hence they are called green energy. The renewable energy resources are important complements to the fossil fuels for their exploitation durability and environment friendliness. In fact, recent research studies and deployment projects are underway across the world for efficient harness of the renewable energy resources [1, 6].

Smart grids bring many benefits to utilities and consumers, including the following:

- Reliability: There were many power outages and several massive power blackouts over the past 40 years. For instance, such outages and blackouts cost the US businesses alone at least $150 billion each year [7, 8].

- Efficiency: If the grid were just 5% more efficient, the energy savings would compare to permanently eliminating the fuel and greenhouse gas emissions from 53 million cars [9]. It is estimated that with a better demand response system, tens of billions of dollars will be saved by avoiding the need to build new power plants and transmission lines [8].

- Affordability: The cost of electricity has increased in recent years due to the removal of rate caps. The costs associated with an under performing grid are unaccounted for and remain largely unreported. Energy prices will rise, but the trajectory of future cost increases will be more gradual due to the smart grid as customers will be given more role to manage electricity consumption; thus they will control their own utility bills.

- Security: The Smart Grid will be more resistant to attacks than the traditional grid [10, 11, 12].

- Scalability: utilizing the smart metering, two ways communications, decentralized power generations and local operation and control are allowing small scale community micro-grids to emerge [13, 14, 15].

- Environment/Climate Change: It is a necessity to integrate renewable energy resources such as solar panels and wind turbines into the power grid. Renewable energy can reduce external environmental impacts produced by fossil energy consumption, including climate change, air pollution, industrial accidents, ecosystems damage, construction erosion, noise and visual impact, etc. Reducing air pollution and greenhouse gas emissions is the most important environmental benefits of renewable energy [9].

1.5 Smart Grid Conceptual Model

The smart grid conceptual model is developed by the National Institute of Standards and Technology (NIST) [1]. The model divides the grid into three conceptual layers ;namely, power and energy, communication and information layers [1, 4]. The physical layer consists of the energy and power subsystems such as generation, transmission, distribution and consumption. The information layer is a set of software packages that are responsible for the grid operation and control such as demand response, demand side management, outage management, distribution automation, and overhead transmission line monitoring and energy consumption. The communication layer is the data transfer and exchange networks that link the above mentioned power subsystems with the information layers. Figure 1.1 shows smart grids three layers conceptual model [4, 8, 16].

1.5.1 Energy and Power Subsystems Layer

This layer consists of generation, transmission, distribution, access and distributed energy resources. It is the well-known typical tradition power grid. In the generation domain of smart grid, electricity is generated in bulk quantities from several renewable and non-renewable energy resources. The renewable resources are categorized as variable and

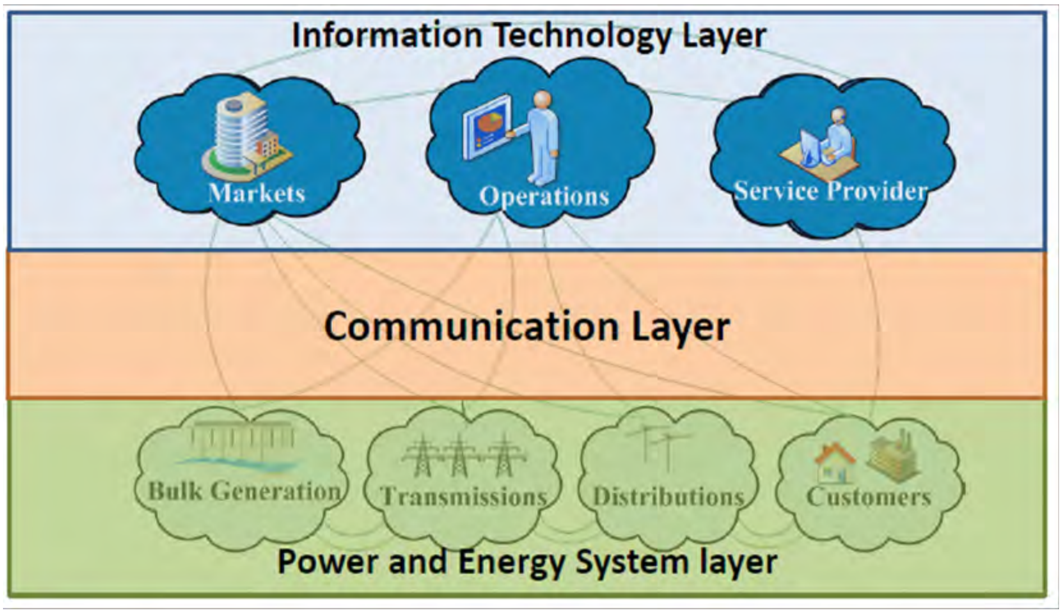

Figure 1.1: Smart Grid Abstract Model

non-variable resources. Renewable variable resources include solar and wind, while renewable non-variable resources include hydro, biomass and pump storage. Another category is the traditional non-renewable non-variable energy resources; i.e., nuclear, coal and gas [1].

The transmission domain connects electrically the generation and distribution premises. The generated high voltage power is transmitted long distances over the transmission lines to the power substations that are spread over a wide geographical area. A regional transmission operator or independent system operator (RTO/ISO) takes the responsibility to manage and maintain the stability of the electric grid by balancing generation (supply of energy) with the consumption across the transmission network. This domain of the smart grid includes remote terminal units, substation meters, protection relays, power quality monitors, phasor measurement units, sag monitors, fault recorders, and substation users interfaces.

The distribution domain in the smart grid hosts the power substations. It is spread across a wide geographical area. The high voltage will be reduced to mid-level voltage (MV) in the substations and to the transformers that are located near the consumers' premises. As the smart grid is evolving, distributed energy resources and storage are becoming integral parts of the distribution domain. A high demand and fast response data and commands exchange in this domain are needed. The domain data and commands are generated by capacitor banks, sectionalizers, reclosures, protection relays, storage devices, and distributed generators [17, 18].

The MV will be reduced down to low-level voltage (LV) by the distribution transforms to supply the customer premises. This domain enables the customers to play an active role in managing their energy consumption, and renewable energy resources and local storage. The access domain has industrial, business, and residential electricity loads [8, 19].

As the smart grid gets more evolved, scalability is becoming an issue. To get around a large scale smart grid, the smart microgrid (SMG) is introduced and emerged as an alternative solution. The SMG is defined as a community grid that supplies a group of loads from local mixed generation sources [5]. It often includes renewable energy sources such as micro wind turbines,photovoltaic (PV) panels and micro-hydraulic turbines [20].

In most cases, the microgrid is an autonomous system that may be disconnected (involuntarily or voluntarily) from the larger grid, and still supports its consumers adequately [20]. An Energy Management System (EMS) for the smart microgrid can communicate with the utility grid or other smart microgrids for maintaining grid stability and to support Automated Demand Response (ADR) and other applications. Figure 1.2 shows the Australian smart microgrid (SMG) model [21].

1.5.2 Information Technology Layer

As the smart grid is evolving from the conceptual model to the implementation phase, in addition to the well-established SCADA, many software applications (services) are enhanced and some are developed to better manage and operate the power grid. Some of these applications are automatic meter reading and billing systems, power quality and outage management, demand-side and demand response managements, distributed generation, substation automation and data storage management [1, 22]. Large amount of data

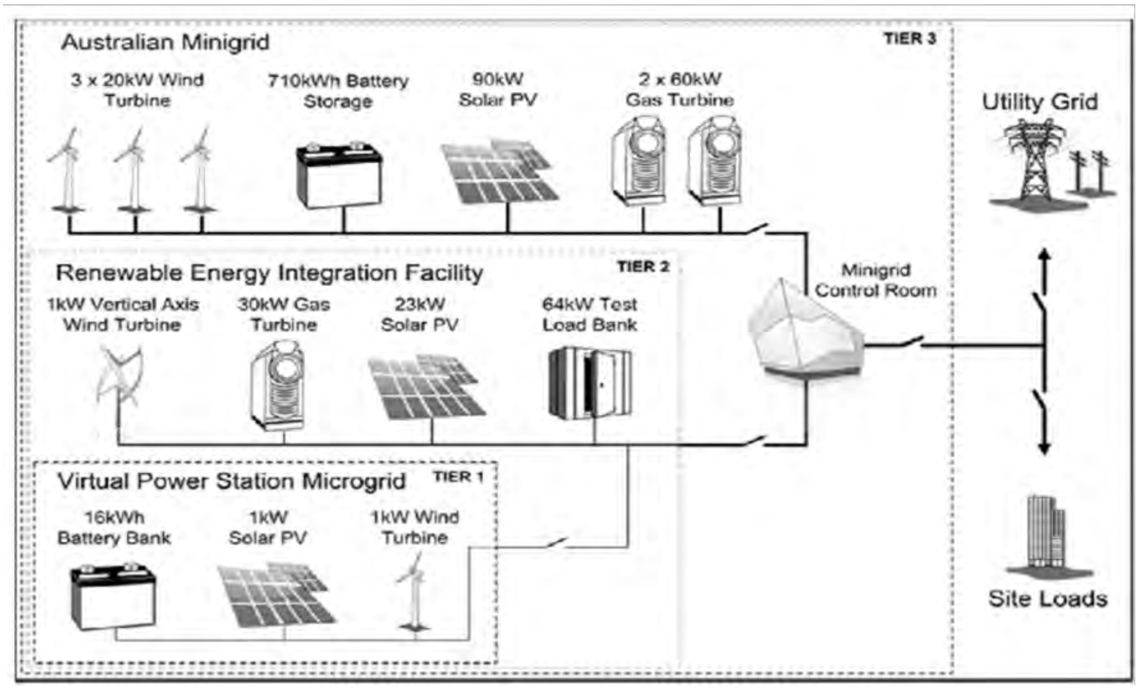

Figure 1.2: Smart Microgrid (SMG) model [33]

are generated and exchanged between these operating software packages to maintain and manage the grid in a better and efficient way.

- Meter Data Management: Smart meters are installed at the consumers premises. These meters report two kinds of readings. Some of these readings report real-time measurements such voltage current and energy consumption and other readings report the power quality measurements such as harmonic, voltage unbalance and voltage sag [8, 23]. While the early smart meter utilizes one-way communication to report the readings, and it is primarily for monthly billing purposes, the smart grid uses smarter meter technology that provides consumers with historical energy consumption data, comparisons of energy use in similar households and online dynamic tariff per KW [24].

  Moreover, it is utilized in outage detection, demand response and demand side management processes [25]. Table 1.1 shows the data transmission format between the smart meter and the Utility. The main feature of the smart meter is the capability of two way communication that enables consumers and utilities to share the power consumption and flow management [25].

Due to the massive number of smart meters (1000s), concentrators are installed locally within the neighborhood and near the distribution transformers and substations. These concentrators are used to collect data from residential, business and industrial meters as well as the meters that report the distribution transformers, substations and transmission lines status. The concentrators form a network and it is defined as the Neighborhood Area Network (NAN) [26]. The bandwidth, intern-arrival interval, inter-arrival units and latency requirements for this network are shown in Table 1.1 [27]. The aggregated data bandwidth requirement is around 500 kbps.

- Wide Area Situational Awareness (WASA): The WASA system collects a large amount of information about the grid current state over a wide area from electric substations and power transmission lines. Collected data are used in Wide Area Monitoring Systems (WAMS), Wide Area Control Systems (WACS) and Wide Area Protection Systems (WAPS). Such implementation has a significant impact on the communication network due to the large data exchange as well as latency responses.

Message/Traffic Description	Size (Bytes)	Inter-arrival Interval	Inter-arrival units	Delay	Direction
Interval data read	480	1	Day	Best Effort	Up
Tamper notification	64	26	Weeks	5 seconds	Up
Meter remote disconnect / reconnect request	20	1	Day	2 seconds	Down
Meter remote disconnect/ reconnect response	500	1	Day	2 seconds	Up
In-home display, load control	60	6	Hours	5 seconds	Down
In-home display, Critical Peak Pricing alert	60	12	Hours	5 seconds	Down
Meter ping (on demand read)	64	4	Weeks	2 seconds	Both ways
Meter firmware patch/upgrade	50,000	1	Year	Best Effort	Down
Firmware patch/upgrade confirmation	20	1	Year	Best Effort	Up
Meter clock synchronization	64	1	Day	2 seconds	Both ways
Meter remote diagnostic	500	1	Day	2 seconds	Both ways

Table 1.1: Smart meter traffic analysis [27]

- Demand Response and Demand Side Management: Demand Response (DR) is an application designed to enable two way communication between the electricity consumers and the utility. It allows electricity consumers to contribute in balancing the supply and demand curve by voluntarily reducing their electric power consumption in response to high real-time electricity prices or incentive price signals [4, 25]. Examples of DR programs are incentive-based programs such as direct load control, time-of-use: real time pricing and critical Peak pricing [4, 8, 25]. Similarly, utilities are developing Demand Side Management (DSM) that are planned to decrease the consumption of the electricity loads by encouraging high-efficiency equipment and green building design [28]. Example of DSM programs is replacing incandescent light bulbs with compact LED and fluorescent bulbs, the use of automatic thermostats and installing new variable speed chillers that deliver cooling to buildings using less energy than typical chillers. Data packets to utilize the DR and DSM systems have different network parameters such as priority, delay, throughput and reliability [28].

- Outage Management: In the traditional power grid, outages are detected at the high voltage side of the distributed transformers. Currently, utilities turn blind eyes to outages at the individual consumer premises or even at a low level feeder at distributed transformers. These problems necessitate the establishment of an efficient Outage Management System (OMS) at the low level distribution. One of the main advantages of the smart grid implementation is the outage detection at the consumer level where it is reported by the smart meters.

  OMS is one of the best methodologies to reduce the recovering time caused from outage by minimizing the outage time. The OMS has many useful functions such as analysis, restoration, notification, and report of outages [29].

- Distribution Automation (DA): Distribution Automation is a set of software packages that are used to monitor and control the distribution power network devices such as circuit breakers; line switches, re-closers, voltage regulators, capacitor banks, IEDs, fault indicators, load tap changers, and transformers [30]. To date, power utilities have been accustomed to manage a limited number of monitoring and control points and segments. DA promises to benefit the utility and customers alike by reducing operation and maintenance costs, improving reliability and power quality, enabling new customers services and providing better information for utility engineers and planners. A DA implementation could be as simple as upgrading a manual switching scheme with remote control to the deployment of sophisticated systems with integrated IEDs. Some examples of DA applications are [31]:

  - Fault Detection, Isolation and Restoration (FDIR)
  - Feeder Reconfiguration
  - Distribution State Estimation (DSE)
  - Voltage/Var Optimization (VVO)
  - Distributed Generation (DG) Management
  - Microgrid Management
  - Protection Coordination
  - Load Forecast and Modeling

- Substation Automation (SA): In order to operate the grid, utilities install Supervisory Control and Data Acquisition (SCADA) system at commands centers and substations. Voltage and current measurements at critical grid nodes are transmitted every two to four seconds [30]. All Intelligent Electronic Devices (IEDs), which are located inside the substation, create an integrated, embedded digital network known as a Substation Automation System (SAS). The SAS deploys substation operation functions such as data acquisition, data processing, tagging, alarms, logging, trending and historical reporting [32].

  SCADA systems require minimal latency. Latency must be low to optimize polling performance and prevent communications from timing out. The SCADA latency level of 10-100 milliseconds is required for command and control applications. The bandwidth requirements for SCADA-like operations may grow with smart grid deployments; traditional SCADA systems are not bandwidth-intensive. As for the reliability requirements, the SCADA requires a very high reliability.

- Distributed Energy Resources and Storage: Renewable Distributed Energy Resources (DERs) will play an important role in future power systems. DERs can be installed close to the load. This reduces the power losses on transmission lines and substitute for power shortage at the peak. Other benefits from having renewable resources utilization are lower carbon imprint and reduced global warming emissions [9, 33].

  Traditional power grid software; such as SCADA, does not include the integration of the DERs. One of the smart grid features is the integration of the DERs to the current grid. Such integration requires major makeover to the SCADA system and other software packages. Also, this will have a major impact on the communication networks.

- Asset Management: Utility companies use asset management programs to prolong the equipment lifetime and minimize the risk of failure, as well as the cost of the unplanned outages. These programs require feedback from the operation centers and other ecosystems which will add more data traffic. Asset management programs for smart grid adopt a variety of advanced automation, computation, communication, information and modern management concepts and techniques. It includes risk costs, construction costs, planning costs and other aspects of power system as well as the environmental benefit [34].

  The smart grid applications and their requirements will be used in a later section as a base to develop the simulation models for the proposed WiMAX Communication Networks.

1.5.3 Communication Infrastructure Layer

The smart grid communication layer is evolving in a way that enables the grid to expand to a wider geographical area as well as enabling the grid shareholder to communicate in two directions to better manage the power system. The recent proposed simplified IEEE 2030 End-to-End smart grid communications model consists of three major network communications [4]. These networks are Consumers Premises Networks (CPN), Distribution Substation Networks (DSN) and Wide Area Networks (WAN) [1, 4, 22, 28, 35].

The End-to-End smart grid communication architecture based on the IEEE 2030 standard is shown in Figure 1.3 with some editorial details for clarification proposes [4].All of these networks have different technology and functions and they can be classified as follows:

- Consumers Domain Networks (CDNs): The CDN major functions are the transfer and exchange energy meter readings, power measurements parameters, demand side commands, smart appliances status to the home gateway. The CDN has three subnetworks: Home Area Network (HAN), Business/Building Area Network (BAN) and Industrial Area Network (IAN). As shown in Figure 1.4, the major wireless network protocols in this layer are Zigbee, Bluetooth, RFID, Home plug, WiFi and Zwave[4, 26, 36, 37, 38].

  In the Home Area Network (HAN), smart home appliances can communicate with one another and response to the utility price signal. This is done by adding intelligence into the home appliances and connecting them through a local area network. For example, a user may activate Direct Load Control (DLC) functions that empower the utility company to turn OFF or ON certain home appliances remotely (e.g. A/C, washer/dryer), when demand and/or the cost of electricity is high.

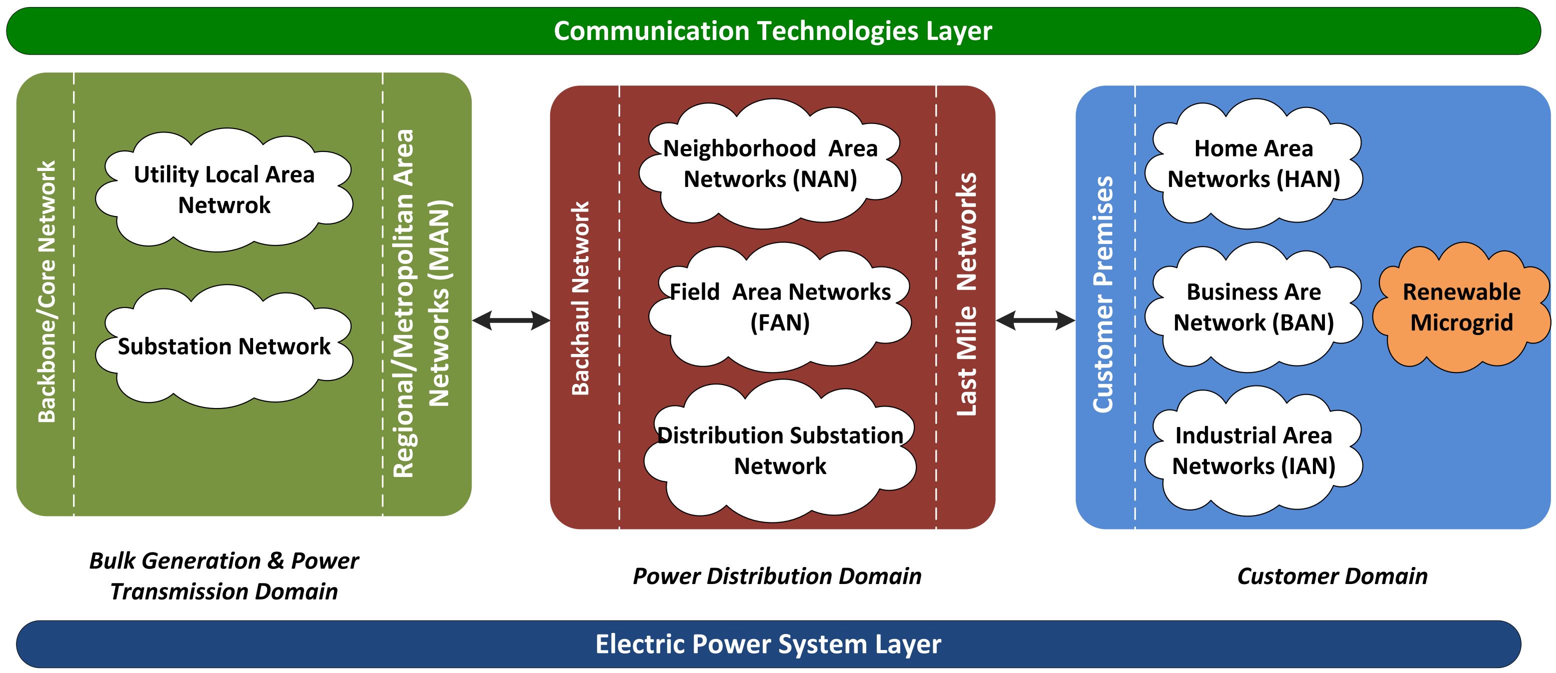

Figure 1.3: End-to-End Smart Grid communications model [4]

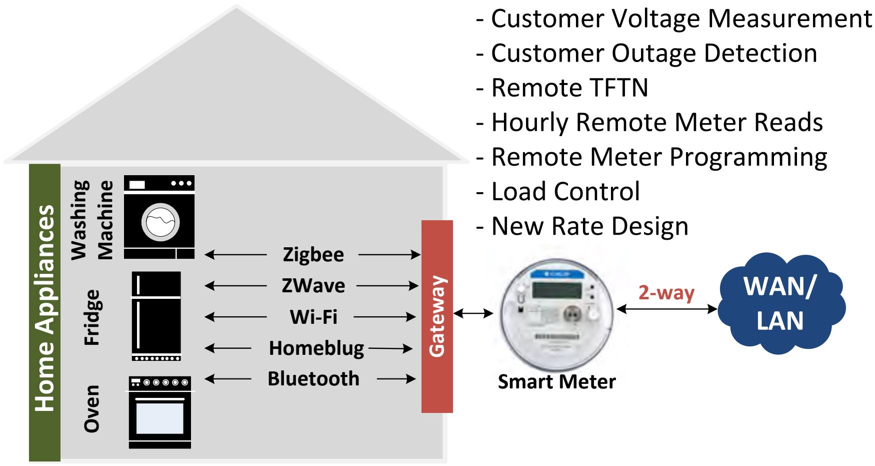

Figure 1.4: CPN major communication protocols

The Business/Building Area Network (BAN) and Industrial Area Network (IAN) transport data between devices in commercial and industrial premises. These networks interconnect meters, DER, PEV charging stations, BEMS (Building Energy Management System), and others. BEMS monitors and controls all conventional BAS (Building Automation System) of electric power and HVAC (Heating, Ventilating, and Air Conditioning) as well as FMS (Facility Management System). Business network guarantees secure and efficient data transport functions that enable the interactions between relevant systems and BEMS, and the interactions between BEMS and utility network. Table 1.2 shows the data transfer rate, ranges, advantages and disadvantages of the CPNs.

- Distribution Domain Networks (DDNs): The DDNs are four different networks: Neighborhood Area Network (NAN), Field Area Networks (FAN), Last Mile Networks (LMNs), and Backhaul Networks (BHN) [37, 39, 40, 41]. Figure 1.3 shows the End-to-End Smart Grid communications model [4]. The functions of these networks are to transfer, exchange data and commands between various smart grid applications such advanced home energy management accommodation of electric vehicles switches, recloses, phase measurements, automated fault detection, workforce and distributed renewable energy recourses [33].

Technology	Data Transfer Rate	Range	Advantages	Disadvantages
Zigbee (802.15.4)	250 Kbps	100+ meters	Suitable for Mesh topology Low power consumption	Lesser data rates Short range coverage
Bluetooth	721 Kbps	1 -100 meters	Low power consumption Faster data and voice Sharing	Spectrum Conflict
Wi-Fi (802.11)	22 128 Mbps	up to mile	Low device cost Suitable to Mesh topology Low latency Good for consumer applications	Medium range Does not penetrate cement buildings No provisions for meeting utility objectives
Z-wave	40-250 kbps	30 meters	Simple and modular low cost features	Need a Network Controller Proprietary

Table 1.2: Wireless Technologies in CPNs [42]

The Neighborhood Area Network (NAN) is the communication network that manages the communications between the utilities and the smart meters that are installed at the customer premises. NANs are flexible packet switched networks whose geographical coverage area could be anywhere from the coverage of a Local Area Network (LAN) to Metropolitan Area Networks (MAN) to Wide Area Networks (WAN). In the smart grid, NAN has a role to play in the HOME-to-HOME or HOME-to-GRID communications. The NAN is a network composed of multiple NAN subnetworks, each defined by a NAN collector. The links between NAN nodes are then defined by the smart meter and home locations, with repeaters and, as necessary, additional NAN Collectors introduced based on the coverage requirements imposed by those locations [4, 43].

The Field Area Network (FAN) connects critical utility assets and transport operations control data. It connects the distribution substations, the distributed/ feeder (field devices), and DERs/microgrids, including the utility scale electric storage, to the utility control and operation center[6].

Last Mile Network (LMN) is a two-way wireless or wire line communication network that lies on the top of the power distribution system. It is usually named as Advanced Metering Infrastructure (AMI) depending on the utility network system features, services offered, network topology and demographics and the vendor technology utilized [26, 36, 38]. In one end, the LMN interfaces with the smart meters - at the customer premise edges, the field IED devices and sometimes the distribution substation hot-spots. In another end, the network Access Point (AP) interfaces with the backhaul network, where the data is collected, aggregated in order to be transported to/from the backhaul to the WAN. The last mile may also provide communications to the Distributed Energy Resources (DERs) - renewable and non-renewable energy sources - connected to the distribution grid [1, 9].

The Backhaul Networks (BHN) connects the WAN to the last mile network. The backhaul can be owned by the utilities or provided by third party service providers.

It aggregates and transports customers smart grid telemetry data, substation automation critical parameters data, distribution plant intelligent devices data field information, mobile workforce information to/from the utility head end to/from the last mile network. It is worth mentioning that, in certain network architectures, a backhaul network may exist with no WAN. Network connections consisting of point-to-point or multi-point data circuits are examples of such cases. The communication technologies that are utilized in this network are wired and wireless networks. Examples of such networks are LTE/ LTE Public, WiMAX, Microwave, Fiber, BPLC and FTTP/FTTH/Ethernet [42].

- Generation and Transmission Domain Networks (GTDNs): The GTDNs consists of four different networks namely; Substation LAN (SLAN), Control Center LAN (CCLAN) and Regional Networks (RNs). These networks transfer and exchange data and commands between the Distribution Domain Networks (DDNs), the zone substations Remote Terminal Units (RTUs), fault detections, wide area situational awareness system data (WASA), corporate data, transmissions and distribution automation, distribution management, on video conferencing, mobile voice and data, market and outsource service provides [4, 36, 42].

  The Substation Local Area Network (LAN) provides a platform for all connected IED relays; Remote Terminal Units (RTUs), station gateways and Local Control Computer (LCC) to exchange messages over the LAN. The main benefits of the substation LAN are: providing high-speed peer-to-peer communications between IEDs, reducing inter-IED wiring, allowing the coexistence of multiple protocols (e.g. DNP, Modbus, IEC61850) [19, 36] on the same physical network and enabling Data over IP for easy access to substation data.

  The smart gird Control Center LAN (CCLAN) surpasses the traditional outage management systems by delivering outage analysis, integrated workforce management, advanced visualization, and real-time monitoring, control, and analysis to put the customer in command of the smart grid operations center. This is achieved through a set of sophisticated servers installed at the Control Center (CC). In the CC, SCADA servers, database, and application servers are linked with Local Area Networks (LAN). Moreover; backup servers are used to improve the reliability and dependability. The CC in one region also connects with the control centers in other regions through Wide Area Networks (WAN) [44].

1.6 Smart Grid Communication Requirements

The smart grid can be divided into applications that are based on the generation, transmission, distribution and consumption domains. Each application has many parameters and requirements that have to be satisfied in order to better manage operate the grid. These parameters depend on the application nature. The IEEE P2030 introduces a framework of features that classifies the applications according to certain ranges and qualitative measures. These features depend on area of coverage latency, data type, reliability and security which in parts help to determine the best communication network technology [4]. Table 1.3 presents the smart grid data characteristics and classification.

As shown in Table 1.3, coverage area is divided into four ranges. The distance or range depends on the power transmission length, substation locations and consumption premises distance. The second data characteristic is the latency which can be defined as the delay of the data transmitted between the smart grid devices and the operation center. It is mainly decided by the transfer rate and the number of switches or hops the data exchanges between the smart grid devices.

The strictest requirement for latency comes from the mission- critical control applications where the data may have to be transferred to the control center and an automatic command is issued within a specific time [36].

An example of such applications is the substation automation which requires 15 to 200 milliseconds latency. Some other applications, such as advanced metering infrastructure (AMI) latency is not critical.

Data Characteristics		Classification/Value Range			
Area of Coverage		< 10 m	< 100 m	< 1 km	> 1 km
Latency		Real Time		Non-real Time	
Synchronicity		Yes		No	
Data Type	Burst Size	Bytes	Kilobytes	Megabytes	Gigabytes
	Occurrence Interval	Milliseconds	Seconds	Minutes	Hours
	Broadcast Method	Unicast	Multicast	Broadcast	All
	Priority	None	Low	Medium	High
Information Reliability	Quality	Informative	Important		Critical
	Availability	Low	Medium		High
	Impact	Limited	Serious	Severe	Catastrophic
Security	Confidentiality	None	Low	Medium	High
	Integrity	None	Low	Medium	High
	Availability	None	Low	Medium	High

Table 1.3: Data classification Table for the IEEE P2030 reference model [4]

The IEEE P2030 reference model categorizes the smart grid applications latency into real time and non-real time categories. Real time category requires 4-20 from few milliseconds response time while Non-real time category that requires a medium ($<$ sec) to high ($>$ sec)response time.

The model divided the smart gird applications into two synchronization groups. Some applications requires to be synchronized with others within the entire network and some do not require any synchronization. The generation data is characterized based on the data burst size, the occurrence interval, the broadcast mode and the priority. The next characteristic of the smart grid applications compiles qualitative measures that are defined by quality of information, availability and impact on the smart grid operations.

Last but not least, data security is measured by its confidentiality, integrity and availability, all of which classifies itself into none, low, medium and high. Table 1.4 shows the smart grid applications reliability, bandwidth, latency and security requirements [36].

Smart Grid Application	Reliability	Bandwidth	Latency	Security
Substation Automation	99.0-99.99%	9.6 -56 kbps	15-200 ms	High
Wide Area Situational Awareness Systems (WASA)	99.0-99.99%	600 - 1500 kbps	15-200 ms	High
Outage Management	99.0-99.99%	56 kbps	2000 ms	High
Distribution Automation	99.0-99.99%	9.6 -100 kbps	100 ms -2 sec	High
Distributed Energy Resources and Storage	99.0-99.99%	9.6 -56 kbps	100 ms -2 sec	High
Smart Meter Reading	99.0-99.99%	10-100 kbps/meter 500 kbps/concentrator	2000 ms	High
Demand Response & Demand Side Management	99.0%	14 - 100 kbps	500 ms-min	High
Assets Management	99.0-99.99%	56 kbps	2000 ms	High

Table 1.4: Smart Grid applications QoS requirements [36]

The IEEE P2030 introduced also a mapping between the smart grid communication layer and the different network protocols standards. A mixture of wired and wireless standards has been defined to connect the smart grid devices in different domains. Figure 1.5 illustrates the future vision of the smart grid using wireless communications proposed by the IEEE P2030 working group [2]. In their proposed communications vision, the utility commands and dispatch center, markets, operations, service providers and the generation domain are connected by a fiber optic backbone. The backbone network includes a local area network (LAN) which connects the smart grid applications servers, firewalls and wireless management services.

The transmission domain is connected by fiber optic networks, private point-to-multipoint (PMP) cellular data networks. These connectivity alternatives intend to create communication channels between the core network and the smart grid devices such as feeders, capacitor banks, regulators, substations and access points operated in the transmission and distribution domains. The vision of the IEEE P2030 standard also described a mesh networking solution for the distribution domain, i.e. automatic metering infrastructure (AMI). Finally, the home area network (HAN) is proposed to connect home appliances using the ZigBee technology [2].

The capabilities of the IEEE 802.16 WiMAX standard may allow the implementation of different communication scenarios for the smart grid. WiMAX standard can serve as a backhaul or a Point to Multipoint access network. In addition, WiMAX can provide full end-to-end QoS that makes it a good alternative for smart grid communication networks. So far, few researches have been carried out to investigate the performance of WiMAX networks for end-to-end smart grid applications which is the main objective of this thesis.

Some developments were reported in recent years that showed how homeowners can communicate with their home smart meters and gateways controllers. Most home area networks (HAN) have utilized wireless network protocols such as ZigBee, RFID, Bluetooth, Zwave, Home-plug and WiFi [37, 45, 46, 47].

For example, ZigBee was used in the design and implementation of smart home energy management systems [48, 49] . ZigBee technologies that are used in the renewable

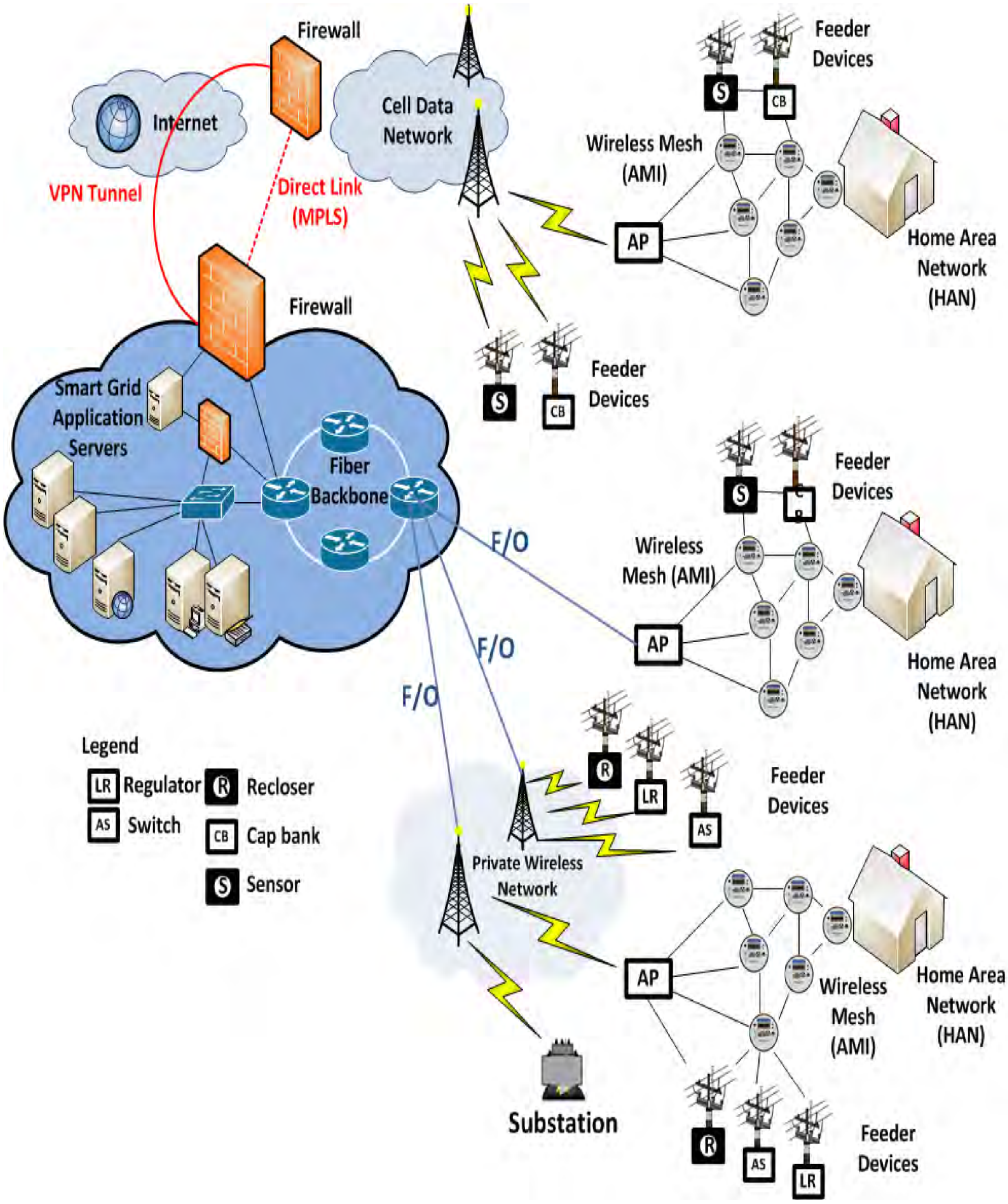

Figure 1.5: The IEEE P2030 Smart Grid future wireless communications network Architecture [2]

energy integration were reported in [50]. Detailed applications reported the use of RFID in photovoltaic and wind energy system monitoring was highlighted in [51, 52].

As described in the above mentioned sections, the distribution domain networks are the smart grid networks that have longer range compared with the short range home area networks. Several wired and wireless network technologies and communication protocols are used such as Power Liner carriers (PLC), GSM/GPRS, DASH7, Satellites, WiMAX and Long Term Evolution (LTE) [3, 22, 46, 47, 53].

Table 1.5 shows that WiMAX utilization in smart grid is still marked as On-going Research and some solutions are still under testing [37]. Therefore, this thesis proposes new WiMAX design models. The models are a single hop and multiple hops networks topologies that take into consideration the smart grid applications latency , reliability and priority requirements as well as the network quality of service .

Some of the ongoing WiMAX researches in the smart grid have reported some good simulation results. A simulation model for smart meter readings was conducted based on WiMAX network architecture [54]. The readings are non-real-time with time latency of 1-5 secs. The authors used one of the WiMAX service flows parameters namely; non-real-time Polling Service (nrtPS), and 2KM-5KM radius cells [54]. Results have showed that polling services are able to support and fulfill the needs of metering application. Even though this study is considered a milestone one and the pioneer, it is built based on one smart grid application and one service flow.

A recent WiMAX smart grid last mile Communication model (SGLM) was discussed in [40]. The model divided the last mile smart grid applications to three different priority classes namely; mission critical, real time and non-real time. It divided the applications into four latency classes very LOW (3 ms), followed by LOW (16 ms), MEDIUM (160 ms) and an unbounded HIGH latency class (greater than 160 ms) [36]. Using a discrete-event simulation, it was found that the lack of persistence of real-time flows was at very low bit rates. However, the authors concluded that the WiMAX Network is rich communication media for smart grid last mile traffic, but they will require engineering efforts.

Another WiMAX Network simulation model was developed for the smart grid wide area monitoring and control (WAMC) application [55]. The proposed model utilized the real-time Polling Service (rtPS), Unsolicited Grant Service (UGS) and Best Effort (BE) scheduling algorithms to analyze the grid preference using the Phasor Measurement Units (PMUs) readings. It was found that the BE is the worst and rtPS is the best.

Communication Technology	Generation		Transmission			Distribution			Consumer			
	Conventional Generation	Distributed Renewable Energy based generation	Transmission Line Monitoring and Protection	Insulator Monitoring	ACTS Monitoring and Control	Substation Automation and Protection	Distribution Line Monitoring and Protection	Equipment Monitoring and Protection	Home Automation and Control	Industrial Automation and Control	Automatic Metering Reading	PEVS
Power Line Communications (PLC)	∞	∞	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\triangle$
Zigbee	$\triangle$	$\triangle$	∞	∞	∞	$\triangle$	$\triangle$	$\triangle$	$\surd$	$\surd$	$\surd$	$\triangle$
Wi-Fi	$\triangle$	∞	$\triangle$	∞	$\triangle$	$\surd$	∞	$\surd$	$\surd$	$\surd$	$\surd$	$\triangle$
WiMAX	$\triangle$	$\triangle$	$\triangle$	∞	∞	$\triangle$	∞	∞	∞	∞	$\triangle$	∞
GSM and GPRS	$\surd$	$\surd$	$\triangle$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
DASH	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$	$\triangle$

Table 1.5: Smart Grid communication Evolution [36]

$\surd$ = in use, some mature solutions available

∞= Not currently in use, solutions can be developed

$\triangle$= On-going Research, some solution available but under testing

Chapter 2

WiMAX Network Models for Smart Grid Communication

This chapter presents the main features of the Worldwide Interoperability for Microwave Access (WiMAX) IEEE 802.16 standard and its application in the design of smart grid communication architecture [38, 55]. The WiMAX standard is defined for a Wireless Broadband Network (WBN) for abstracted data exchange such as emails, internet browsing, file transfer protocols. As the smart grid is rolling out, few attempts were made to utilize it in the smart grid communications [54]. As mentioned in Chapter 1, smart grid applications does not include abstract data only but it carries operational data that has command and control actions. Command and control data requires near real-time actions such as monitoring substations and turning ON/OFF re-closures, adding and removing capacitors banks, reading intelligent electronic devices (IED)and activating relays within 4-10 msec.

WiMAX supports a long distance i.e. coverage radius of a WiMAX cell may go up to 50 km [56]. Moreover, WiMAX standard is designed to operate in NLOS (Non Line of Sight) mode at operating frequencies equal to 11GHz or below and LOS (Line of Sight) mode at operating frequencies between 10 - 66GHz [57]. In addition, WiMAX data rates may go up to 70Mbps depending on the radio channel condition and the type of Adaptive Modulation and Coding (AMC) used [56].

WiMAX supports Quality of Service (QoS) using service flows that makes it suitable for the smart grid applications. Service flows such as the unsolicited grant service, real time polling service, extended real time polling service, non-real time polling service and best effort are excellent features that make WiMAX a healthy network media to serve in the smart grid. As mentioned in the introduction, some of the smart grid applications requires real-time response, others may require non-real-time or best effort. Such features were not explored or fully utilized in the smart grid communications.

2.1 Smart Grid WiMAX network topologies

In order to explore the WiMAX aforementioned mentioned features, two WiMAX network designs are proposed namely; the Single Hop and the Multiple Hops. The selection of Single Hop versus Multiple Hops topology is based on the geographical distribution of the smart grid endpoints as well as the smart grid applications Quality of Service (QoS) requirements.

2.1.1 Single Hop Topology

In this topology, each application has a dedicated bidirectional connection to the command and dispatch center i.e. it is a point to multipoints topology. This topology is useful for suburban and rural areas where the average number of smart meters is about 800/km^2 and 10/km^2 respectively [58]. Also, there is no need for that number of distributed transformers. It is expected that this design will serve more consumers per WiMAX cell because the aggregation and the service of data as well as the commands take place at a single point, i.e. the command and dispatch center. Figure 2.1 shows the proposed Single Hop topology network.

2.1.2 Multiple Hops Topology

In this topology, the smart grid data and commands are transmitted from multiple applications to the control center using multiple WiMAX hops. Each hop has the capability of data aggregation and scheduling. Having multiple hops may expand the area of coverage over a wider geographical area compared to the single hop topology [59]. It may also reduce the number of dedicated communication links from the smart grid devices to the command and dispatch center optimizing the communications bandwidth. Figure 2.2 shows the proposed multiple hops network topology. Data traffic from the distribution automation, distributed energy resources, demand response management, demand side management and outage management applications is aggregated and forwarded to the utility

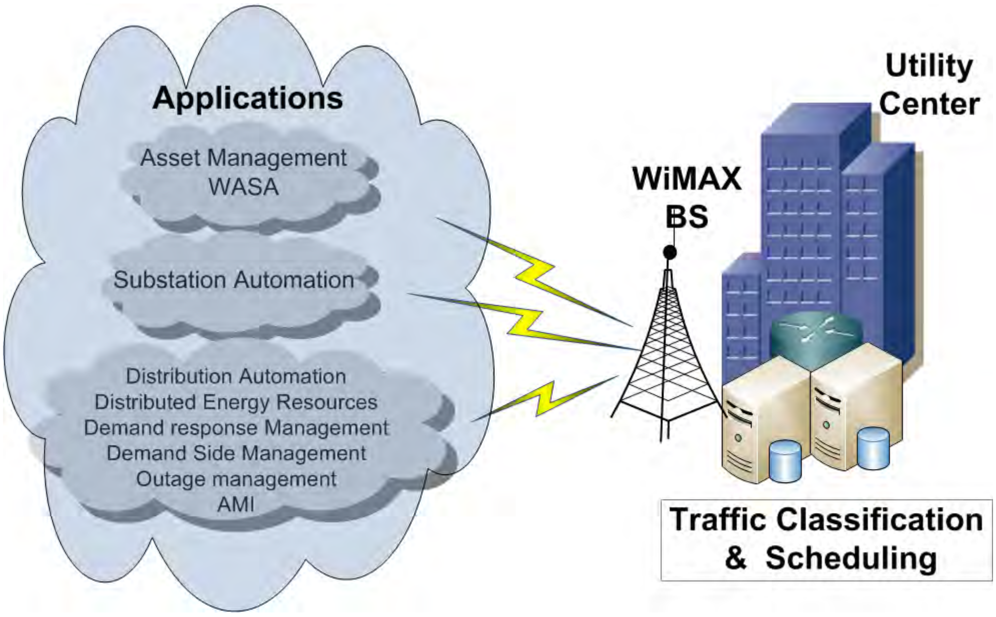

Figure 2.1: Single Hop Topology

command center through multiple network hops. Data traffic from substation automation, asset management and wide area situational awareness applications is transmitted directly to the command and dispatch center ; i.e. one base station is used. It is believed that this topology may be suitable for dense urban areas that have a large number of smart meters, i.e. 2000 /km^2 [58].

Although it is expected that more services can be handled, signaling overhead and accumulated latency between multiple hops may not satisfy the latency requirements of some of the smart grid applications, and this will be decided in the simulation.

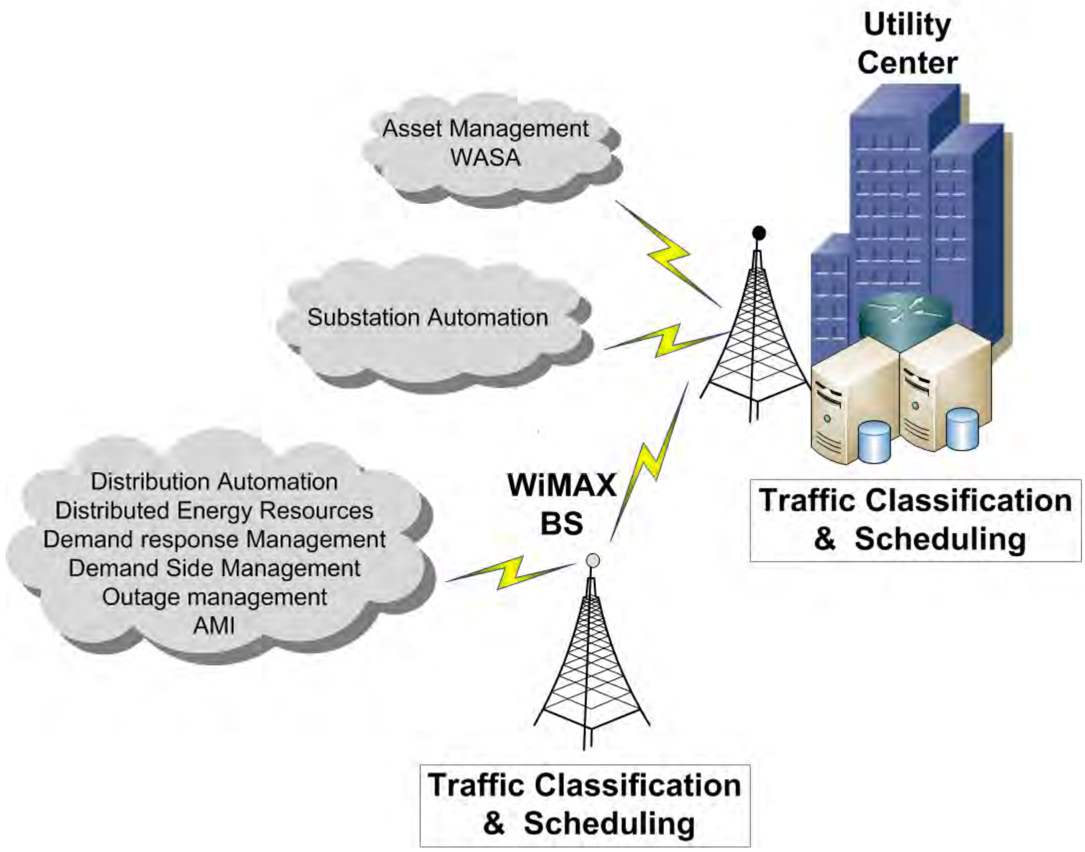

Figure 2.2: Multiple Hops Topology

2.2 WiMAX Physical Layer Parameters

Regardless the network topologies, the WiMAX physical layer controls some of the network performance parameters such as the cell capacity and size, the entry procedures, power management and resource allocation. This section presents the WiMAX physical layer within the smart grid applications context.

2.2.1 Network Entry Procedures

Ranging is a process that allows a base station to receive the transmitted signal from the WiMAX cell devices such as smart meters in a specific time slot, even if the devices are positioned at different distances from the base station. This process prevents the overlapping between the multiple devices transmitted bursts. Ranging is done dynamically by calculating the timing offset and by correcting the initial device transmitting parameters. Figure 2.3 shows the ranging and parameter-adjustment state diagram [60].

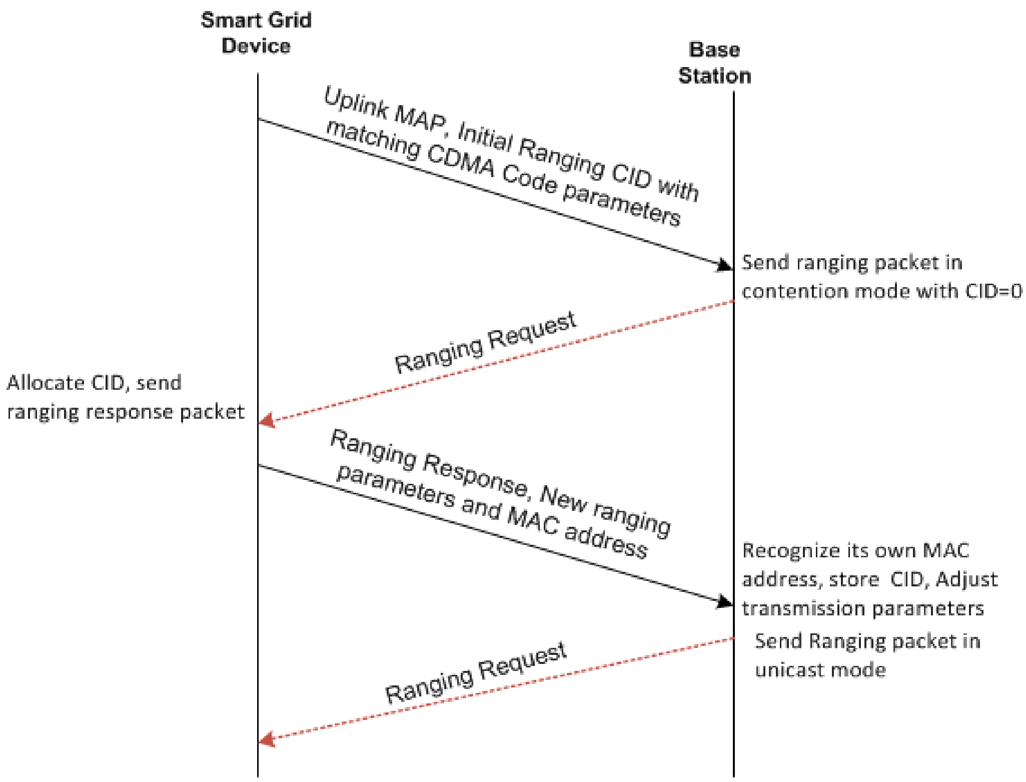

Figure 2.3: Ranging and parameter-adjustment procedure [60]

2.2.2 WiMAX OFDMA Frame Structure and Parameters

The WiMAX physical layer could be used either in a single carrier mode (SC) or in a multicarrier mode that uses the Orthogonal Frequency Division Multiple Access (OFDM) channels. In the OFDMA, the large frequency band is divided into many separate subcarriers (up to 2048). These subcarriers are grouped into a number of sub-channels which is allocated for a certain amount of time per user [57, 61]. The time frame is divided into an integer number of symbols. The number of symbols per frame depends on the underlying implementation of the PHY layer. A block of sub-channel/symbols could be assigned to each device. Figure 2.4 shows an example of the multiple access capability of the OFDMA [57, 62].

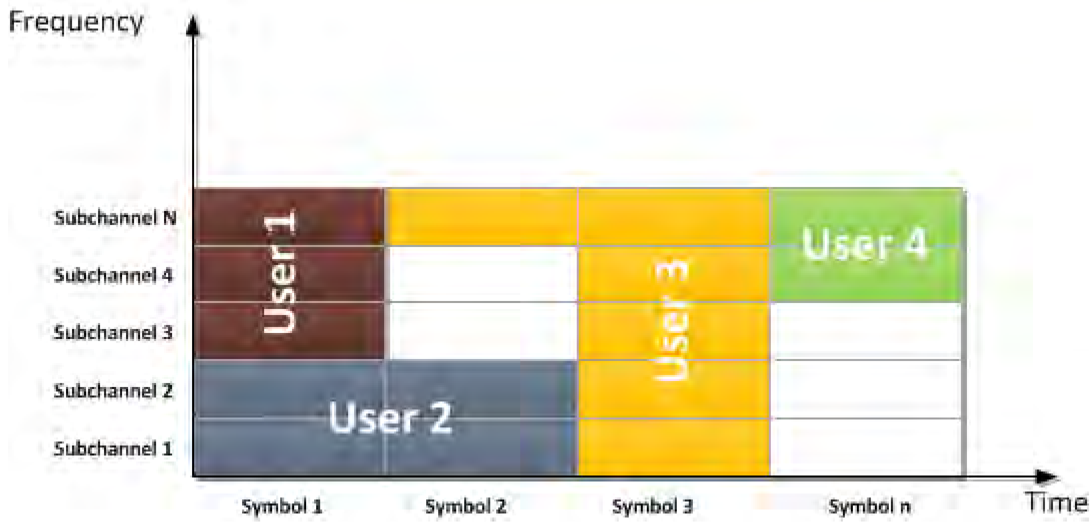

Figure 2.4: Multiple access capability of the OFDMA based on [62]

The total length of the symbol is determined by the carrier frequency. The symbols are divided into a useful time T_{symb} and a guard time T_{guard}. The guard time is defined as 12.5 % of the useful time [63]. The total bandwidth, B_{T}, is derived from the channel bandwidth, B_{ch}, and the sampling factor , f_{s}, using the following equation [62, 56]:

$$B_{\text{T}} = B_{\text{ch}} \times f_{\text{s}} \tag{2.1}$$

for B_{ch} = 20 MHz and f_{s} = 8/7, the total bandwidth B_{T} = 22.857 MHz. The total bandwidth B_{ch}, and the number of subcarriers ,N_{sc}, is used to calculate the subcarrier spacing Δf, as follows:

$$\Delta f = \frac{B_{\text{ch}}}{N_{\text{sc}}} \tag{2.2}$$

for N_{sc} = 2048, the subcarrier spacing Δf = 11.16 kHz. The useful symbol time T_{symb} is calculated using the following equation:

$$T_{\text{symb}} = \frac{1}{\Delta f} \tag{2.3}$$

for $\Delta f = 11.16$ kHz, $T_{\text{symb}} = 89.60$ μs. The T_{symb} is used to derive the guard time

,T_{guard}, as follows:

$$T_{\text{guard}} = T_{\text{symb}} \times 12.5\% \tag{2.4}$$

for $\text{T}_{\text{symb}} = 89.60 \quad \mu\text{s}$, $\text{T}_{\text{guard}} = 11.2 \quad \mu\text{s}$. The total number of symbols ,N_{symb}, is calculated using the equation below:

$$N_{\text{symb}} = T_{\text{guard}} + T_{\text{symb}} \tag{2.5}$$

for $\text{T}_{\text{symb}} = 89.60\mu\text{s}$ and $\text{T}_{\text{guard}} = 11.2\mu\text{s}$, the N_{symb} = 100.8 μs. The total number of symbols N_{symb} is derived from the frame length, L_{f} , and from T_{symb} using the following equation :

$$N_{\text{symb}} = \frac{L_{\text{f}}}{T_{\text{symb}}} \tag{2.6}$$

for L_{f} = 5 ms , $\text{N}_{\text{symb}} = 49$ symbols.

In smart grid applications environment, the utility commands and dispatch center frequently sends requests to read data from the smart grid devices. However, the data throughput direction is generally biased towards the uplink direction, i.e. from the smart grid devices to the base station. This is because many smart grid devices such as the IEDs respond to requests from the utility center or report to an event occurrence. Also, other devices such as smart meters report periodic meter readings to the utility center. In order to achieve maximum data rate, the downlink (DL) to uplink (UL) ratio may be adjusted to increase the UL data rate in order to accommodate the uploaded data from the smart grid devices [62, 64].

Therefore, the OFDMA frame is configured using the time division duplexing (TDD) scheme utilizing that the TDD scheme better serves the smart grid asymmetric traffic environment [65]. The first part of the frame which is for the downlink communication, called the DL sub-frame and the second part which is for the uplink communication, called the UL sub-frame [56]. The number of symbols in each sub-frame could be varied or fixed and can be determined in the mapping and allocation processes based on capacity of the channel at a certain instant. A fixed resource allocation algorithm is used where UL/DL ratio = 1: 1 to achieve the maximum possible uplink rate.

The TDD-OFDMA frame structure is presented in Figure 2.5. The frame size has a length of 5 milliseconds as the value defined by the IEEE 802.16e standard [56]. The transmit-transmit gap (TTG) and the receive-transmit gap (RTG) require around 1.6 symbols leaving 44 OFDMA data symbols. These remaining symbols are used for uplink and downlink communications.

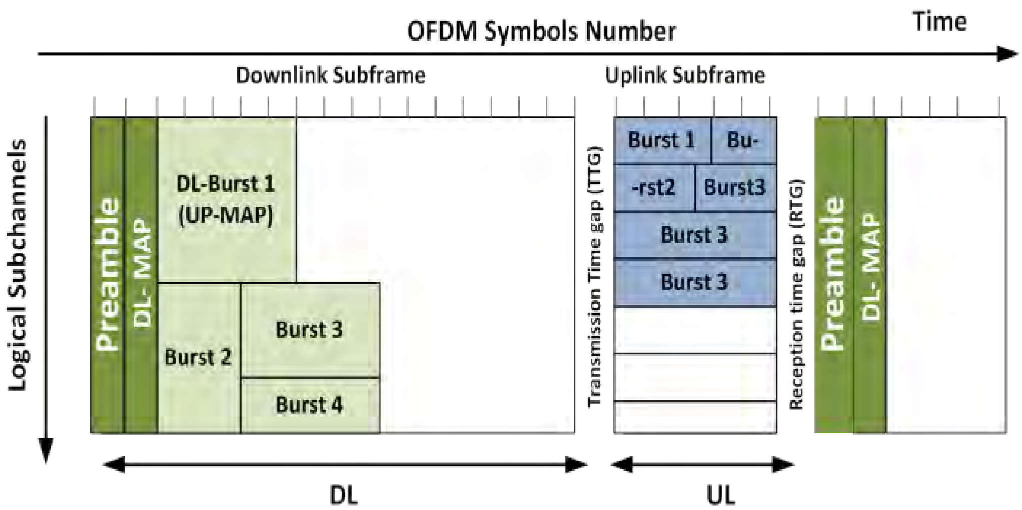

Figure 2.5: TDD-OFDMA frame structure [63]

The minimum data allocation unit in IEEE 802.16 is called a slot. A slot has two dimensions, which are the time and the sub-channel. The size of the slot may vary according to multiple factors such as OFDMA symbol structure and the permutation modes. The three different permutation modes are Partially Usage Sub-Channels (PUSC), Full Usage of Sub-Channels (FUSC) and Adaptive Modulation and Coding (AMC). In this thesis, the Partially Used Sub-channels (PUSC) mode is used for both uplink and downlink. Table 2.1 shows the parameters of PUSC permutation.

2.3 WiMAX MAC Layer Services

The IEEE 802.16 MAC layer is divided into three sub-layers that perform different functions. Figure 2.6 shows the functions and services that the IEEE 802.16 MAC sub-

Parameter	Value
Frequency	2048
Subcarriers per channel	14
Subchannels	60
Data Subcarriers	1140
Pilot Subcarriers	240
Left Guard Subcarriers	184
Right Guard Subcarriers	183

Table 2.1: The parameters of PUSC permutation [56]

layers are responsible for [64]. The Convergence Sub-layer (CS) performs header suppression on the packets that arrive from the network layer above. It also classifies Service Data Units (SDUs) and associates them with the appropriate MAC Service Flow Identier (SFID) and Connection Identier (CID). The second sub-layer is the Common Part Sub-layer (CPS) which handles most of the key functionalities of MAC layer such as bandwidth allocation, connection establishment and maintenance of the connection between the two endpoints. The last lower MAC sub-layer is called the Security Sub-layer (SS) [56]. This sub-layer is responsible for the support of privacy, user/device authentication and key management. In order to convert the Service Data Units (SDUs) to Protocol Data Units (PDUs) or vice versa, Service Access Points (SAP) are placed between these three sub-layers as shown in Figure 2.6.

2.3.1 Traffic Service Classes

In order to handle applications with different QoS requirements, the IEEE 802.16 standards define five service classes that are associated with uplink/downlink scheduling. These classes are:

- Unsolicited Grant Service (UGS): The UGS class is designed for constant rate applications because it serves a constant traffic rate of fixed packet sizes in a periodic manner.
- Real Time Polling Service (rtPS): The rtPS class is used for delay sensitive applications that do not need frequent allocations like error and alarm messaging.

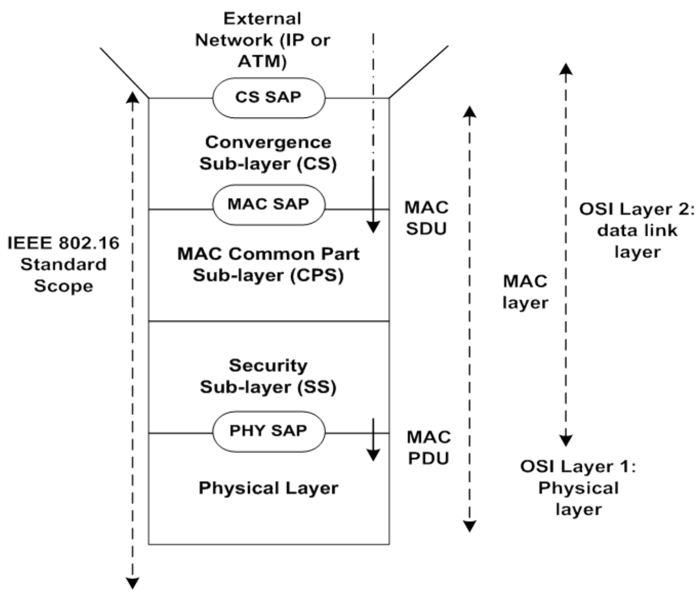

Figure 2.6: IEEE 802.16 MAC layer sub-layers based on [79]

- Extended Real Time Polling Service (ertPS): The ertPS class is designed for variable burst sizes with periodic allocations.

- Non-Real Time Polling Service (nrtPS): The nrtPS class provides a minimum QoS support for delay sensitive applications with low data traffic rate.

- Best effort (BE): Finally, the BE connections do not support delay constraints and the resource allocation is done based on the networks resource availability. Table 2.2 shows the traffic service classes in IEEE 802.16 and the suggested delay guarantees under both premium and basic service QoS requirement [66]. Table 2.3 presents the smart grid application mapping based on the applications service flows requirements.

For each service class, a set of required QoS parameters is defined to provide better system level priorities. The QoS parameters include the following:

- Maximum Sustained Traffic Rate (MSTR): The MSTR parameter is used for a connection to define the maximum rate that is allowed to transmit. This is a six-bit code describing the transmission rate in bits per second and does not include the overheads of the upper layer protocols. The MSTR parameter is calculated based on a long term

Class of Service	QoS Requirements		
	QoS Factors	**Premium**	**Basic**
UGS	Packet Delay	<150 ms	<250 ms
	Delay Jitter	<30 ms	<50 ms
	Packet Loss	<0.3 %	<0.5 %
	Guarantee	>99.9 %	>99.5%
rtPS	Packet Delay	<300 ms	<600 ms
	Delay Jitter	<50 ms	<100 ms
	Packet Loss	<1 %	<5 %
	Guarantee	>99 %	>95%
nrtPS	Packet Delay	-	-
	Delay Jitter	-	-
	Packet Loss	<0-2 %	<0-5 %
	Guarantee	>99 %	>95%
BE	Packet Delay	-	-
	Delay Jitter	-	-
	Packet Loss	-	-
	Guarantee	-	-

Table 2.2: Traffic Classes in 802.16 and their QoS requirement [66]

Applications	**Service Class**
Substation Automation	rtPS
Wide Area Situational Awareness Systems (WASA)	
Outage Management	
Distribution Automation	
Distributed Energy Resources and Storage	
AMI	nrtPS
Demand Response Management	
Demand Side Management	
Asset Management	BE

Table 2.3: Service class proposed definition for smart grid Applications

average of transmission bursts rather than using the instantaneous burst size. This parameter provides an upper limit of the data transmission, but the base station is not obligated to serve at this rate.

- Minimum Reserved Traffic Rate (MRTR): The MRTR presents the lower limit of the traffic rate that the scheduler needs to guarantee for a particular connection.

- Maximum Traffic Burst: The maximum burst parameter defines the maximum transmission rate of an instantaneous burst. This value is configured in bits per second, and the size of the burst in the frame is calculated according to the size of the OFDMA frame.
- Maximum latency: The maximum queue latency represents the maximum time that a packet could wait in the queue before it is transmitted. This parameter is optional, but it helps to determine the maximum delay accepted prior to the transmission.
- Unsolicited Grant Interval (UGI) & Unsolicited Polling Interval (UPI): The UGI is defined as the time between consecutive grants for UGS and ertPS connections. It is calculated by dividing the configured average burst size by the UGS and is only used for UGS and ertPS connections [66]. The Inter-polling Time (IPT) is used for rtPS and nrtPS connections. It is defined as the time between consecutive polls. Table 2.4 shows the proposed WiMAX service flows parameters used in this thesis.

Traffic Class	MSTR (bps)	MRTR (bps)	Max Burst (kbps)	Max Latency (ms)	Service Flow
Class1	200	200	1	100	rtPS
Class2	100	100	1	300	rtPS
Class3	40	40	1	2000	nrtPs
Class4	40	40	1	5000	nrtPs
Class5	1024	-	-	-	BE

Table 2.4: Proposed WiMAX Service flows parameters

2.3.2 Admission Control

The number of connections that can be allowed in a network will be constrained by the available capacity and the QoS requirements of the services. The admission control module in the base station limits the number of connections in a network. This is achieved by examining each configured service flows bandwidth parameters and comparing them with the available capacity in order to decide whether to accept or reject a particular connection. The most important principle is to make sure that the current existing connections

QoS will not be degraded, and the QoS requirements of the new connection can be satisfied. The admission control makes the decisions depending on the QoS parameter defined in the standard which is the minimum reserved traffic rate r_{min}. The formula shown in equation (2.7) specifies when a new connection j will be admitted by a base station [79].

$$r_{\mathrm{min}}(j) \leq B_{\mathrm{T}} - \sum_{i \in N} r_{\mathrm{min}}(i) \tag{2.7}$$

where B_{T} is the total bandwidth of the link , i is a connection and N is the set of admitted connections.

2.3.3 Bandwidth request techniques

In WiMAX system topologies, a large number of smart grid devices share the same uplink bandwidth to the base station on a demand basis. This is accomplished by sending a request of bandwidth reservation from the smart grid devices to the base station each time the smart grid device has data to send. Upon the acceptance of the request, the base station scheduler shall assign the requested number of time slots to the smart grid device to transmit its data using the selected scheduling algorithms. While performing the scheduling, the base station considers the requirements from all authorized WiMAX network nodes and the available channel resources.

WiMAX standard defines three key approaches to grant the authorized WiMAX network nodes the transmission opportunities. These approaches are the centralized polling, contention-based random access and unsolicited bandwidth grants [56]. The first approach works by allowing each node to send its request when it is polled by the base station. In the second approach, all nodes contend to send bandwidth requests using contention resolution mechanisms. Unsolicited bandwidth grants approach consists of dedicated slots reserved for UGS class. This access grant is used only by the UGS class of QoS [66]. In this thesis, the centralized polling mechanism is used as the bandwidth request mechanism. Figure 2.7 shows the centralized polling bandwidth request mechanism.

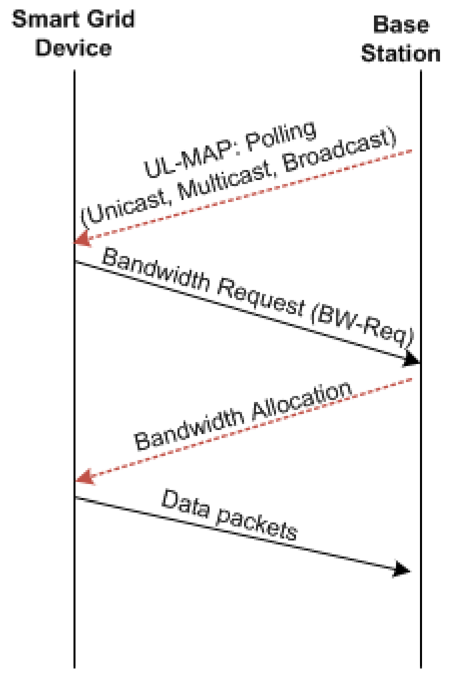

Figure 2.7: Centralized polling bandwidth request mechanism

2.3.4 Scheduling Techniques

Each device has local scheduling mechanism where the generated traffic is locally queued based on the traffic service flows. Then, the local queues contents are forwarded to the base station uplink scheduler for further processing. Based on the QoS parameters, the base station uplink scheduler determines the transmission period and the burst profile for every connection. This thesis proposes three different uplink scheduling algorithms namely; class-based weighted fair queuing, class-based strict priority queuing and class-based deficit weighted round robin.

- **Class-Based Weighted Fair Queuing (CB-WFQ)**: The smart grid applications have a multi-classes traffic applications which makes it a good candidate to utilize a scheduling algorithm such as CB-WFQ that is used in multi-class traffic environment. CB-WFQ is used mainly to enhance fairness by giving lower priority queues the opportunity to transmit packets even if higher priority classes are not empty [67]. One of the major processes of the CB-WFQ scheme is a weight assignment to each class queue. This process specifies the decided bandwidth ratio that will be dedicated to the queues.The weights are assigned to reflect the relative priority and QoS requirements for each traffic class. Based on the bandwidth ratio, the CB-WFQ scheduler examine the traffic classes queues and forward the selected packet to the output link accordingly. Figure 2.8 shows the CB-WFQ scheme.

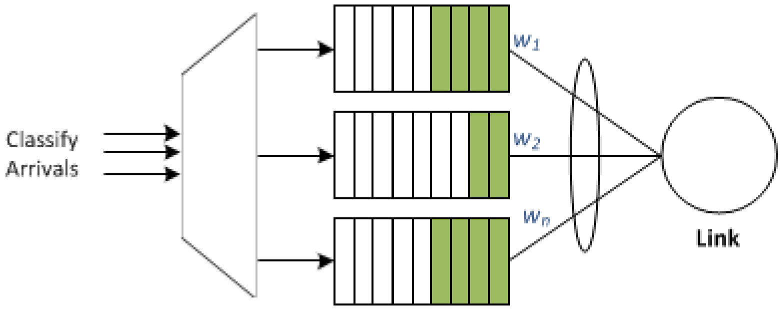

Figure 2.8: Class Based Weighted Fair Queuing

The CB-WFQ is based on the work conversing mode where a packet is always transmitted when there is traffic waiting [67]. If the queue doesnt use the assigned bandwidth ratio within a time window, the bandwidth is divided among the other non-empty queues proportionally to its weights. CB-WFQ uses the concept of virtual time $v(t)$ to track the progress of the packets in the system. Consider the following variables:

$r_{\min}(i)$: is the minimum reserved rate to session i

C : is the total capacity of the uplink channel

S_{j} : is the set of sessions that are busy in the interval $(t_{\mathrm{j}-1}, t_{\mathrm{j}})$

t_{j} : is the arrival and departure time of a packet j

For a time interval τ, virtual time $v(t)$ is updated as follows [68]:

$$V(0) = 0$$
$$v(t_{\mathrm{j}-1} + \tau) = v(t_{\mathrm{j}-1}) + \tau / \textstyle\sum_{i \in S_{\mathrm{j}}} r_{\min}(i) \tag{2.8}$$

An arriving packet is stamped with virtual finish time as follows:

$$S_{\mathrm{i,k}} = max\{F_{\mathrm{i,k-1}}, v(a_{\mathrm{i,k}})\} \tag{2.9}$$

$$F_{\mathrm{i,k}} = S_{\mathrm{i,k}} + \frac{L_{\mathrm{i,k}}}{r_{\min}(i)} \tag{2.10}$$

where $S_{\mathrm{i,k}}$: is the virtual start time of the k^{th} packet from the session i

$F_{\mathrm{i,k}}$: is the virtual finish time of the k^{th} packet from the session i

$a_{\mathrm{i,k}}$: is the arrival time of k^{th} packet of the session i

$L_{\mathrm{i,k}}$: is the length of k^{th} packet of the session i

The role of $v(a_{i,k})$ is to reset the value of $S_{i,k}$ when queue i becomes active (i.e., receives one packet after being empty for a while) to account for the service it missed. The minimum reserved rate $r_{\min}$ of the flow i is used as the weight.

- **Class-Based Strict-Priority-Queuing (CB-SPQ)**: This queuing algorithm transmits the highest priority packets first. Once the higher priority queue is empty, the next priority queue packets are transmitted. This feature is most suitable for the smart grid applications that require the fastest response time. In this context, the wide area situational awareness and substation automation application requires 15-200 msec response time compared with the 2000 msec response time in the smart meter application. CB-SPQ has two main queuing disciplines: non-preemptive priority and preemptive priority. The difference between the two queuing disciplines is that the transmission of a packet in a non-preemptive queuing discipline is not interrupted once it has begun. For example, if class (1) has non-preemptive priority over class (2), then class (2) packets cannot be preempted once it enters service. Class (1) packets still have priority over class (2) packets that are still waiting but not being served. However, if class (1) has preemptive priority over class (2), then if class (1) packet arrives to find class (2) packet in service, class (2) packet is preempted so the class (1) packet can run immediately.

- **Class-Based Deficit Weighted Round Robin (CB-DWRR)**: CB-DWRR visits non-empty queues and determines the number of bytes of the packet at the head of the queue. The variable DeficitCounter is incremented by the value quantum. When the size of the packet is larger than the variable DeficitCounter, the system scheduler skips the queue and moves on to serve the next queue. If the size of the packet at the head of the queue is less than or equal to the variable DeficitCounter, then the variable DeficitCounter is reduced by the number of bytes in the packet, and the packet is transmitted on the output port. The scheduler continues to dequeue packets and decrement the variable DeficitCounter by the size of the transmitted packet until either the size of the packet at the head of the queue is larger than the variable DeficitCounter, or the queue is empty. If the queue is empty, the value of the DeficitCounter is set to zero. When this occurs, the scheduler moves on to serve the next non-empty queue. Figure 2.9 shows the CB-DWRR scheduling scheme [69].

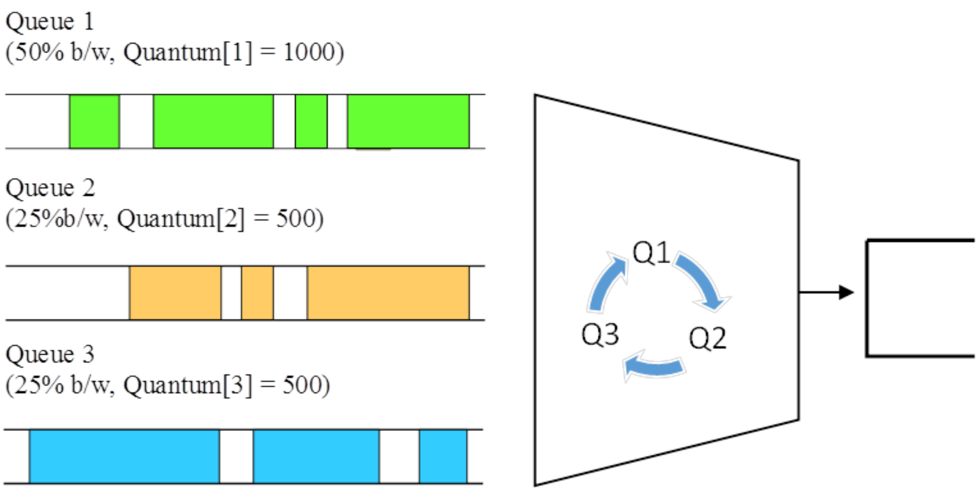

Figure 2.9: Deficit Weighted Round Robin Queuing (CB-DWRR)

In DWRR, each queue is configured with a number of parameters as follows:

  - A weight that defines the percentage of output bandwidth allocated.

– A DeficitCounter that specifies the total number of bytes the queue is permitted to transmit each time it is visited by the scheduler.

– A quantum of a service is proportional to the weight of the queue. The Deficit-Counter for a queue is increased by quantum each time it is visited by the scheduler. If quantum [i] = 2 $\times$ quantum [x], then queue i will receive twice the bandwidth as queue x when both queues are active.

However, the basic algorithm is modified because in WiMAX, base Stations do not schedule packets but slots. In the UL direction, the base station does not even know the size of the head-of-line packet. In each frame, the virtual uplink bandwidth request and real downlink queue sizes are converted from bytes to slots. The number of required slots depends on the Modulation and Coding Scheme (MCS) of the connection. The quantum then is calculated by multiplying the number of slots by the bytes per slot that the current MCS of the connection can deliver. The quantum parameter is then divided by six, which are bytes per slot for QPSK-$1/2$ used in this thesis. It is worth mentioning that bigger quantum size decreases the MAP overhead because a fewer connections per frame is served [69]. The quantum parameter is directly related and proportional to connection QoS parameters, i.e. Maximum Sustained Traffic Rate and the Minimum Reserved Traffic Rate values.
Let n be the total number of flows, $r_{\min}$ be the lowest reserved rate for flow i and C is the available channel capacity. Since all the flows shares the same output link, a necessary constraint is that the sum of all reserved rates should not exceed the transmission rate of the output link.

$$\sum_{i=0}^{n} r_{\min} \leq C \tag{2.11}$$

In order that each flow receives service proportional to its guaranteed service rate, the CB-DWRR scheduler assigns weight $w_{\rm i}$ to each flow. The weight assigned to flow i

can be calculated by:

$$\mathrm{w}_i = \frac{100 r_{\min}}{C} \quad \forall \quad i \in n \tag{2.12}$$

Quantum Q_{i} is calculated based on the weight of the queue and the interface Maximum Transmission Unit (MTU) which is the maximum packet size that could be dequeued. At the start of the execution of the first round, the deficit counters for all the flows are initialized to zero. $DC = 0$. The total bandwidth available to any flow i during this round is equal to its quantum.

$$Q_{\mathrm{i}} = MTU + 512 w_{\mathrm{i}} \tag{2.13}$$

2.4 Differentiated Service Code Point (DSCP)

The DSCP is one of the major QoS measures. It is used to reserve the network resources based on priority traffic classes rather than individual service flows. The Diffserv classes are Expedited Forwarding (EF), Assured Forwarding (AF), Class Selector (CS) and Default Diffserv [79]. For the smart grid applications, at the network point of entry, the DSCP is calculated for each application [70]. A mapping between the Diffserv classes and WiMAX service classes is performed based on the QoS characteristics such as delay, jitter and packet loss tolerance. Table 2.5 shows the mapping between Diffserv classes and WiMAX service classes. Since the WiMAX UGS class carries traffic with minimum delay and jitter requirements, it is mapped to the EF class of Diffserv; hence it requires higher priority than other kinds of traffic. The WiMAX rtPS class is mapped to AF3 and AF2 because it can prioritize real time traffic with minimal loss tolerance. As extended rtPS class is a combination of UGS and rtPS class, the ertPS traffic is mapped to higher AF class like AF4. On the other hand, nrtPS class traffic has higher delay and loss tolerance, makes it better candidate to map to the AF1 class. The best effort class is mapped to default DiffServ class [71].

As discussed in section 2.2.1, the smart grid applications are classified and assigned to three WiMAX service classes, i.e. rtPS, nrtPS and BE. Based on this classification and

WiMAX MAC Services	Diffserv Class
UGS	EF
rtPS	AF2 , AF3
ertPS	AF4
nrtPS	AF1
BE	Default

Table 2.5: Mapping between Diffserv and Service flows

the mapping between the Diffserv and WiMAX service classes shown in Table 2.5, new tailored DSCP implementation is proposed for supporting smart grid applications. For example, the smart meter application data is divided into periodic and non-periodic traffic (mission critical). The DSCP is used to distinguish between these traffics by assigning relative priority weight for each. In this example, the DSCP relative priority weights are 15 and 31 for the periodic and the non-periodic traffic respectively. Table 2.6 shows the DSCP relative priority weights in octal for all the proposed smart grid applications.

Smart Grid Application	DSCP
Substation Automation	67,64
Wide Area Situational Awareness Systems (WASA)	55
Outage management	43
Distribution Automation	
Distributed Energy Resources and Storage	33
Meter Readings (periodic)	15
Meter Readings (critical)	31
Demand Side Management	
Demand Response Management	11
Asset Management	BE

Table 2.6: Smart Grid Applications and the Mapped DSCP

2.5 Queuing Model

This study proposes a single server multiple queue system scheduled with different schemes, i.e. CB-WFQ, CB-DWRR and CB-SPQ. The scheduling schemes are used for bandwidth scheduling. Five separate queues Q_{j} with exponentially distributed interarrival times $(1/\lambda_{\text{j}})$ and service rate μ_{j} where j is the traffic class, is used to host five classes of traffic. The queues have finite capacities $L_{\text{j}}$and follow a First-In Frist-Out (FIFO) queuing approach. The arrival rate λ_{j} of each queue can be further broken down to $\lambda_{(\text{i,a})}$ probabilities, which one represents the arrival probability for i-priority packets generated from smart grid application a, where $a = 1...k$ and k is the number of applications that belongs to the same priority class. It holds that:

$$\lambda_{\text{i}} = \sum_{\text{a}=1}^{k} \lambda(j, a) \tag{2.14}$$

Each priority queue Q_{j} is assigned a weight, which specifies the bandwidth ratio that will be dedicated to that particular queue. The weights of the classes are determined according to their QoS requirements.

$$w_{\text{j}} = \frac{BW_{\text{j}}^{\text{req}}}{\sum_{\text{j}=1}^{p} BW_{\text{j}}^{\text{req}}} \tag{2.15}$$

where, $BW_{\text{j}}^{\text{req}}$ is the bandwidth required for each traffic class in bit per second , p is the number of traffic classes, i.e. five .

In IEEE 802.16,time frames are divided into a constant number of time slots S with same time-slot duration (5 milliseconds). Therefore, priority queues Q_{j} are allocated a number of time slots according to their weights.

$$S_{\text{j}} = Sw_{\text{j}} \tag{2.16}$$

where S is the total number of slots and S_{j} is the allocated number of slots for class j .

To calculate the end-to-end delay for processing a complete smart grid application request, let $D(i, n)$ denotes the delay of the packet i at the n^{th} hop of the network [72, 73, 74] .

$$D_{\mathrm{(i,n)}} = KD_{\mathrm{(n)}} + \textstyle\sum_{\mathrm{n=1}}^{\mathrm{k}}[D_{\mathrm{Q(i,n)}} + D_{\mathrm{S(i,n)}} + D_{\mathrm{R(i,n)}}] \tag{2.17}$$

$$D_{\mathrm{(n)}} = d_{\mathrm{p}} + d_{\mathrm{g}} + d_{\mathrm{t}} + \mu \tag{2.18}$$

$D_{\mathrm{Q(i,n)}}$ is the queuing delay and can be calculated by the following equation:

$$D_{\mathrm{Q(i,n)}} = T_{\mathrm{(a,n)}} - T_{\mathrm{(d,n)}} \tag{2.19}$$

where $T(a,n)$ and $T(d,n)$ respectively are the arrival and departure time of the i^{th} packet at the n^{th} hop of the network.

$D_{\mathrm{S(i,n)}}$ is the scheduling delay, which is defined as the time interval from the end of sending a corresponding bandwidth request message to the time when the corresponding BS grant becomes the first one in the BS grants shared buffer.

$D_{\mathrm{R(i,n)}}$ is the reservation delay, which is defined as the time interval from the packet arrival at the smart grid device to the start of sending a corresponding bandwidth request message to the BS.

d$_p$ is the processing time , which is the time a BS or smart grid device spends processing a packet; this includes error checking time, reading the packet header time and time for finding the link to the next hop .

d_{t} is the transmission time which is defined as the time interval from the time when a BS bandwidth grant becomes the first one in the BS grants buffer to the start of the successful transmission of the corresponding packet in the UL sub-frame [74] .

μ is the transmission time of a data packet and d_g is the propagation delay which is the time that it takes a signal to propagate through the communication media from a hop to the next hop. It can be calculated using the below equation, where L is the distance between hop and the next hop and s_{g} is the propagation speed.

$$d_{\mathrm{g}} = \frac{L}{s_{\mathrm{g}}} \tag{2.20}$$

Figure 2.10 shows the end-to-end delay model for the Single Hop topology.

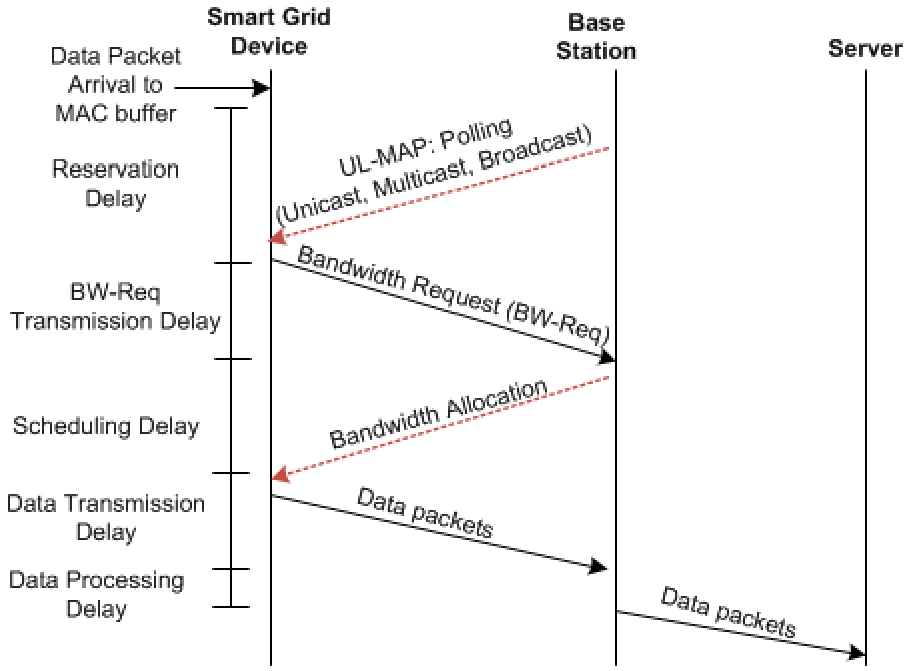

Figure 2.10: End-to-End delay in a Single Hop topology

In the multiple hop topologies, the main reason for the increase in latency is the signaling overhead. All network entry procedures and bandwidth request management should be made at each hop. An intermediate base station has the ability to respond to the bandwidth request from their subordinate devices, at the same time it requires a bandwidth request to send data to the main base station. Considering that a signaling message from one hop to another cannot be transmitted in one frames duration; the delay of control messages transfered from the base station to the smart grid device will increase significantly. The increased delay affects the performance of the services offered by the WiMAX network especially in rtPS where lower latency is required as a QoS metric. Furthermore, even for the BE using TCP as the transport protocol, the increased delay degrades the throughput. Figure 2.11 shows the end-to-end delay model in the Multiple Hops topology.

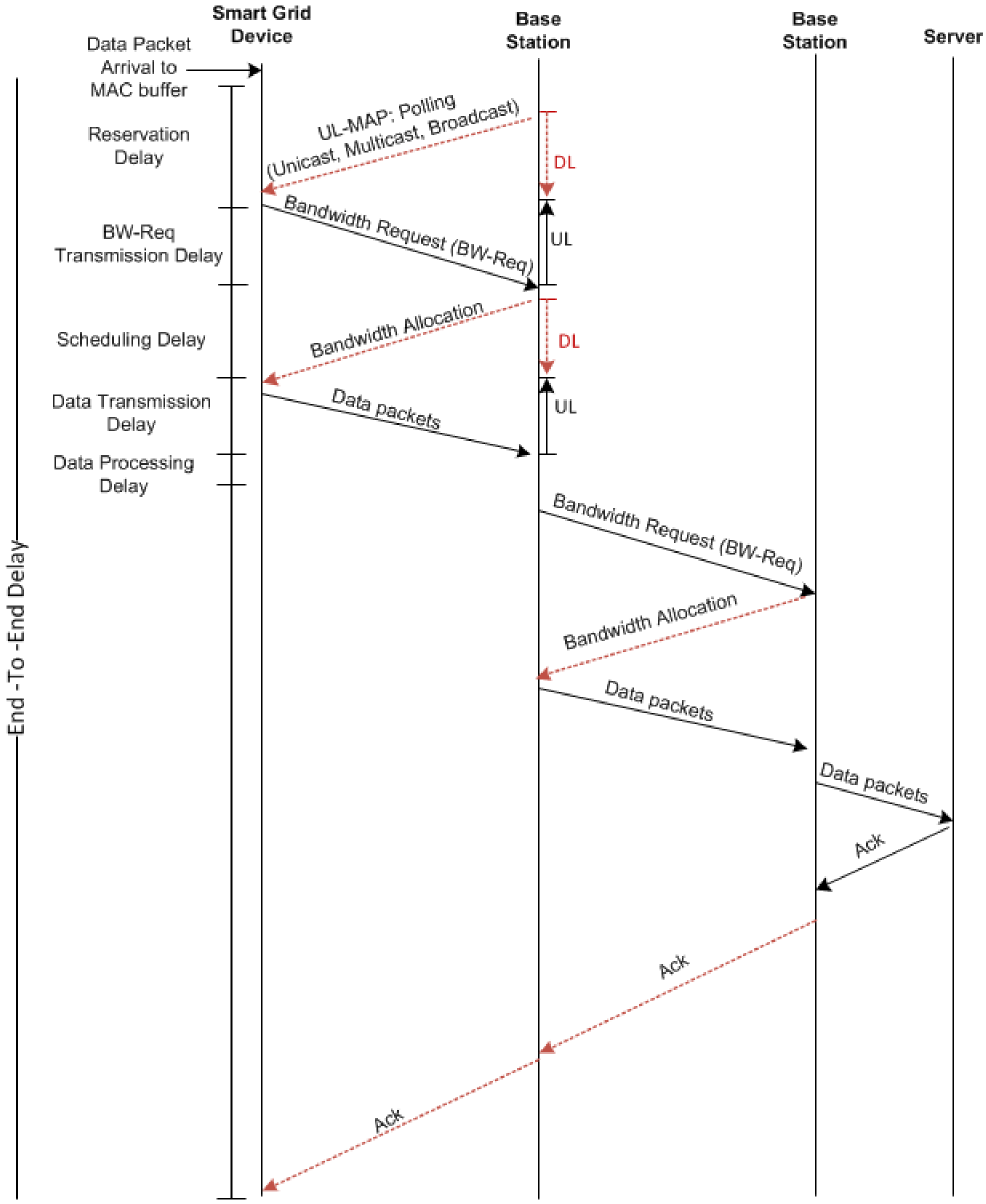

Figure 2.11: End-to-End delay in a Multiple Hops topology

Chapter 3

Modeling and Simulation Scenarios

3.1 OPNET Modeler Overview

Given the ICT role in the smart grid, the co-simulation of both power system dynamics and communication network events is a multidisciplinary challenging task. This is due to the large number of simultaneous and concurrent real-time events in the power system and the communication networks. Moreover, tackling the coupled impact of the interdepended networks and their communication overhead on the performance of the power system is essential when evaluating the performance of the real-time mission critical smart grid applications such as substation automation and wide area situational awareness systems.

OPNET (Optimized Network Engineering Tools) modeler provides a comprehensive environment that supports the design and analysis of communication networks, devices, protocols and applications with great flexibility [75]. It uses a hierarchical approach to build a system model from different sub models that are organized together. As shown in Figure 3.1, the first sub model is the process model that consists of a finite state machine (FSM), protocols such as MAC, IP, TCP and the functions that define how processes react to events [76]. The second sub model is the node model which is an organized set of modules describing the various functions of each node. The last sub model is the network model that defines the network layout and characterizes the node attributes for a particular scenario.

Compared with other simulators, OPNET is more advanced with a powerful capability of simulating physical links and wireless antennas as well as the network regular devices. Also, it has a more detailed simulation tools which allow the developer more flexibility and better configuration as well as visualization features.

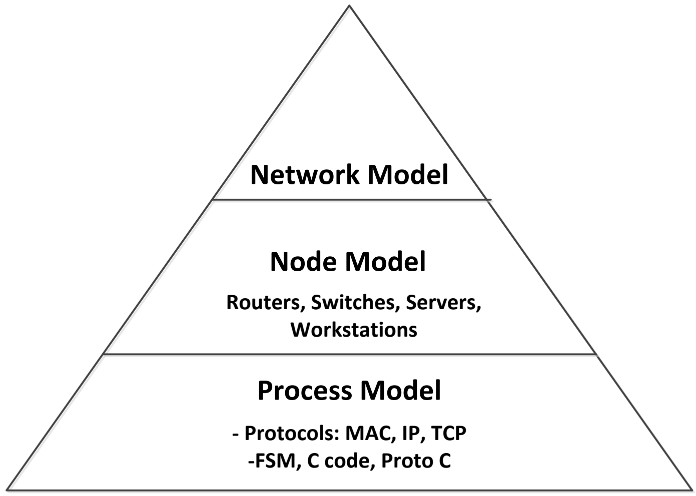

Figure 3.1: Hierarchical structure of OPNET models based on [75]

3.2 OPNET Sub Models

As mentioned above, OPNET has three sub models that are organized to create the desired overall system. This section explains the three sub models namely; process, node, and network sub models.

- **Process Sub Model:** OPNET process sub model defines the detailed functionality, attributes and statistics of a software or hardware implementation inside the node model such as protocol layers, queues, processors, etc. For example, a smart meter is a WiMAX subscriber that applies the OSI- seven layer protocol. WiMAX MAC layer is part of this protocol. The process sub model of a WiMAX MAC layer is shown in Figure 3.2. The model implements the behavior and functionality of the smart meter WiMAX MAC layer through a set of states, transitions and information blocks. States represent the mode of process such as the arrival of a packet from higher layers. Transitions specify a possible path a process can take based on a condition statement such as the classification of the arrived packet. The information blocks specify additional components of the process such as the declaration of a state and the temporary variables.

  The root process sub model to implement the functionality of a WiMAX base station

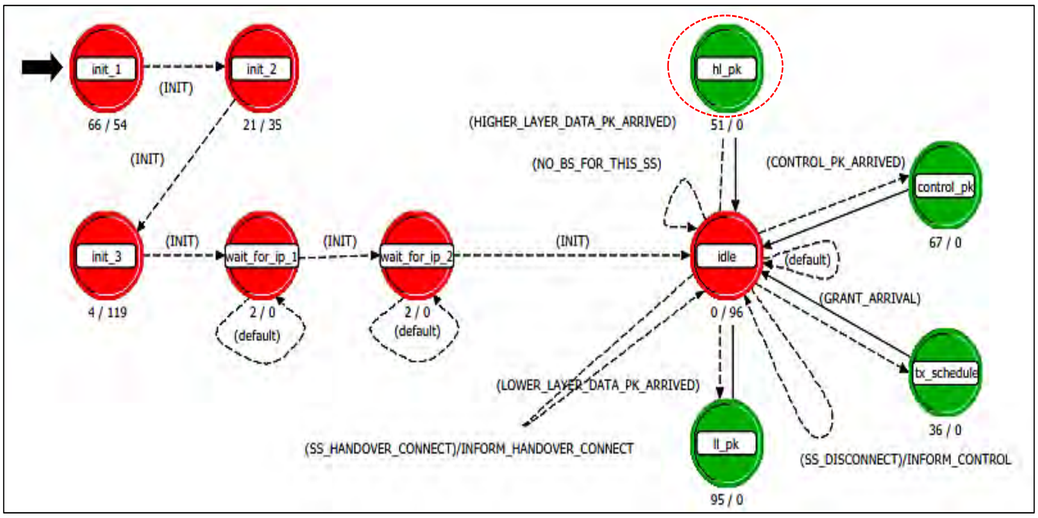

Figure 3.2: OPNET process model-WiMAX MAC layer

and a WiMAX smart grid node is the wimax_mac. This process is responsible for the following key functions :

- Mapping higher layer packets generated by the smart grid applications with the WiMAX MAC layer service flows: mapping and classification could be done based on the source IP address of the packet i.e. smart grid application, destination IP address, source port, destination port, or IP Type of Service (ToS) /DiffServ field. Type of Service (TOS) /DiffServ field in the IP header of the arrived packets is used as a scaffold for mapping and classification of the smart grid applications as mentioned earlier in this thesis. For example, smart meter data packets are mapped with the nrtPS service flows, meanwhile assets management data packets are mapped with best BE service flows. Figure 3.3 illustrates the implementation of the mapping function based on the ToS field.
- Encapsulation/Decapsulation of higher-layer packets in MAC frames: as a result, Service Data Units (SDUs) will be packed into Protocol Data Units (PDUs).
- Defining the bandwidth request mechanism : a polling bandwidth allocation mechanism has been used in this simulation. Figure 3.4 demonstrates the function of the polling WiMAX bandwidth request mechanism.

```
static Compcode
wimax_mac_service_class_find (IpT_Pkt_Socket_Info* socket_info_ptr, char* class_str, int* class_id_ptr)
    {
    List*                       service_class_lptr = OPC_NIL;
    WimaxT_Classifier_Info*     ith_classif_ptr = OPC_NIL;
    int                         i = 0;
    InetT_Address               address;
    int                         port;
    int                         ip_tos;
    int                         num_classifiers = 0;

    FIN (wimax_mac_service_class_find (socket_info_ptr, class_ptr));

    for (i = 0; i < num_classifiers; i++)
        {
        ith_classif_ptr = (WimaxT_Classifier_Info*) op_prg_list_access (service_class_lptr, i);

        switch (ith_classif_ptr->match_info.match_criterion)
            {
            case WimaxC_IPTos:
                /* First transform the match value string into an integer */
                ip_tos = atoi (ith_classif_ptr->match_info.match_value);

                /* Compare ... */
                if (ith_classif_ptr->match_info.match_operator == WimaxC_Equals)
                    {
                    if (ip_tos == socket_info_ptr->packet_tos)
                        {
                        strcpy (class_str, ith_classif_ptr->service_class_name);
                        *class_id_ptr =     ith_classif_ptr->class_id;
                        FRET (OPC_COMPCODE_SUCCESS);
```

Figure 3.3: Classification of packets based on ToS field

```
static void
wimax_mac_poll_consume (WimaxT_Request_Element* grant_ptr, WimaxT_Shaper_Queue_Elem** sq_elem_pptr, Packet** bw_req_pkpptr)
    {
    WimaxT_Service_Flow*        service_flow_ptr = OPC_NIL;

    /* Function steers a poll towards the corresponding bandwidth */
    /* request queue. It returns a bandwidth request packet.      */
    FIN (wimax_mac_poll_consume(grant_ptr, sq_elem_pptr, bw_req_pkpptr));

    /* Initialize return values */
    *bw_req_pkpptr  = OPC_NIL;
    *sq_elem_pptr   = OPC_NIL;

    if (grant_ptr == OPC_NIL)
        FOUT;

    /* Retrieve the shaper queue element. */
    *sq_elem_pptr = (WimaxT_Shaper_Queue_Elem*) wimax_sup_mux_conn_get(data_plane_ptr->mux_ptr, grant_ptr->conn_id);

    /* Verify that the shaper queue element is valid.*/
    if ((*sq_elem_pptr) == OPC_NIL)
        FOUT;

    /* Retrieve service flow, in order to check this */
    /* is one of the scheduling types that allows    */
    /* bandwidth requests.                           */
    service_flow_ptr = (*sq_elem_pptr)->service_flow_ptr;

    if (service_flow_ptr == OPC_NIL)
        FOUT;
```

Figure 3.4: Polling bandwidth allocation Mechanism

  – Delivering packets to UL/DL slots: the MAC PDUs are uploaded to its assigned uplink slots toward the base station or downloaded to its assigned downlink slots toward the smart grid device. Figure 3.5 shows the packet delivery function.

- **Node Sub Model:** The node sub model specifies the architecture and the interfaces of the node objects such as workstations, packets, routers, base stations, etc. that

```
static Packet*
wimax_mac_fragment_dequeue (int grant_size_bits, int grant_size_symbols, WimaxT_Shaper_Queue_Elem*  sq_elem_ptr)
    {
    Packet*                     fragment_pkptr    = OPC_NIL;
    WimaxT_Service_Flow*        service_flow_ptr  = OPC_NIL;
    int                         sdu_count         = 0;
    int                         still_avail_bits  = 0;
    int                         payload_size_bits = 0;
    Packet*                     sdu_pkptr         = OPC_NIL;
    Packet*                     control_pkptr     = OPC_NIL;
    int                         control_size_bits = 0;
    int                         sdu_size_bits     = 0;
    WimaxT_Seg_Buffer*          seg_buffer_ptr    = OPC_NIL;
    Boolean                     is_frag_subheader = OPC_FALSE;
    int                         head_of_buffer_sdu_bits = 0;
    Boolean                     is_no_subheaders = OPC_FALSE;
    int                         piggyback_bwr_size = -1;
    int                         available_granted_size_bytes;


    /* The function returns a MAC PDU to be sent inside the   */
    /* grant.                                                  */
```

Figure 3.5: Packet delivery function

construct the network model. Nodes are composed of different modules. Modules are black boxes with different attributes which are configured to control their behavior. They represent functions of the nodes operation and behavior such as the WiMAX connectivity of a smart meter. WiMAX connectivity is implemented through the addition of multiple modules such as WiMAX antenna, WiMAX physical layer, WiMAX MAC layer, etc. Different types of connections are used to carry data between the modules within a node. The node model embraces processor, queue transmitter, receiver, packet stream, statistic wire, etc. Figure 3.6 shows a node sub model for a WiMAX workstation and Figure 3.7 shows a node model for one interface in a WiMAX base station.

- **Network Sub Model:** As mentioned in Chapter 2, two network topologies have been proposed that will serve as a communication network for the smart gird. The single hop network model consists of random placement of various node models in a hexagon cell over a 5km x 5km area.

  The node models contain one WiMAX base station and a number of WiMAX workstations such as smart meters and sensors. The WiMAX workstations are configured to have different traffic profiles. The access technology for all the nodes is OFDMA 20 MHz TDD duplexing.

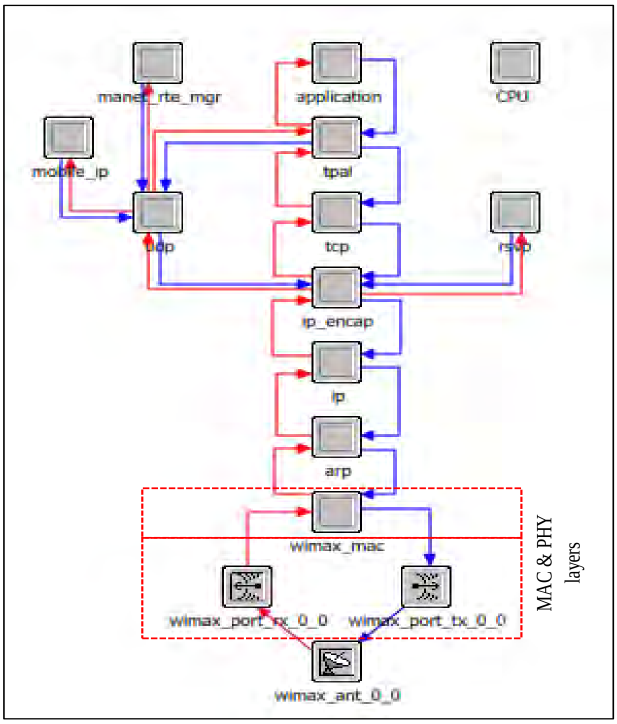

Figure 3.6: OPNET Node Model - WiMAX Workstation

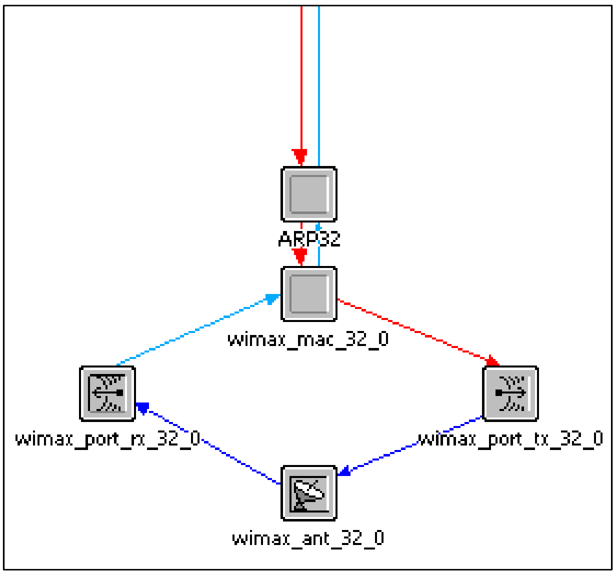

Figure 3.7: OPNET Node Model - WiMAX Base Station (only one interface is shown)

The base station is connected to an IP backbone cloud via a Point-to-Point (PtP) link. The IP cloud is then connected to the application server. The application server is configured to serve all the proposed smart grid applications. The network model of the single hop is shown in Figure 3.8.

The multiple hops network model consists of two hexagonal cells that are identical to the hexagon cell in the single hop model. A backhaul base station is placed 10 km away from the two cells. All the other connections and parameters are kept the same as the single hop model. The multiple hops network model is shown in Figure 3.9.

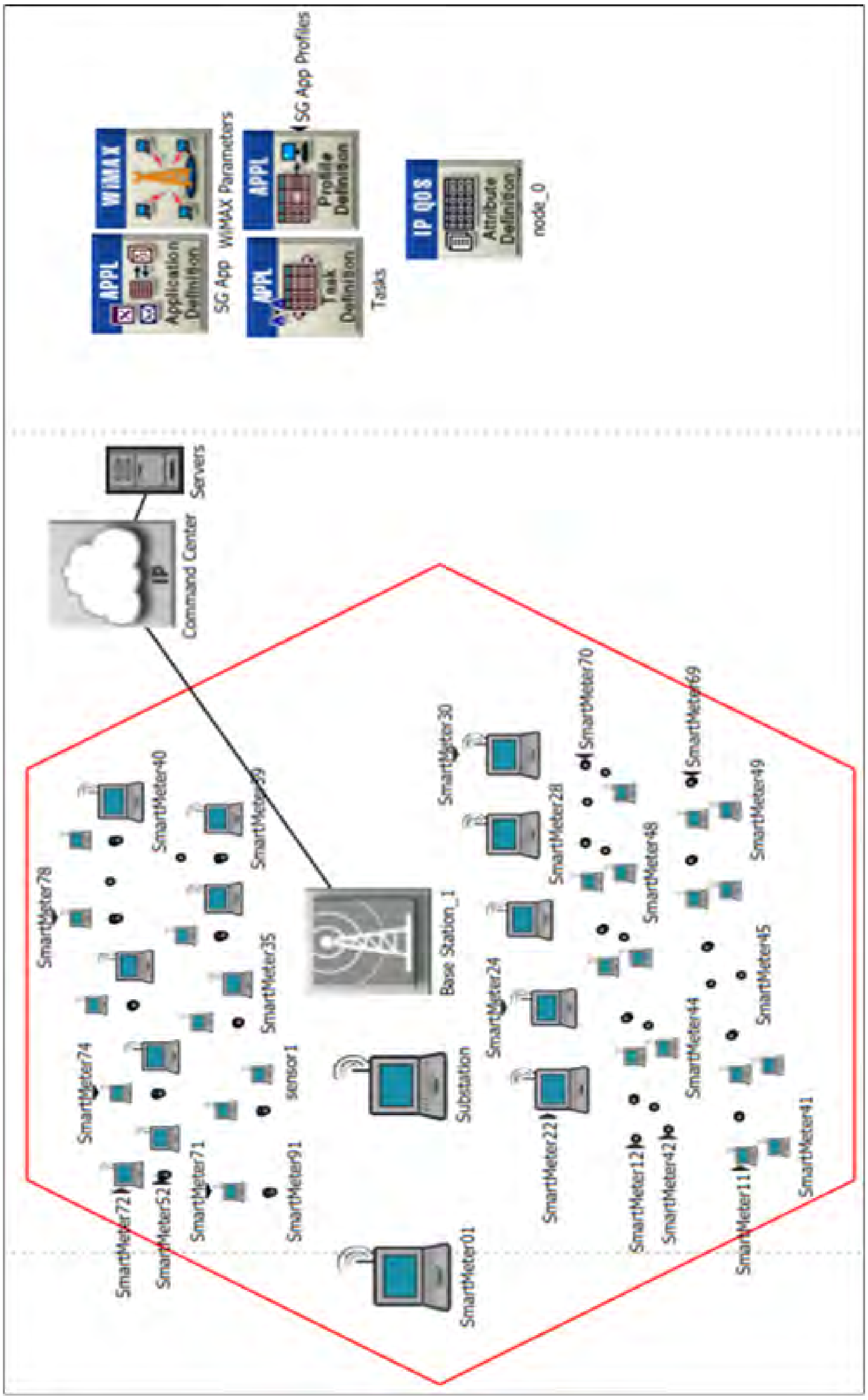

Figure 3.8: OPNET Network Model- WiMAX Single Hop

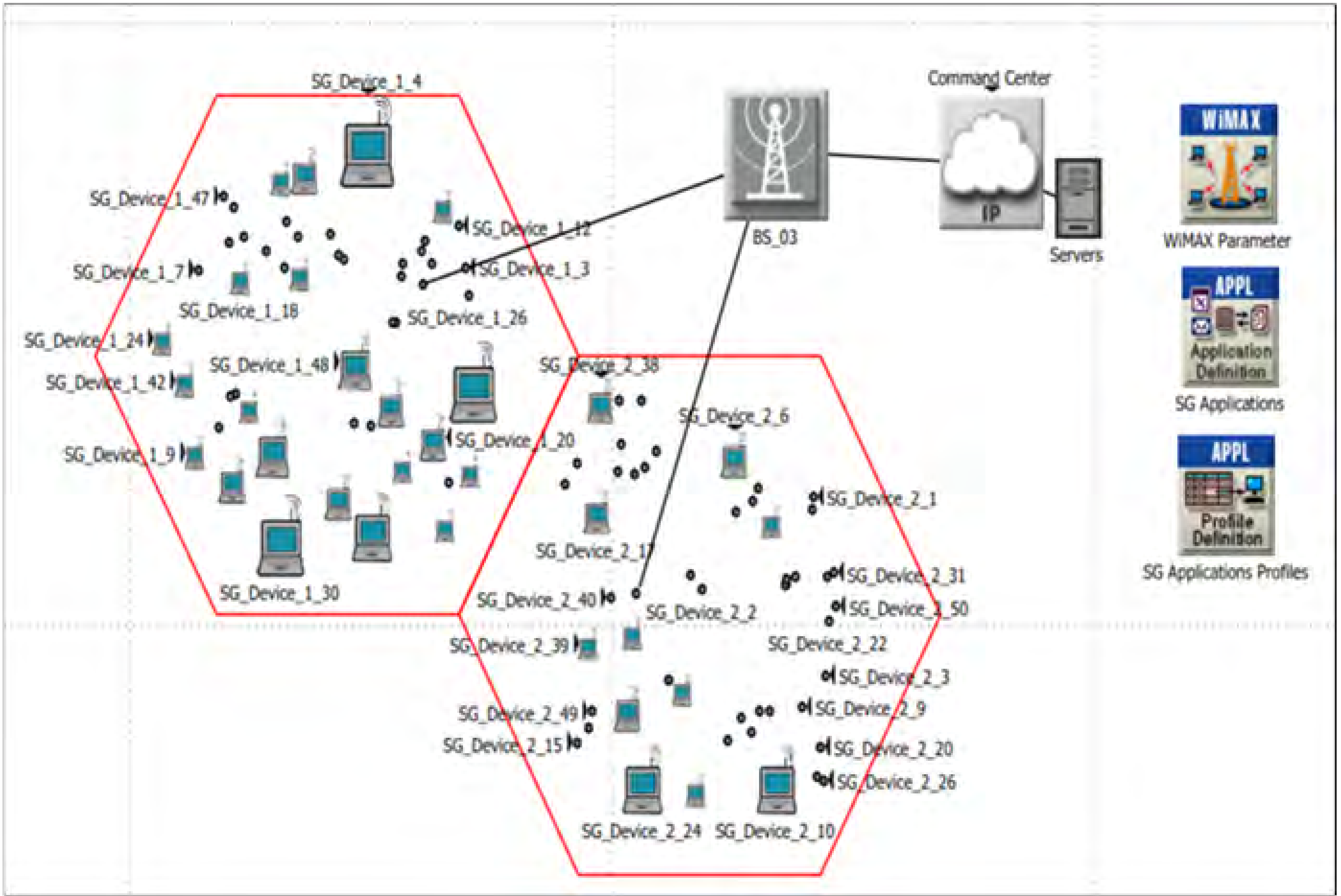

Figure 3.9: OPNET Network Model- WiMAX Multiple Hops

3.3 Profiles Parameters

In order to simulate the WiMAX single hop and multiple hops proposed topologies, the smart grid applications must be profiled. As described in the previous chapters, the smart grid applications were classified into nine different services (Table 1.4). The nine services have been profiled based on their functionality. The operation mode, start time, duration and repeatability for each profile is defined. The new five profiles are: substation, distribution, utility, distributed resources and smart meter. Table 3.1 shows the five different profiles and their related parameters. Figure 3.10 shows the definition and configuration of the smart grid applications profiles in OPNET.

Profiles	Operation Mode	Start Time	Duration	Repeatability
Substation_Profile	Random	30-300 msec	One cycle	Running for the whole simulation time
Distribution_Profile				
Utility_Profile				
DistributedResource_Profile				
SmartMeter_Profile	Simultaneous			

Table 3.1: Profiles Parameters

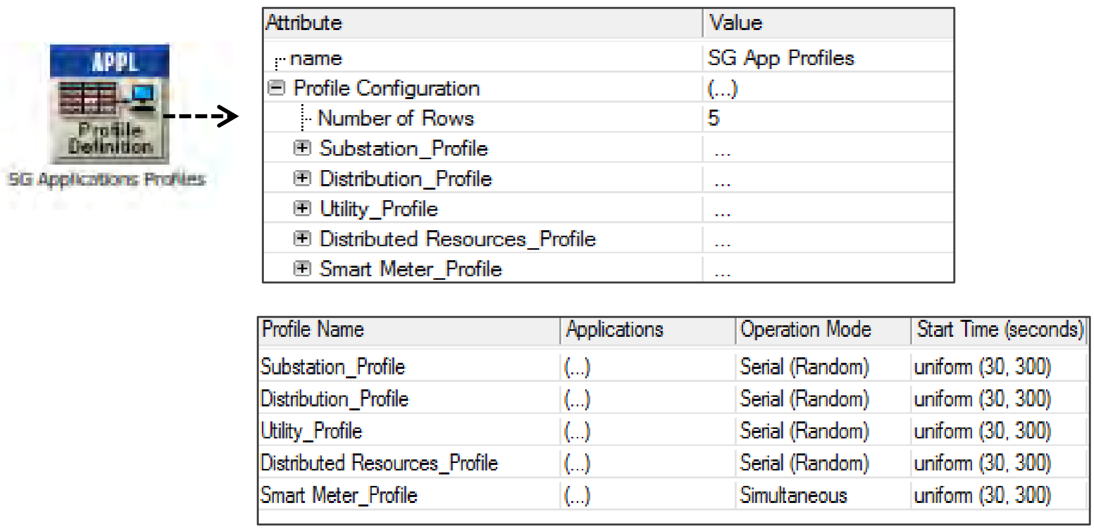

Figure 3.10: OPNET Profile Definition

Profile definition allows any reasonable number of applications per device or user such as the smart meter profile that has the demand response, outage management, distributed energy resources, energy consumption reading and assets management applications. It also specifies related requirements for each device or user of WiMAX such as the application service type, start time, duration,cycle of repetition and operation mode. The operation mode defines when an application will start. The available operation modes are:

- Serial (ordered): applications can start one after another sequentially.
- Serial (random): applications can start one after another in asynchronous manner randomly.
- Simultaneous: applications can start all at the same time.

3.4 Applications Profiling and Parameters

Depends on the smart grid application, a profile may have different inter-arrival rates and distributions, however, all share the same communication protocol and UL/DL file size. For example, the distributed resource profile has five different inter-arrival times and two different distributions.

On the other hand, substation automation profile has one inter-arrival time, one communication protocol and one file size. Table 3.2 shows the nine smart grid applications along with their related profiles, inter-arrival times, distributions, communication protocols and file sizes.

No	Smart Grid Application	Profiling	Inter-arrival Time	Distribution	Protocol	File Size
1	WASA	WASA_Profile	5 sec	Exponential	FTP over TCP	UL=1500 DL= 512 (bytes)
2	Outage management	SmartMeter_Profile DistributedResource_Profile Distribution_Profile	5 mins	Exponential		
3	Distribution Automation	Distribution_Profile	1 sec	Exponential		
4	Distributed Energy Resources and Storage	SmartMeter_Profile DistributedResource_Profile	5 mins	Exponential		
5	Energy Consumption Reading	SmartMeter_Profile DistributedResource_Profile	15 mins	Periodic		
6	Demand Response	SmartMeter_Profile	30 mins	Exponential		
7	Demand Side Management	Utility_Profile	30 mins	Exponential		
8	Asset Management	WASA_Profile SmartMeter_Profile DistributedResource_Profile Distribution_Profile	1 sec	Exponential		
9	Substation Automation	Substation_Profile	1 sec	Exponential		

Table 3.2: Applications Profiling and Parameters

OPNET simulation environment provides traffic applications that are represented as simple traffic sources, complex protocols or a discrete set of tasks. Examples of applications are FTP, E-mail, Remote Login, Video Conferencing, Database, HTTP, Print and Voice. As shown in Figure 3.11, the "Application Definition" window can be used to define the application specifications. The parameters of each application are defined as shown in Figure 3.12 below.

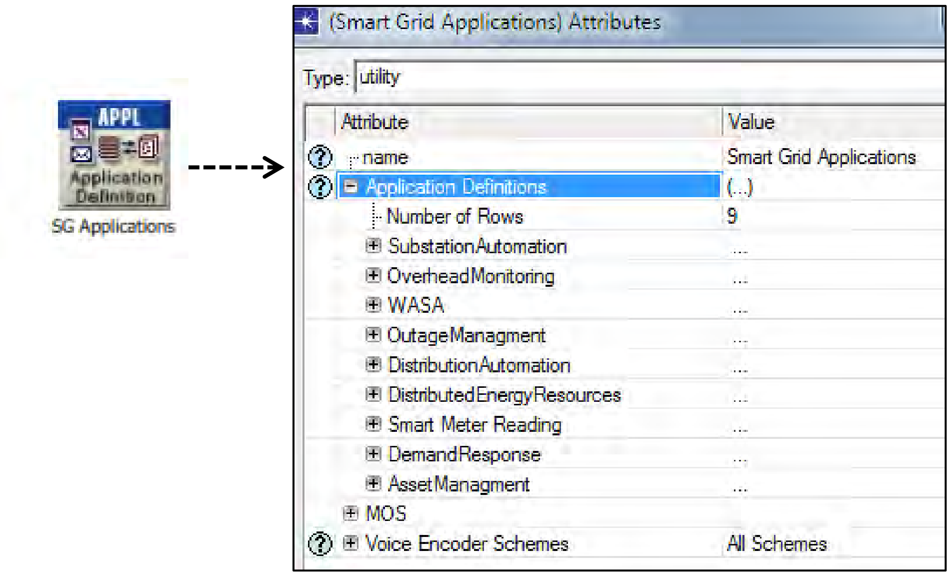

Figure 3.11: OPNET Application Definition

Attribute	Value
Command Mix (Get/Total)	100%
Inter-Request Time (seconds)	exponential (900)
File Size (bytes)	constant (1024)
Symbolic Server Name	FTP Server
Type of Service	Excellent Effort (3)
RSVP Parameters	None
Back-End Custom Application	Not Used

Figure 3.12: OPNET FTP Application Parameters

As showing in Figure 3.14, the FTP application has a three step process: opening connections, data transmission and closing connections. When an FTP client (smart meter, for example) generates a packet that has to be transmitted to the FTP server (utility server, for example), the MAC layer places this packet in the UL queue waiting to be sent. When the poll arrives i.e. a bandwidth request (BWReq) opportunity from the base station, the smart meter sends a bandwidth request (BWReq) message to the base station. The base station replies with a bandwidth grant to the smart meter. The smart meter uses the granted bandwidth to send an opening connection request message to the FTP server. The FTP server replies with an ACK and a connection between the smart meter and the FTP server is established.

Following the connection establishment, the smart meter is ready to send the packet with the metering load information. This packet is placed in the queue. After one IPT (Inter Polling Time) later, the FTP client gets an opportunity from the base station to transmit the packet. When the metering load information packet is received at the FTP server, a response with a control message to the smart meter is sent. However, if the ACK packet is not received by the TCP layer of the smart meter, the packet is retransmitted until the ACK is received. This process increases the DL traffic. The connection between the smart meter and the FTP server is closed after sending a close connection request message from the smart meter to the FTP server.

3.5 Configuring WiMAX Network Parameters

After the nine proposed smart applications were profiled with their related parameters that are needed at the network point of entry, the WiMAX network setup and configuration should be specified. This section illustrates the implementation of the WiMAX functionality in using ẄiMAX Configuration Objectäs shown in Figure 3.13.

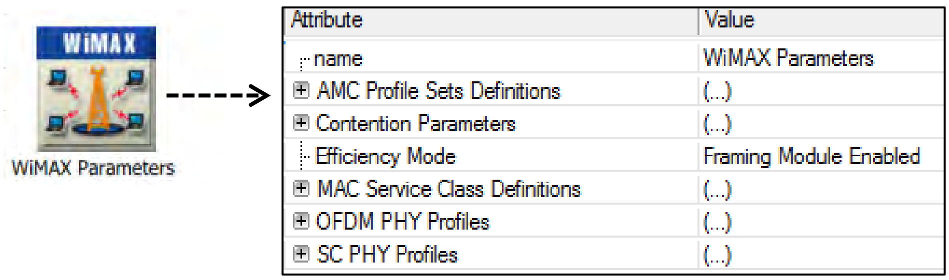

Figure 3.13: WiMAX Configuration Object

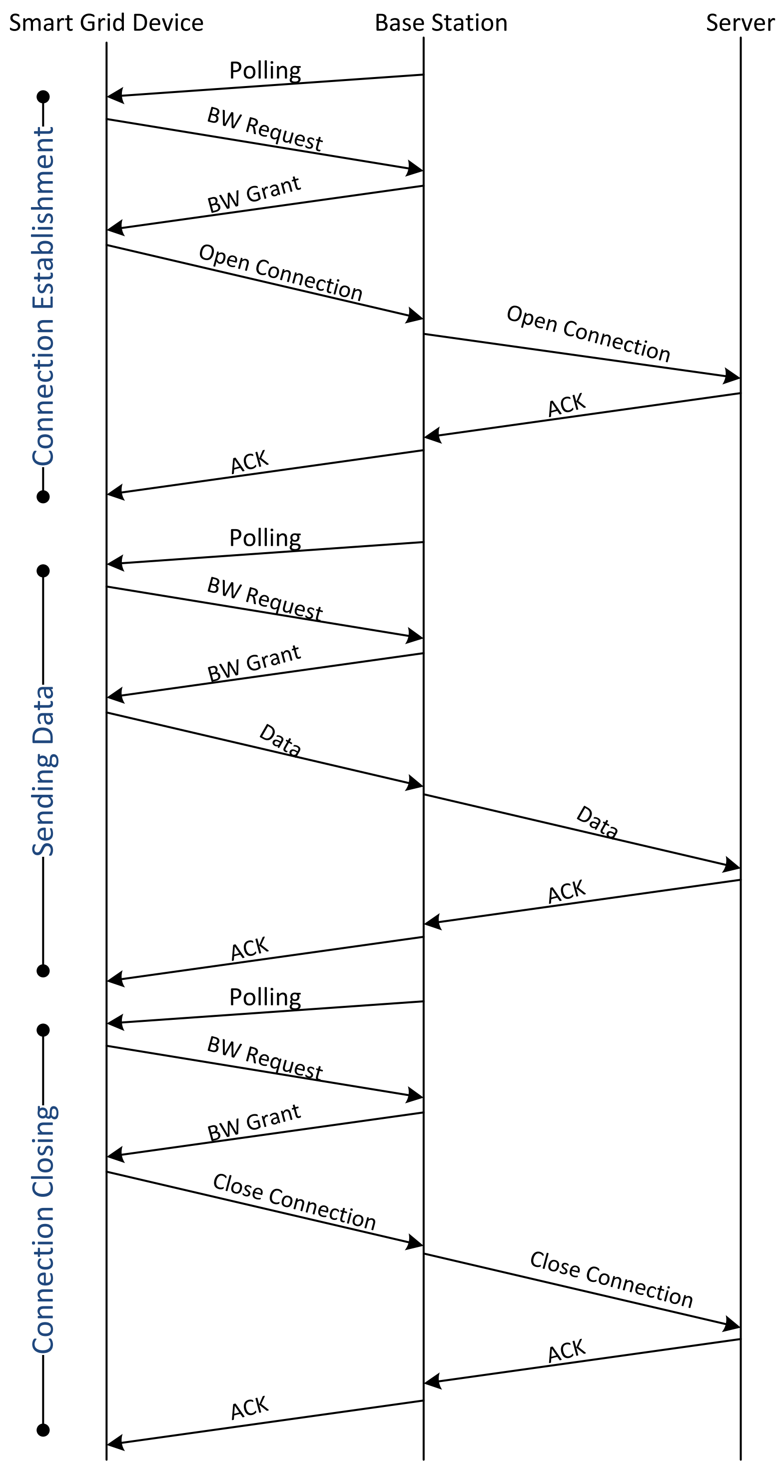

Figure 3.14: Connection Model using FTP over TCP

3.5.1 MAC Service Class Definitions

The service classes that will be used by the WiMAX stations in the network topology must be defined in the M̈AC Service Class Definitionsättribute of the ẄiMAX Configuration Object. This attribute allows configuration of parameters that make up a service class. A service class groups the QoS requirements of a service flow. Any service class definition can be referenced by any service flow (uplink/downlink) defined in the network. In this study, five custom service classes have defined and configured with different parameters as shown previously in Table 2.4.

3.5.2 Physical Layer (OFDM) Profiles

PHY layer profiles are used for estimating link capacities during admission control, determining uplink/downlink boundary information using the configured frame structure information and determining PHY-layer overheads. A base station and its associated workstations should be configured with the same PHY-layer profile. Table 3.3 shows WiMAX network base and workstations antenna gain transmitted power used in this simulation.

Parameters	Base Station	Workstation
Antenna gain (dB)	15 dB	-1 dB
Transmitted power	38 W	0.5 W
PHY profile	wireless OFDMA 20 MHz	
PHY profile type	OFDM	

Table 3.3: WiMAX Configuration Parameters

The WiMAX cell radius, models, frequency, frame parameters, total bandwidth and multiple timing requirements must be specified to satisfy the proposed smart grid applications latency. Table 3.4 lists the WiMAX physical parameters.

Parameters	Configuration
Network	2 Celled WiMAX Network
	1 Celled WiMAX Network
Cell Radius	5-15 Km
No. Of workstations per BS	50-450
Base Station Model	wimax_bs_ethernet4_slip4_router
Workstation Model	WIMAX Workstation
IP Backbone Model	router_slip64_dc
Server Model	ppp-Server
Frequency	2.5 GHz
Physical Layer	OFDM
Frame Structure	TDD
Frame duration	5 ms
Symbol duration (us)	102.86
Number of Subcarriers	2048
TTG/ RTG (microseconds)	106/60
Uplink / Downlink Modulation	QPSK
Code Rate	1/2
Scheduling Algorithms	CB-WFQ, CB-DWRR, CB-SPQ
Total Capacity (Mbps)	11.6544 Mbps
Total Uplink/ Downlink Capacity	5.3184/ 6.3360 Mbps

Table 3.4: WiMAX Physical Parameters

3.5.3 Smart Grid Devices Association with the Base Stations

The MAC address attribute on the smart grid devices (WiMAX workstations) is used to specify the base station to which a smart grid device is connected to. In this thesis, this attribute is set to be distance based. This means that the smart grid device will choose the closest base station to connect to. However, smart grid devices can always be connected to a particular base station (rather than the closest one) by specifying the base station MAC address in the base station MAC address attribute on the smart grid devices.

3.5.4 Service Flows

After the definition of the service classes in the WiMAX configuration object, these service classes are assigned to the service flows that were mapped between smart grid devices and the base station. Uplink service flows specify the service flows from the smart grid devices to the base station. Downlink service flows specify the service flows from the base station to the smart grid devices. All service flows are defined and configured. If a smart grid device has no defined service flow, then the simulation will define a best effort service flow in each direction between the smart grid device and its base station at the runtime. Figure 3.15 shows defining uplinks and downlinks on a smart grid device.

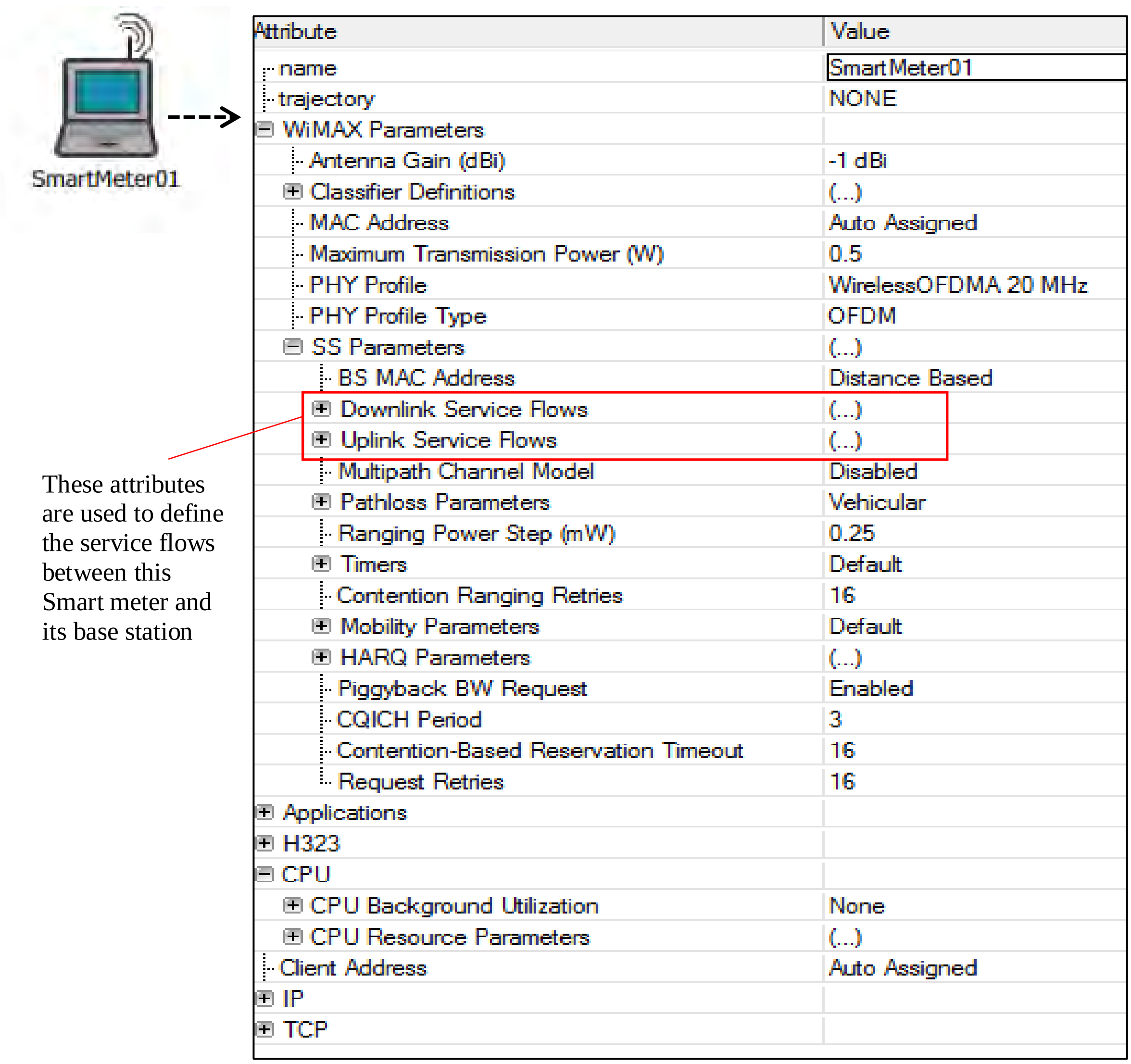

Figure 3.15: Defining Uplinks and Downlinks on smart grid devices

Service Class	MCS	Average SDU	Buffer Size
Class1			
Class2			
Class3	QPSK$\frac{1}{2}$	1Kbyte	64 kbyte
Class4			
Class5			

Table 3.5: Service Class Definition

3.5.5 Modulation

In this thesis, the uplink and downlink channels were configured with QPSK+ $1/2$ for the reason that QPSK+ $1/2$ is the optimal choice for long transmission distances [77]. The rest of scheduling parameters and rates are shown in the Table 3.5.

Chapter 4

Results and Discussions

In order to validate the proposed WiMAX designs, two sets of simulations are developed with their related parameters. The first set of simulations is used to validate the single hop topology, and the second set of simulations is used to validate the multiple hops topology. Three base station scheduling algorithms are used to analyze the networks latency performance for traffic classes.

4.1 Single Hop Topology Results

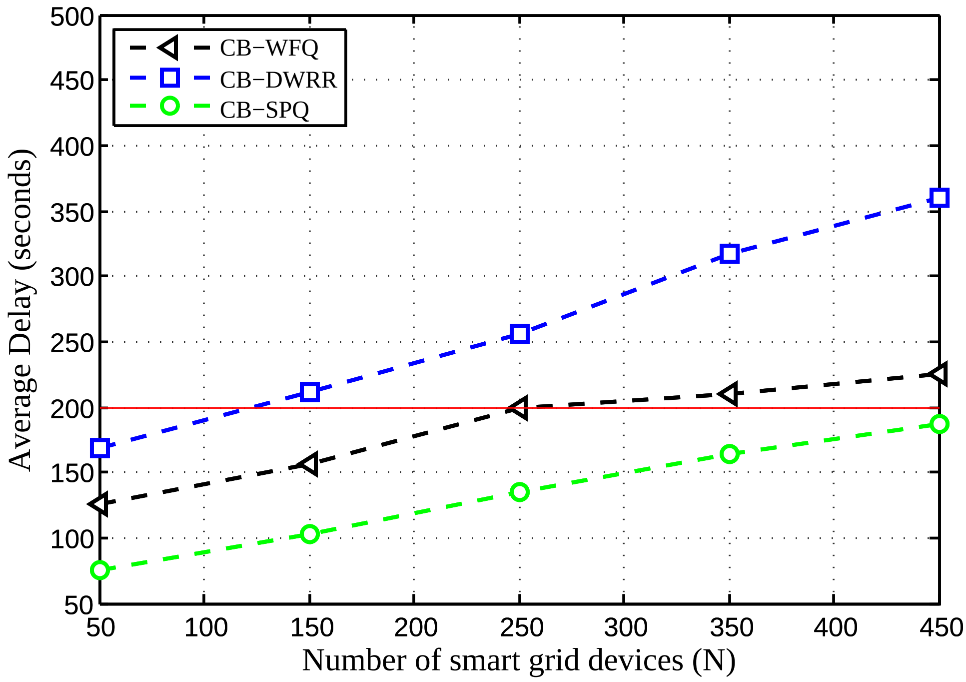

Figure 4.1: Class (1) End-to-End delay under different queuing disciplines

To validate the proposed five different priority classes, a simulation program for each class is developed and run utilizing the base station scheduling algorithms namely; CB-WFQ, CB-DWRR and CB-SPQ. The applications of class (1) are mapped with rtPS WiMAX service flow. As mentioned in the previous chapters, delay requirement for this class is 200 milliseconds. The simulation is run with 50 smart grid devices; the result showed that the three scheduling algorithms satisfied the class delay requirements. With 100 incremental step, the simulation was repeated. The network performance started to deteriorate as the number of devices increases. It was found that the CB-DWRR does not satisfy the class applications latency once the devices number exceeded 150 devices, moreover, the CB-WFQ failed after the devices number reached more that 250 devices. Once the number devices reached 450, the three scheduling algorithms are not any more stratifying the time latency. Figure 4.1 shows that the maximum value of the average delay experienced by class (1) rtPS connections. Therefore, we claim the following:

Claim 1:

In single hop topology, for class (1) applications it is recommended that no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-SPQ scheduling algorithm is the best.

It is worth mentioning that the average delay starts to increase as the number of smart grid devices increase. This increase will generate larger uplink map (UL-MAP) size to accommodate more numbers of the burst information elements (IEs). Therefore, the connected smart grid devices have to wait more time to extract the uplink grant information and leads to higher delay. For the reader reference, class (1) traffic that is assigned for critical- mission applications such as substation automation, wide area situational awareness and outage management.

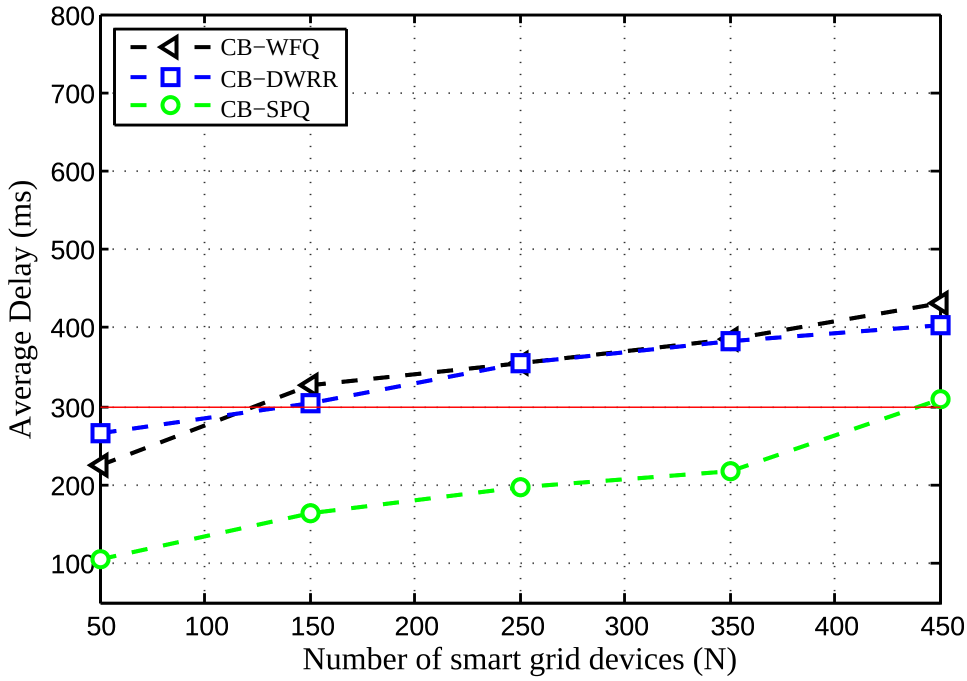

Figure 4.2: Class (2) End-to-End delay under different queuing disciplines

Class (2) traffic is generated from high priority applications such as distribution automation, distributed energy resources and storage energy. Following the same simulation pattern that was used in class (1), the result showed that the CB-SPQ scheduler is giving the best delay performance for class (2) traffic. This is due to the reason that packets generated from these applications are mapped to rtPS connections. The CB-SPQ scheduler serves the highest priority traffic (rtPS) at first, and then it tries to serve the lower level of priority traffic. Thus, class (2) traffic is affected by the low priority traffic flows from class (3), class (4) and class (5). It can also be noticed that the CB-WFQ scheduler acts indistinguishably to the CB-DWRR scheduler, but it has more variation in distributing the bandwidth among the traffic types. Figure 4.2 shows that the maximum value of the average delay experienced by class (2) rtPS connections. Therefore, we claim the following:

Claim 2:

In single hop topology, for class (2) applications it is recommended that no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-SPQ

scheduling algorithm is the best.

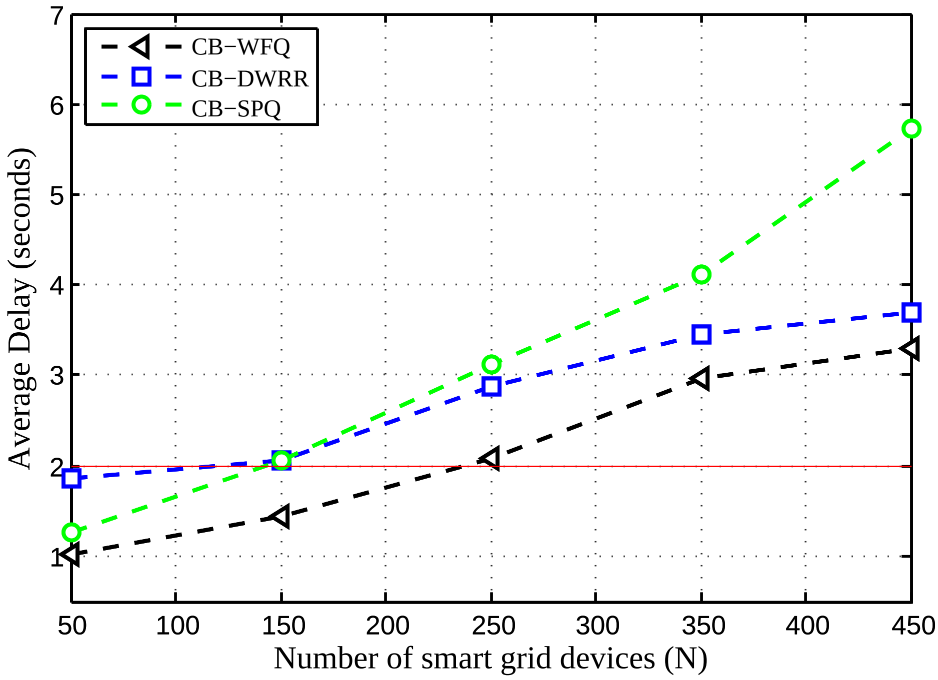

Figure 4.3: Class (3) End-to-End delay under different queuing disciplines

Figure 4.3 shows the simulation results for class (3) traffic. This traffic is generated from the smart meters. It includes interval data reads, meter remote disconnect / reconnect requests and critical peak pricing alerts. It is noticed that the number of smart grid devices, smart meters, in this class, that can be served dropped to 250.

To serve more than 250 meters, the delay exceeds the 2sec time delay limit. From the result that is shown in Figure 3, the CB-WFQ is the most suitable scheduling algorithm that satisfied class (3) traffic. The CB-DWRR and CB-SPQ algorithm failed to service the smart meters traffic once the number of meters exceeded 250.

Claim 3:

In single hop topology, for class (3) applications, it is recommended that no more than 250 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

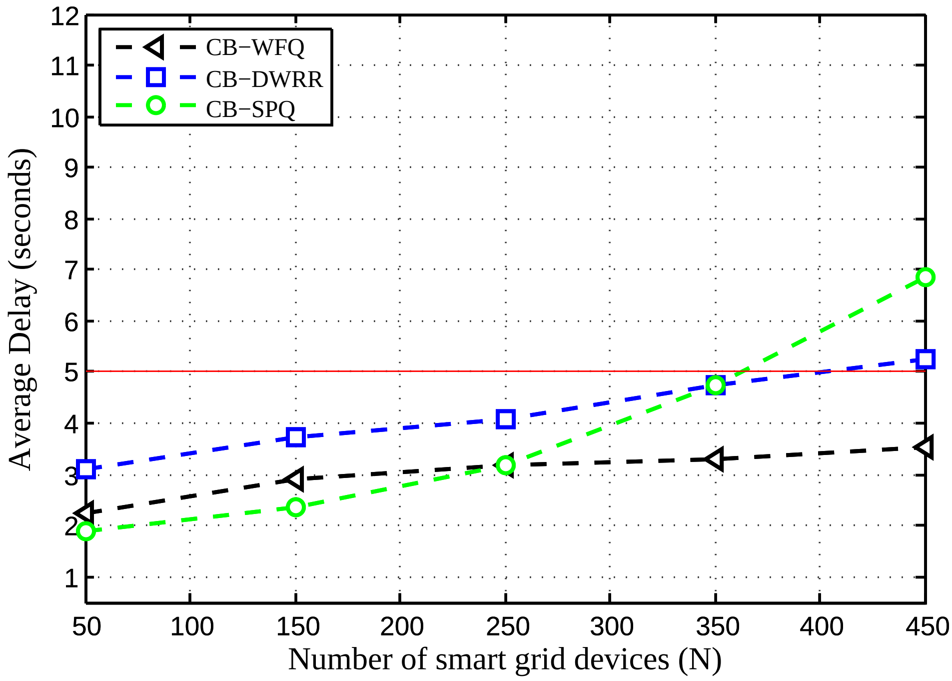

Figure 4.4: Class (4) End-to-End delay under different queuing disciplines

Figure 4.4 shows the simulation results for class (4) traffic. The data traffic is generated from demand response and demand side management applications with a minimum delay requirement of 5000 msec compared with 200 msec, 300 msec and 2000 msec in class (1), class (2) and class (3) respectively. This is due nature of these applications.

Figure 4.3 and Figure 4.4 show also that CB-WFQ algorithm achieves the most favorable results among all schedulers. This has been done through sacrificing the delay of the higher classes traffic i.e., class (1) and class (2), within a tolerable range. From the same perspective, the excess time slots of any higher traffic class are allocated to the other lower classes which enhance their performance without degrading the higher traffic class QoS performance.

Claim 4:

In single hop topology, for class (4) applications, it is recommended that no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

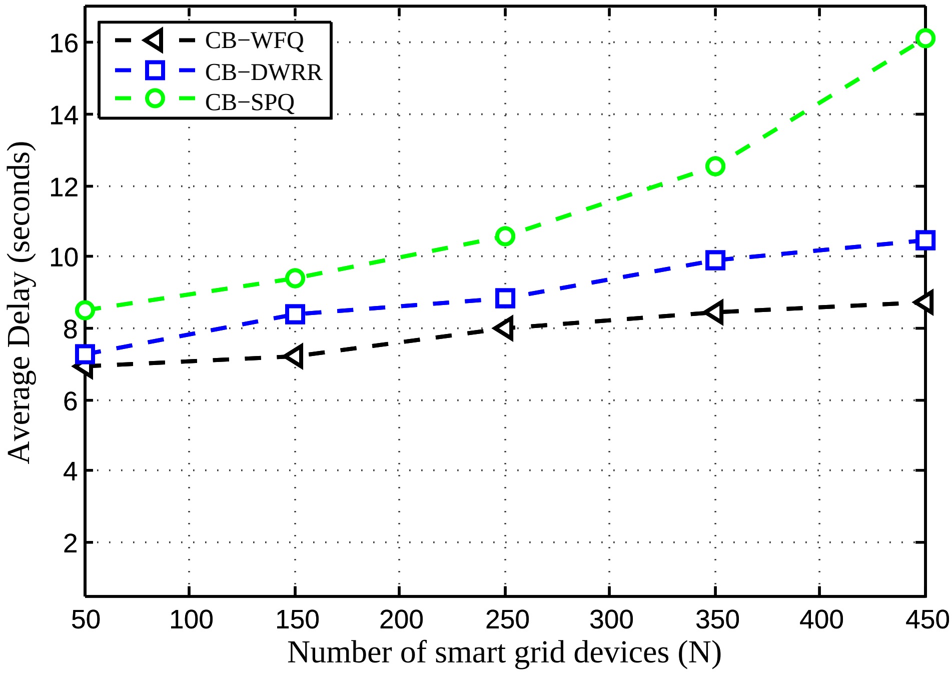

Figure 4.5: Class (5) End-to-End delay under different queuing disciplines

In Figure 4.5, the simulation result of class (5) showed that the three queuing disciplines satisfied the time delay latency. This is due the nature of the application delay requirements which is classified as best offer. It is worth mentioning that this class traffic is generated from the assets management application that quite large delay times that may run into minutes.

Claim 5:

In single hop topology, for class (5) applications, it is recommended that no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best and the other two can best used, as well.

4.2 Multiple Hops Topology Results

The same simulation methodology is followed to validate the multiple hops topology. Five different simulations run were conducted. It is worth mentioning that, in the multiple hops topology, the network geographical distance is extended and the network coverage became larger. Figure 4.6 shows the simulation result the multiple hops topology network for class (1) traffic .

The Figure shows that the scheduling algorithms CB-WFQ, CB-DWRR and CB-SPQ are able to meet the maximum delay requirement of 200 milliseconds; keeping in mind that Class (1) traffic is aggregated only at the command and dispatch center. Therefore, delay values in the multiple hops topology will be close to the ones in the single hop topology. Table 4.1 shows the difference in the values.

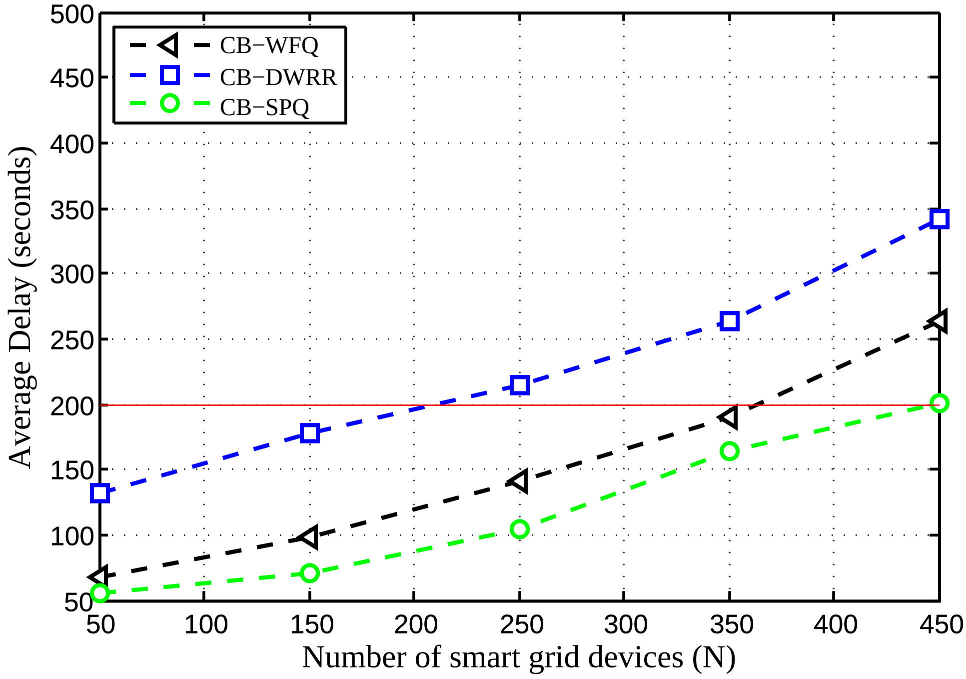

Figure 4.6: Class (1) Average End-to-End delay under different queuing disciplines using the multiple hops topology

Traffic Classes	Single Hop			Multiple Hops		
	CB-WFQ	CB-DWRR	CB-SPQ	CB-WFQ	CB-DWRR	CB-SPQ
Class1	126.43	168.91	75.36	67.20	131.44	55.78
Class2	157.11	212.05	102.88	98.76	177.57	70.55
Class3	198.61	255.38	135.04	141.48	214.70	103.76
Class4	210.03	317.16	163.65	190.10	263.51	164.35
Class5	225.70	360.40	187.31	264.25	341.52	200.70

Table 4.1: Class (1) traffic average delay in single hop vs. multiple hops topologies in milliseconds

Claim 6:

In multiple hops topology, for class (1) applications, it is recommended that no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-SPQ scheduling algorithm is the best and the other two can best used, as well.

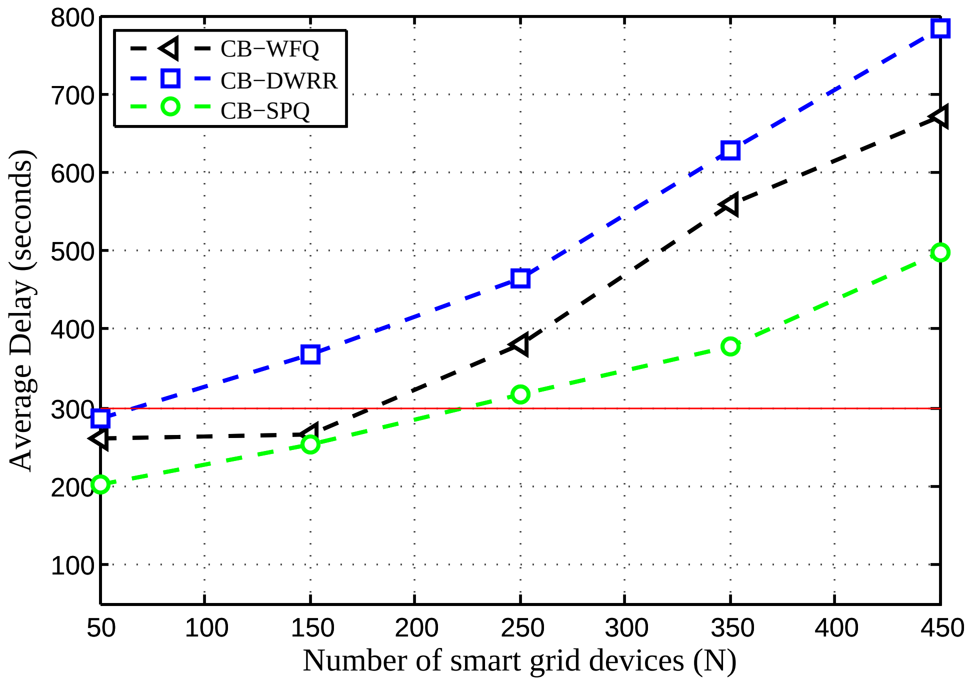

Figure 4.7: Class (2) End-to-End delay under different queuing disciplines using the multiple hops topology

Figure 4.7 shows the simulation result for the average delay of class (2) traffic in the multiple hops topology. The average delay has increased in this topology compared to the single hop topology. This is because one of class (2) applications, i.e. the distribution automation is aggregated and scheduled at the distribution level and then once more at the command and dispatch center. Accordingly, the bandwidth request, the queuing as well as the scheduling are performed twice.

It was found that the three scheduling algorithms have met the maximum delay boundary at a small number of smart grid devices, 250, 150 and 50 under CB-SPQ, CB-WFQ and CB-DWRR respectively. In spite of that Class (2) has rtPS connections; it suffers large delays because of the signaling overhead in the bandwidth request process and the accumulated queuing as well as scheduling delays.

Claim 7:

In multiple hops topology, for class (2) applications it is recommended that no more than 250 smart grid devices should be used to satisfy the latency requirement and the CB-SPQ scheduling algorithm is the best.

Figures 4.8 and 4.9 show the average delays of class (3) and class (4) traffic respectively in the multiple hops topology network. CB-WFQ is still showing a fair resource distribution, so a reasonable delay can be offered to nrtPS connections assigned to class (3) and class (4) traffic. Each connection has its own First In- First-Out queue and the weight is assigned for each queue according to the requested bandwidth.

Claim 8:

In multiple hops topology, for class (3) applications, it is recommended that no more than 150 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

Therefore, nrtPS connections are unlikely starved even under the high load of rtPS connections generated from class (1) and class (2) applications. Class (3) and class (4) are aggregated and scheduled at concentrators first, and then forwarded again from concentrators to the command and dispatch center for further scheduling. Polling for bandwidth at two hops results in high delay values compared to the single hop topology.

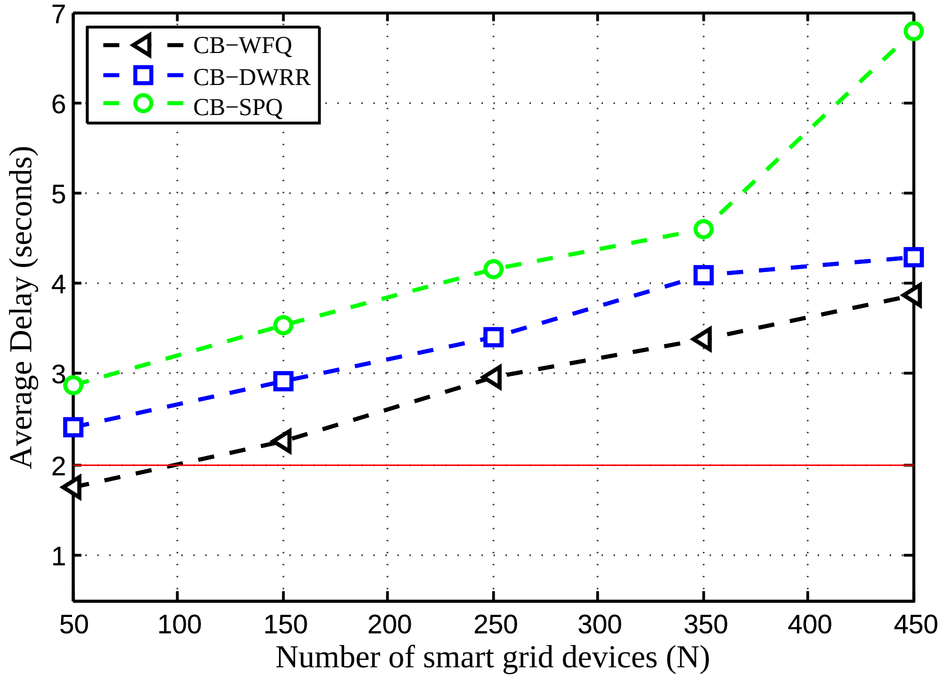

Figure 4.8: Class(3) Average End-to-End delay under different queuing disciplines using the multiple hops topology

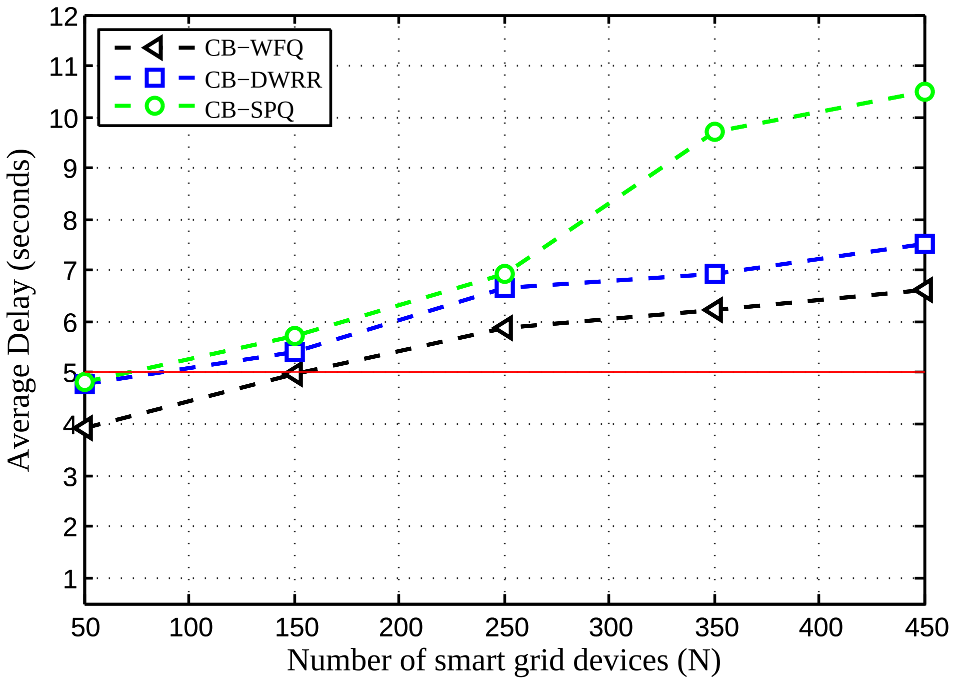

Figure 4.9: Class(4) Average End-to-End delay under different queuing disciplines using the multiple hops topology

Claim 9:

In multiple hops topology, for class (4) applications, it is recommended that no more than 150 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

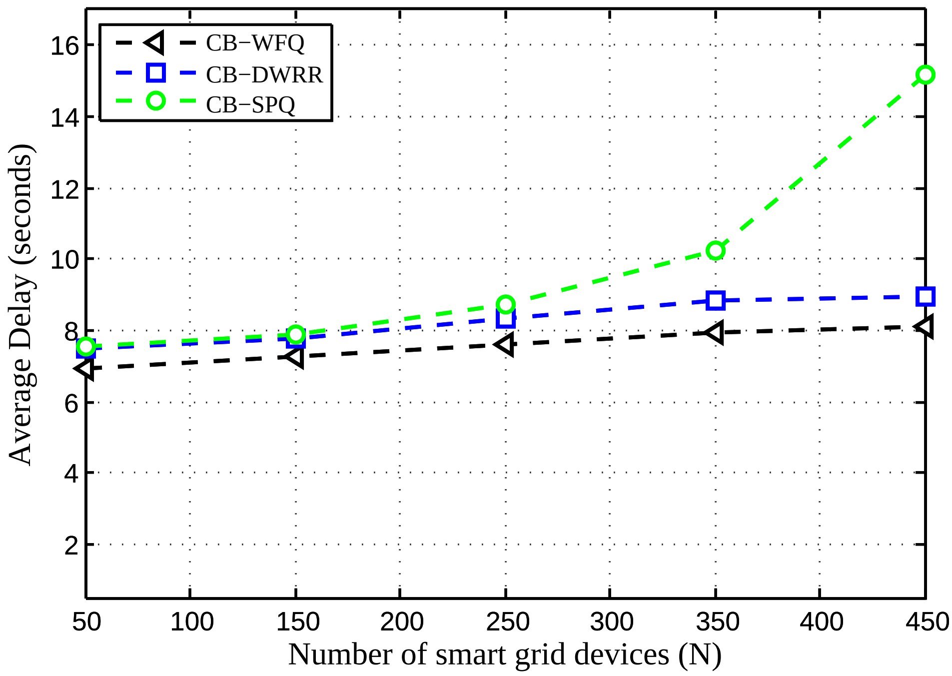

Figure 4.10: Class (5) End-to-End delay under different queuing disciplines using the multiple hops topology

In Figure 4.10, the two topologies reflect a very slight difference. This is because class (5) traffic is aggregated and scheduled only at the command and dispatch center.

Claim 10:

In multiple hops topology, for class (5) applications, it is recommended that no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best and the other two can best used, as well.

Table 4.2 summarizes the performance of all traffic classes under the different queuing disciplines in the single hop topology. The green, yellow and red colors represent the best, medium and worst performance respectively.

Delay		50 SGD	150 SGD	250 SGD	350 SGD	450 SGD
CB-SPQ	Class1					
	Class2					
	Class3					
	Class4					
	Class5					
CB-WFQ	Class1					
	Class2					
	Class3					
	Class4					
	Class5					
CB-DWRR	Class1					
	Class2					
	Class3					
	Class4					
	Class5					

Table 4.2: Summary of single hop delay performance

Queuing Discipline	Best	Medium	Worst
CB-SPQ	48%	12%	40%
CB-WFQ	52%	36%	12%
CB-DWRR	0%	52%	48%

Table 4.3: Single hop delay performance

The table shows clearly that CB-SPQ achieved the best performance for high priority classes and worst performance for the low priority classes. CB-WFQ achieved relatively medium performance for high priority classes and the best performance for the rest of priority classes. CB-DWRR failed to achieve the best performance under any priority class.

Table 4.3 shows that for the different priority classes and under varying the number of smart grid devices, CB-WFQ, CB-SPQ and CB-DWRR achieved the best performance with a percentage of 52% (13 green/25 total), 48% (12 green/25 total) and 0% (0 green/25 total) respectively. CB-WFQ, CB-SPQ and CB-DWRR also achieved the worst performance with a percentage of 12% (3 red/25 total), 40% (10 red/25 total) and 48% (12 red/25 total) respectively.

Table 4.4 depicts the delay performance of all traffic classes under the different queuing disciplines in the multiple hops topology. The difference between the queuing disciplines is more evident in the multiple hops topology. The table exhibits clearly that CB-SPQ achieved the best performance for high priority classes and worst performance for the rest of priority classes .

CB-WFQ achieved relatively the medium performance for high priority classes and the best performance for the rest of priority classes. CB-DWRR failed to achieve the best performance under and priority classes.

Table 4.5 shows that for the different priority classes and under varying number of smart grid devices, CB-WFQ, CB-SPQ and CB-DWRR achieved the best performance with a percentage of 40%, 60% and 0% respectively. CB-WFQ, CB-SPQ and CB-DWRR also achieved the worst performance with a percentage of 60%, 0% and 40% respectively.

Delay		50 SGD	150 SGD	250 SGD	350 SGD	450 SGD
CB-SPQ	Class1					
	Class2					
	Class3					
	Class4					
	Class5					
CB-WFQ	Class1					
	Class2					
	Class3					
	Class4					
	Class5					
CB-DWRR	Class1					
	Class2					
	Class3					
	Class4					
	Class5					

Table 4.4: Summary of multiple hops delay performance

Queuing Discipline	Best	Medium	Worst
CB-SPQ	40%	0%	60%
CB-WFQ	60%	40%	0%
CB-DWRR	0%	60%	40%

Table 4.5: Multiple hops delay performance

Given the above delay analysis, resource allocations and scarce bandwidth tolerance for all priority classes, it can be seen that CB-WFQ algorithms assign a weight parameter to each traffic class and distribute the available bandwidth to the classes based on the weights. On the contrary, CB-SPQ algorithms distribute the bandwidth in the order of priority; thus the traffics with higher priority are transferred earlier than the low priority traffic.

CB-WFQ ensures the fairness of resource allocation and avoids the starvation problem that arises by the absolute priority process of CB-SPQ. On the other hand, CB-SPQ maximizes the usage of resources of high priority classes by allocating its resources and avoiding the added delay of weight calculations and assignments. So, active rtPS connections can reach the maximum throughput in a lower available bandwidth than those under CB-DWRR and CB-WFQ.

However, under high priority traffic loads, CB-SPQ can create a network environment where a reduction in the QoS delivered to the rtPS is delayed until the entire network is devoted to the rtPS packets processing only.

Despite the good performance results, scalability could be an issue for the CB-WFQ. This is because CB-WFQ is originally designed to support fair allocation for variable sized packets which resulted in a high computational complexity of the algorithm. Expanding the network range for more than two hops may significantly degrade the performance of the CB-WFQ. In addition to that, for low priority traffic such as smart metering, minimizing delay to the granularity of a single packet transmission may not be worth the computational expense.

Even though CB-DWRR failed to achieve the best delay performance for any traffic class, it should be noted that CB-DWRR is usually used in a variable-sized packets networks. The assumption that all the generated packets have the same size; i.e., 1024 kByte may have obstructed the CB-DWRR algorithm to gain over the performance of the other algorithms. Furthermore, the implementation of CB-DWRR has lower computational complexity compared to the CB-WFQ, which makes it a good candidate for the multiple hops topology as well as bursty networks ;i.e., distribution domain networks .

Claim 11:

Under the given assumptions, for rtPS high priority applications, it is recommended that no more than 250 smart grid devices should be used to satisfy the latency requirement and the CB-SPQ scheduling algorithm is the best . For nrtPS and BE applications, it is recommended that no more than 150 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

4.3 The impact of WiAMX service flows on the delay performance

As mentioned in Chapter 2, smart grid applications are mapped to rtPS, nrtPS and BE service flows . Figures 4.11 - 4.13 compare the delay performance for the different service flow types under the three queuing disciplines. The CB-WFQ and CB-DWRR schedulers have a better performance for low QoS classes on the expense of the high QoS classes. Both CB-WFQ and CB-DWRR can control the performance of each class by assigning a different weight to each queue to prevent a bandwidth starvation of low QoS classes.

None of the packets experienced a delay around zero because the CB-WFQ and CB-DWRR schedulers monitor the delay boundaries of packets, as well as the MSTR and MRTR configured in the service flows parameters. If packets can tolerate the delay until the next frame arrival, the scheduler reserves the corresponding time slot to be assigned to the BE traffic to avoid its starvation; otherwise, the packets are scheduled in the current frame to provide delay bound guarantees for the connections.

CB-SPQ scheduling has the minimum delay level for rtPS traffic, as the algorithm always grants a bandwidth for rtPS first. If there is no packet in the rtPS queue and there is available bandwidth left for the smart grid device, then the bandwidth is allocated for the nrtPS service flows. If there are no packets in rtPS and nrtPS queues and there is available bandwidth left for the smart grid device, then the bandwidth is allocated to the BE service flows.

In CB-SPQ, when rtPS traffic increases significantly by the increase in the load submission, there will be no resource left for nrtPS and BE flows. Therefore, no packets from the nrtPS or BE will be served, and their throughputs will be dropped to zero. As a result, nrtPS and BE flows may starve under high rtPS traffic.

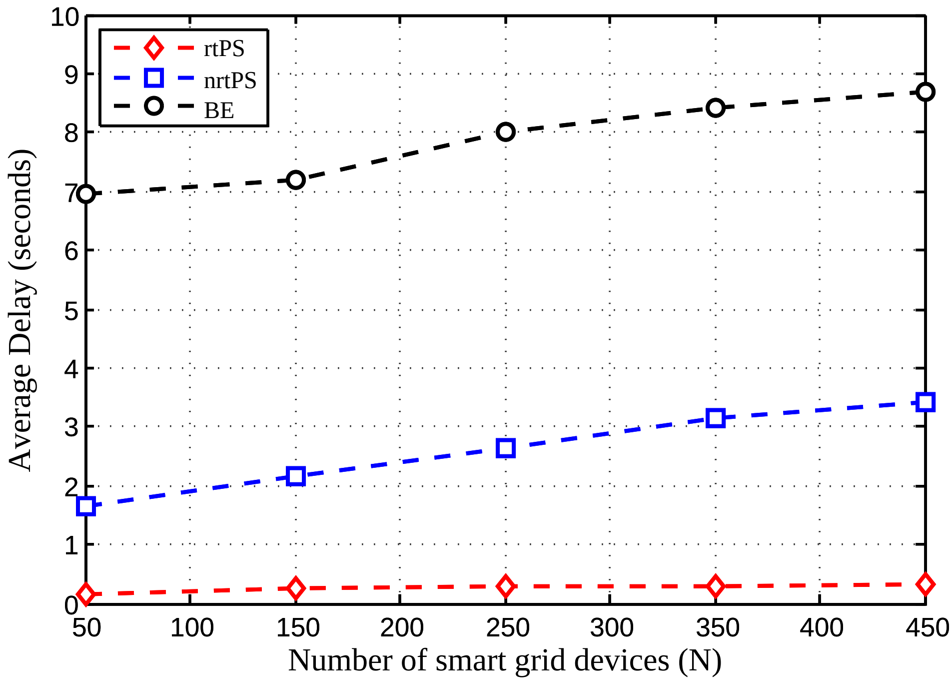

Figure 4.11: End-to-End delay of different traffic types under CB-WFQ

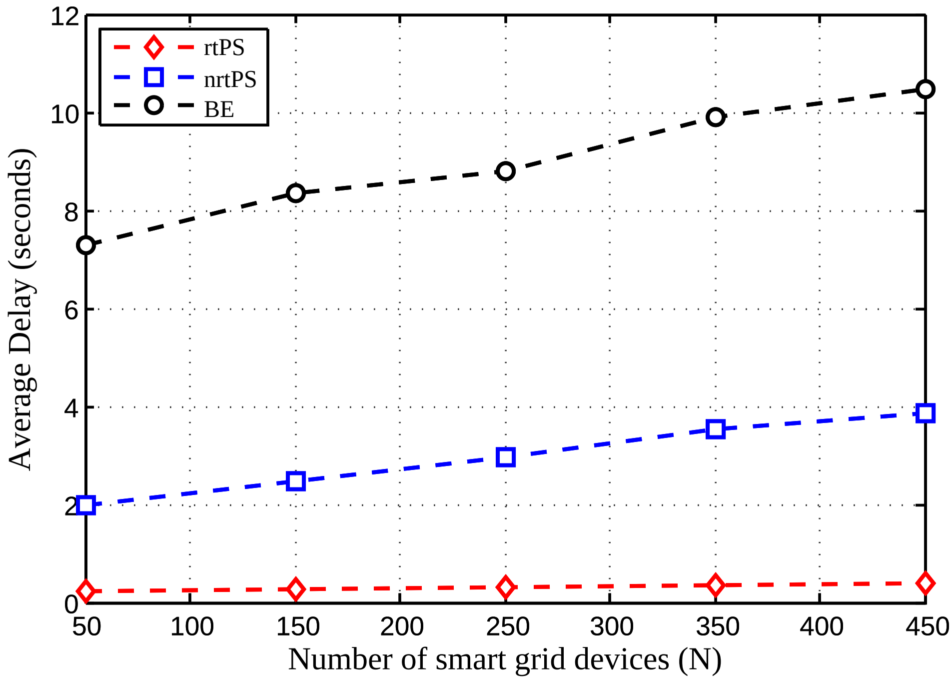

Figure 4.12: End-to-End delay of different traffic types under CB-DWRRQ

4.4 The impact of DSCP on the delay performance

Figures 4.14- 4.15 display the effect of having another level of QoS, i.e. differentiated service code point, on the delay performance of the smart grid applications.

Figure 4.14 demonstrates the variation in the average delay of the substation automation, distribution automation, outage management and distributed energy resources and storage applications. Substation automation and distribution automation are mapped to the same service flow i.e. rtPS and have an equal inter-arrival time (1 second).

However, the substation automation traffic accomplished with lower average delay value. This is due to the fact that the DSCP for the substation automation is equal to 67 while the DSCP for the distribution automation is equal to 33. The DSCP code provided an inter-class QoS assurance for the same service flow class.

Outage management and distributed energy resources and storage applications are mapped to the same service flow i.e. rtPS have an equal inter-arrival time (5 minutes).

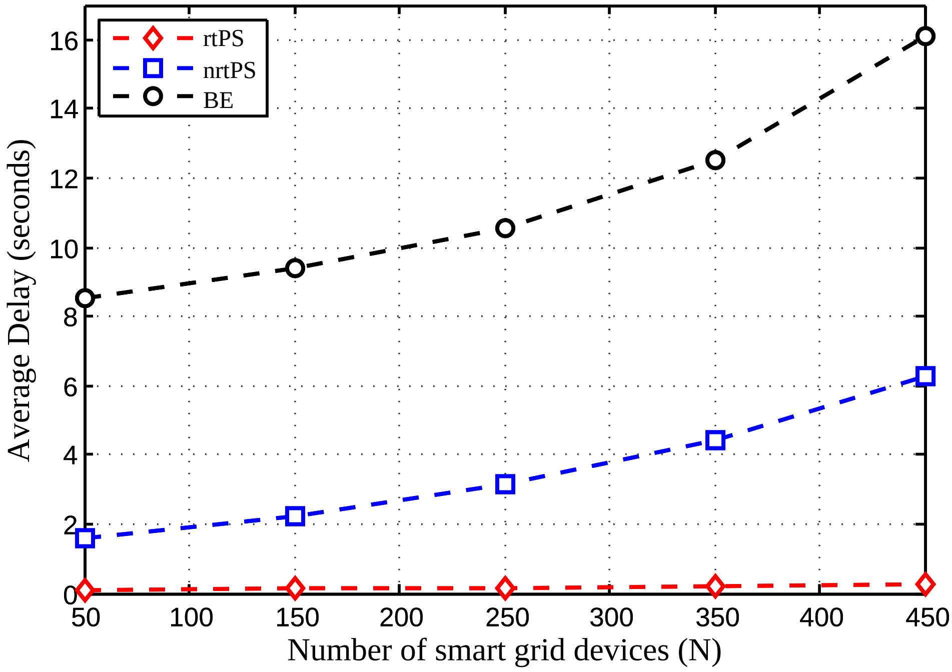

Figure 4.13: Average End-to-End delay of different traffic types under CB-SPQ

However, the outage management application has a higher DSCP value (DSCP =43) than the distributed energy resources and storage (DSCP =44). Therefore, outage management traffic has lower delays values.

Figure 4.15 exposes the variation in the average delay of the demand response and demand side management applications. The two applications are mapped to the same service flow i.e. nrtPS and have an equal inter-arrival time (30 minutes). The two applications also have the same DSCP value (DSCP =11). The Figure indicates a minor variation in the delay of the two applications.

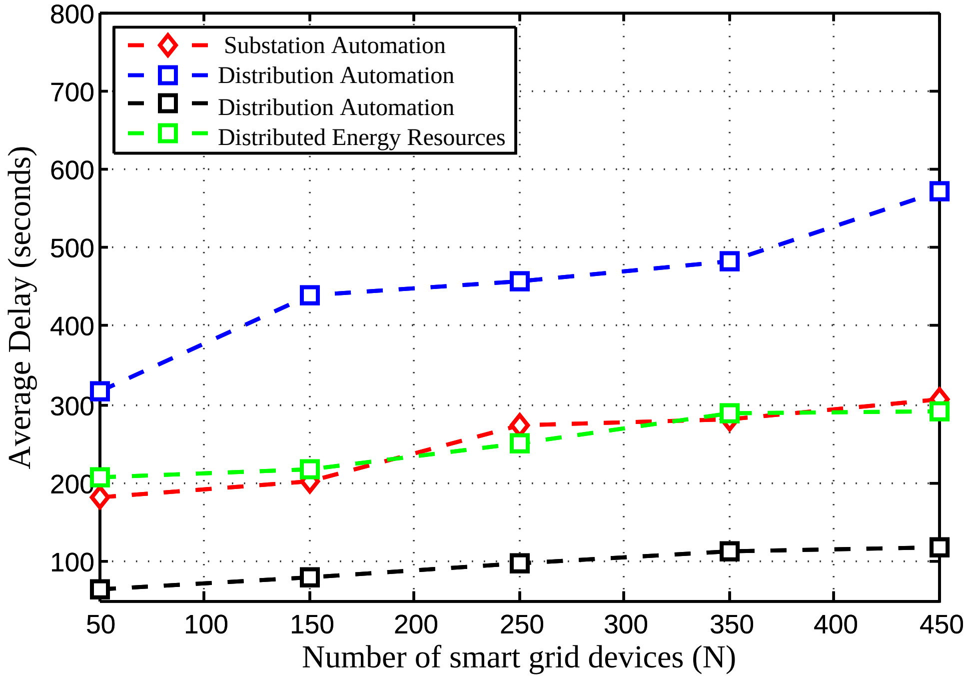

Figure 4.14: End-to-End delay of rtPS connections with different DSCP under CB-WFQ

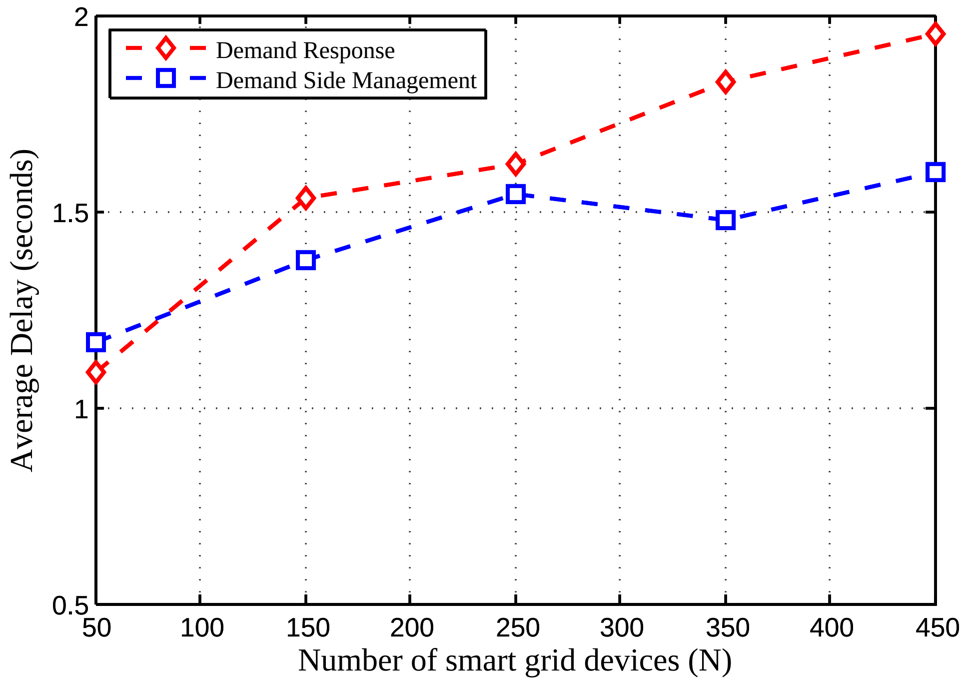

Figure 4.15: End-to-End delay of nrtPS connections with the same DSCP under CB-WFQ

The results presented in this chapter are in line with the results presented in [54], [78] and [55]. In [54] , a simulation model for the metering application was conducted based WiMAX Network Architecture. The authors categorized the smart meter readings to be non-real-time Polling Service (nrtPS) over 2KM and 5KM WiMAX radius cells. The blue line in Figure 4.16 shows the delay values presented in [54]. The average delay is between 2.5 -2.6 seconds. The red dashed line in Figure 4.16 shows the average delay of smart metering application presented in this study.

Figure 4.16: Average delay in seconds vs. Number of users for the smart meter application [54]

In [78], a simulation model for the Distribution Area Network (DAN) is implemented. The DAN integrates the AMIs payload from the consumer area. Different smart grid applications have been considered in the simulation; i.e. substation automation, PHEV, video surveillance voice, and metering data. The average delay for different traffic is shown in Figure 4.17. Applications experienced different average delays from less than 50 milliseconds to more than 400 milliseconds.

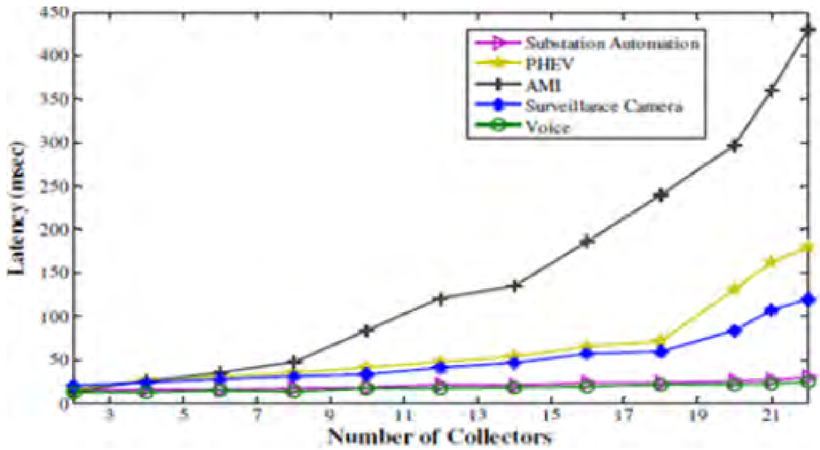

Figure 4.17: Average delay in seconds vs. Number of collectors for the smart grid applications [78]

In [55], the authors studied the performance of a WiMAX smart grid last mile network. The network serves the customers Energy Services Interfaces. The trafc model included alarm commands, network joining, metering data, pricing signals, telemetry signals, ESI information reports, information broadcast and firmware updates. As shown in Figure 4.18, applications experienced different average delays from less than 200 milliseconds to more than 1000 milliseconds.

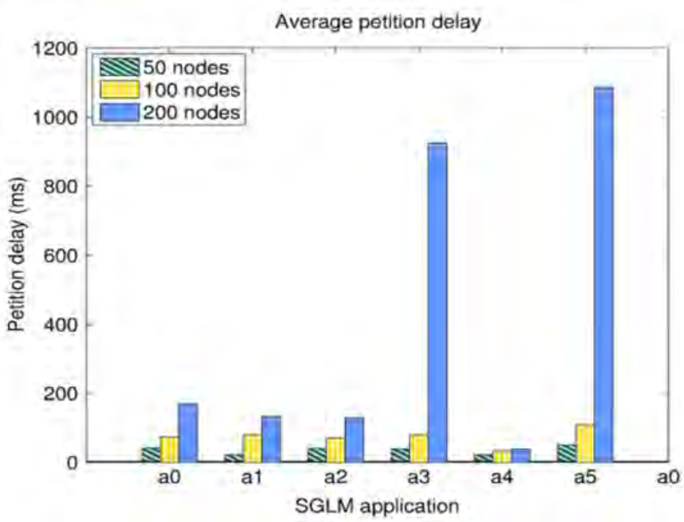

Figure 4.18: Average delay experienced by smart grid last mile network applications in the WiMAX scenario. [55]

Chapter 5

Conclusion and Future Work

The smart grid model seeks to enhance the current energy and power management systems in terms of efficiency, reliability, economics and environment. A two-way communication network will be an indispensable component for developing the smart grid. Many research efforts are still required before the communication infrastructure can be developed and implemented for intelligent energy and power management. The selection of a suitable communication media is essential in smart grid design as it has a direct consequence on the speed, reliability, latency and coverage area to achieve a stable monitoring and control system.

This research has been carried out to design and simulate the IEEE802.16 WiMAX single hop and multiple hops deployment models to serve as a wireless communication infrastructure for the smart grid. Based on the bandwidth, latency and service flow of the AMR and AMI+ smart grid applications and communication requirements, the traffic was classified into five priority classes. Three priority queuing algorithms namely; weighted fair, deficit weighted round-robin, and strict priority queuing. The scheduling algorithms were used to simulate the proposed single and multiple hops network architectures to find the a deployment solution that satisfies the QoS requirements of the smart grid applications.

Each proposed model maps the smart grid applications with the WiMAX MAC service flow types and the differentiated service code point. The simulation results demonstrated that different DSCP values and service flow types affect the delay of the network. It was found that no more than 450 smart grid devices should be used to satisfy the delay requirement of class (1) and class (2); and the CB-SPQ scheduling algorithm is the best in the single hop topology. As for class (3) applications, results showed that in order to satisfy the latency requirements, the maximum number of smart grid devices that can be placed in a cell should not be more than 250, and CB-WFQ scheduling algorithm is the best. Results also showed that for class (4) applications, a cell could accommodate up to 450 smart grid devices and the CB-WFQ scheduling algorithm is the best.

In multiple hops topology, for class (1) applications, no more than 450 smart grid devices should be used to satisfy the latency requirement. For class (2) applications, a maximum of 250 smart grid devices could be placed in one cell in order to satisfy the latency requirement. For both classes and under the recommended number of smart grid devices, it was found that the CB-SPQ scheduling algorithm is the best for the satisfactory performance. For class (3) and class (4) applications, a cell can accommodate a maximum of 150 smart grid devices and the CB-WFQ scheduling algorithm is the best.

For class (5) applications, no more than 450 smart grid devices should be used to satisfy the latency requirement and the CB-WFQ scheduling algorithm is the best.

Possible future research directions include:

- Investigating the performance of other scheduling algorithms such as the earliest deadline first (EDF), or other hybrid implementations such as the earliest deadline first round robin (EDFRR).

- Other smart grid applications can be included such as video surveillance, and voice data.

- Virtual Private Network (VPN) implementations between the customers premises and the utility control and dispatch center can be investigated.

- Investigating the performance of hybrid wireless and power line network architecture for the smart grid applications.

- Investigating other performance metrics such as the loss rate, the utilization and the throughput.

- Expanding the range of the network for more than two hops.

- Investigating the performance of centralized vs. distributed scheduling of traffic.

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Vita

Ban Abdul Elah Al-Omar was born on October 24^{th}, 1981, in Syria, and moved to the United Arab Emirates (UAE) in 1983. After completing her high school in 1999, she joined the Computer Engineering program at Sharjah University. In 2004, she completed a Bachelor degree of Computer Engineering. In 2010, Ms. Ban began the master program in Computer Engineering at the American University of Sharjah.