Wireless Communication Network Architecture for the Smart Grid applications

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I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

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ABSTRACT

Smart grid is a novel initiative in the power electric distribution network that aims to provide an intelligent, self-healing and self-aware grid. The smart grid is divided into four major technological fields: telecommunications, power engineering, control and information technology. The role of communications in the smart grid is to provide adequate transmission capacity to exchange information between all the devices in the grid, supporting their operational and functional needs. Requirements of a communication network in electricity grids are not necessarily limited by the transmission capacity but also by the connectivity requirements to all the devices deployed in the network. Wireless communications, in particular the Worldwide Interoperability for Microwave Access (WiMAX), is seen as a well-recognized technology able to fulfil the requirements of smart grid's applications. The WiMAX provides wide area connectivity and the quality of service (QoS) differentiated services; the two most important issues for the communication requirements in the smart grid.

This research investigates the performance of a WiMAX-based network architecture used to support the communications needs of the smart grid applications. It proposes communications network architecture, presents the simulation model and performance results using OPNET simulation models. Simulation results are compared with analytical calculations of path loss, network capacity, and delay constrains for multiple smart grid applications, such as smart metering, consumer demand control and emergency sensor messaging.

The simulation results demonstrate that the WiMAX network could be used as an efficient and reliable communication network for the smart grid applications fulfilling the coverage needs and application QoS constrains. A communication network architecture was finally proposed by providing appropriate network configurations and inclusion of necessary algorithms in the WiMAX standard to support the different needs of the smart grid.

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AC	Alternating current
ACK	Acknowledge
AMC	Adaptive Modulation and Coding
AMI	Automatic Metering Infrastructure
AMR	Automatic Meter Reading
API	Application Programming Interface
ARQ	Automatic Repeat Request
BAN	Business Area Network
BE	Best Effort
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
BWReq	Bandwidth request
CBS	Capacitor Bank Controller
CDMA	Code Division Multiple Access
CDRR	Customized Deficit Round Robin
CID	Connection Identifier
CINR	Carrier to Interference Noise Ratio
CIS	Customer Information System
CRC	Cyclic Redundancy Check
DA	Distributed Automation
DAC	Distributed Application Controller
DCC	Data Control Centre
DCD	Downlink Channel Descriptor
DERs	Distributed Electric Resources
DG	Distributed Generators
DHCP	Dynamic Host Configuration Protocol
DL	Down Link
DLC	Direct Load Control
DMS	Demand Management System
DRA	Dynamic Resource Allocation
DRR	Deficit Round Robin

DRRF	Deficit Round Robin Fragmentation
DSA	Dynamic Service Addition
DSC	Dynamic Service Change
DSCADA	Distributed SCADA
DSD	Dynamic Service Deletion
DSEM	Demand Side Energy Management
DSM	Demand Side Management
EAN	Extended Area Network
EDF	Early Deadline First
EIRxP	Equivalent Isotropic Received Power
EMS	Energy Management System
EPRT	Expected Packet Rate Time
EPS	Electric Power System
ertPS	Extended Real-Time Polling Service
ESI	Energy Services Interface
EUMD	End User Measurement Device
EVSE	Electric Vehicle Service Element
FAN	Field Area Networks
FCH	Frame Control Header
FFT	Fast Furrier Transform
FiFo	First-In First-Out
FTP	File Transfer Protocol
FUSC	Full Usage Sub-Channel
GIS	Geographic Information System
GLL	Geographic Latitude and Longitude
GMSH	Grant Manager Sub-Header
GPS	Global Position System
GSM	Global System for Mobile Communications
HAN	Home Area Network
HARQ	Hybrid Automatic Repeat Request
HCS	Header Check Sequence
HVAC	Heating, Ventilating, and Air Conditioning
HVDC	High Voltage Direct Current
IAN	Industrial Area Network
ICT	Information and Communication Technologies
IE	Information Element
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and electronics Engineers
IHD	In Home Device
IP	Internet Protocol
IPT	Inter-Polling Time
ISO	Independent System Operator
ISO	International Standard Organization
IT	Information Technology

LAN	Local Area Networks
LDC	Load Control Device
LMS	Load Management System
LoS	Line-of-Sight
LTE	Long Term Evolution
LWDF	Light Weight Deadline First
M2M	Machine to Machine
MAC	Media Access Controller
MAN	Metropolitan Area Network
MCS	Modulation and Coding Scheme
MDM	Master Data Management
MDRR	Modified Deficit Round Robin
ML	Maximum Latency
MPLS	Multiprotocol Label Switching
MRTR	Minimum Reserved Traffic Rate
MSTR	Maximum Sustainable Traffic Rate
MTU	Maximum Traffic Unit
NAN	Neighbourhood Area Network
NIST	National Institute of Standards and Technology
NLOS	Non-Line of Sight
nrtPS	Non-Real-Time Polling Service
ODW	Open Desktop Workstation
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
PDF	Probability Density Function
PLC	Power Line Communication
PM	Poll-Me
PMP	Point To Multipoint
PQ	Priority Queuing
PS	Polling Services
PUSC	Partial Usage Sub-Channel
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RFC	Request For Comments
RNG-Req	Ranging Request
RNG-Rsp	Ranging Response
RR	Round Robin
RSSI	Received Signal Strength Indicator
RTG	Receive-to-transmit Time Gap
RTO	Regional Transmission Operator
rtPS	Real-Time Polling Service
RTU	Remote Terminal Unit
SC	Single Carrier
SCADA	Supervisory Control And Data Acquisition

SDU	Service Data Unit
SF	Service Flow
SFID	Service Flow Identifier
SG	Smart Grid
SINR	Signal to Interference Noise Ratio
SM	Smart Metter
SNR	Signal to Noise Ratio
SS	Subscriber Station
TCP	Transport Control Protocol
TDD	Time Division Duplexing
ToS	Type of Service
TTG	Transmit-to-receive Time Gap
UDC	Uplink Channel Descriptor
UDP	User Datagram Protocol
UF-DRR	Uniformly Fair Deficit Round Robin
UGI	Unsolicited Grant Interval
UGS	Unsolicited Grant Service
UL	Up Link
UMTS	Universal Mobile Telecommunications System
UPI	Unsolicited Polling Interval
UTC	Universal Time Coordinated
VCR	Voltage Regulator Controller
VPN	Virtual Private Networks
WAN	Wide Area Networks
WBN	Wireless Broadband Networks
WFQ	Weight Fair Queuing
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WN	Wireless Network
WRR	Weight Round Robin

CHAPTER 1.

INTRODUCTION

1.1. COMMUNICATION NETWORKS IN ELECTRIC GRIDS

The evolution of electric distribution networks during the past century has introduced several challenges to the power grid in order to support reliable delivery of electricity in different deployment scenarios. The efficiency of an electricity grid can be enhanced by providing effective and timely management of generation and consumption processes. Control algorithms are implemented in different segments of the electricity network to maintain adequate service quality of the electricity delivery system. These algorithms need on-time information about the state of the diverse devices distributed across the energy network. To deliver energy in an efficient manner communication networks should be introduced to offer information path to all control devices that transmits all the necessary messages within the electricity grid.

Various domains of the electric network would need different kinds of communication systems according to the information exchange requirements in each domain. Examples of communication networks are; Ethernet standard in the Generation domain, Fiber Optics based high speed networks in the transmission domain, Power Line Communications (PLC) and wireless communications in the distribution domain and short range wireless communications in the customer domain. Wireless communication networks are able to support QoS requirements of different service classes which are needed to transport the vast majority of traffic from diverse applications. Two wireless network technologies are studied to support smart grid traffic, namely the Long Term Evolution (LTE) and the Worldwide Interoperability for Microwave Access (WiMAX)[1, 2] standard. Researchers are currently investigating and evaluating different wide area networking technologies including the LTE and the WiMAX standards for smart grid applications. The main characteristic of the WiMAX wide area network is based on the Orthogonal Frequency Division Multiple Access (OFDMA) which uses the adaptive modulation codes (AMC) technique to support various applications QoS for the smart grid.

Finally, new technologies recently included in the energy network for example the distributed energy generators such as solar electricity systems in residential and industrial premises, the electric vehicles and the capacity for customer to control their energy consumption, etc., requires communication network in the consumer premises. The communication network from the customer premises will be able to send local energy information to the energy service provider by supplying the server with various applications requirements and their service QoS. The energy providers can use that information to supply appropriate amount of energy in a sustainable manner to improve the electric grid efficiency and to reduce the carbon footprint.

1.2. RESEARCH MOTIVATION AND CONTRIBUTIONS

As discussed above, the smart grid introduces new challenges to the energy distribution companies. This research work investigates the communication requirements of the smart grid to develop some feasible solutions of the communication problems which will be experienced by future energy industry. One of the important issues with the new energy demand management system is the collection of consumption information from user equipment in a timely and reliable manner. Moreover, the increasing penetration of distributed generators at the consumer premises requires appropriate support of demand management system to stabilise the total energy distribution system.

Wireless communications standard such as WiMAX has been recommended to support the communication needs of the consumer premises, in particular the Smart Meter connections. In this case, the large number of smart meters in neighbourhoods and the small volume of traffic from each smart meter presents a challenge to this network due its initial design which is to sever in a typical wireless broadband configuration, where the network is used by a relatively small numbers of users with large volume of traffic on each connection. This difference has created the need for new packet schedulers, power control methods and resource allocation algorithms that could maintain the applications QoS while maintaining reasonable network throughput.

To satisfy above requirements, the main aim of this research is to design appropriate wireless network architecture to satisfy the communication needs of the smart grid applications. This wireless network is needed to provide seamless connectivity and the QoS assurance capabilities. Worldwide Interoperability for Microwave Access (WiMAX) is a versatile wide area wireless network, standard which has been chosen to support smart grid applications. It offers long-range communication channels and QoS support for diverse applications.

The main contribution of this work is the study of the WiMAX network standard for the smart grids applications and to develop communication architecture and application models for different smart grid devices using diverse QoS requirements. These contributions include the analysis of path loss models for the WiMAX network and the power control algorithms for the physical layer using the OFDMA technique. Also, it includes the usage of polling techniques a resource allocation method for applications with diverse QoS requirements. Finally, this work contributes with the mapping of smart grid applications and QoS parameters used in the WiMAX standard.

1.3. OUTLINE OF THE THESIS DOCUMENT

The document concentrates on the smart grid wireless communication network design based on the WiMAX standard. Chapter 2 introduces the concept of the smart grid in relation with the energy distribution network. It defines the energy network using a seven domains model that includes the generation, transmission, distribution, consumption, operators, markets and service provider’s domains. Each of these domains is described and related with the reference models of the National Institute of Standards and Technology (NIST)[3] and the IEEE P2030[4], which defines the smart grid as a three-system model with information technologies, communication and power as the main ones. Then this chapter focuses on the view of the reference models to develop a wireless communication network to access the consumer and distribution domains. It finalises with the study of three specific applications used in this project named, smart meter reading, demand side management and sensor reading. These applications are defined according to the smart grid reference model recommendations and the wireless network definitions.

Chapter 3 reviews the relevant aspects of the WiMAX network standard pertinent to the communication of information in the smart grid architecture, for different applications. The chapter starts describing the services provided by the WiMAX network in smart grids including the long-range connectivity, the network capacity and the QoS support. Then the chapter continues with the physical layer aspects of the WiMAX standard including the power control mechanisms, adaptive modulation and coding schemes followed by a description of the WiMAX OFDMA frame structure. Finally, the chapter analyse the MAC layer procedures implicated in the creation, configuration of data connections and it support mechanisms to the

QoS requirements. It includes service flow creation, bandwidth request process, scheduling algorithms and allocation of network resources.

Chapter 4 presents an initial smart grid communication model using a simple metering application, which through diverse experiments and analysis is further developed to offer better QoS for smart metering applications. First, an analysis of the user distribution is performed in order to provide an understanding of the effect of wireless channel characteristics, including the power transmission, receivers' sensitivity, and power control methods for the smart metering applications. Then, a simulation model is used to study the system. The simulation results are used to understand the implication of various applications QoS issues on the network performance. Next, the chapter analyse the polling technique used in the WiMAX network model to support smart grid meter application. Finally, the simulation results of packet losses are investigated to find the causes of these losses and reconfigure the network parameters to fulfil the desired QoS requirements.

Chapter 5 introduces the concept of diverse smart grid applications running on the same network and investigate how those applications affect the network performance. It starts introducing the demand management system (DMS) architecture and describes in detail the applications used in this model, which includes meter reading, demand management and sensor data communication. Then the chapter presents the distribution model for the applications running on these devices. It continues with the study of the QoS requirements for diverse service classes in the designed model. The chapter also present an enhanced version of the initial model presented in chapter 4. The enhanced model includes the meter reading data and the demand control applications running on the same WiMAX network using different QoS parameters to satisfy applications requirements. Finally, the chapter introduces the impact of the sensor data application and presents the results of simulations performed using above applications. The model also analyses the sensor network communication requirement and presents simulation results for these ones.

Finally, chapter 6 presents the conclusion of this research and the suggestions for future work related with smart grid wireless communication architecture based in WiMAX.

1.4. PUBLICATIONS

As a result of this research, a conference paper exploring the scheduling algorithms for short burst communication in WiMAX was published in the IEEE LATINCOM Conference[5] as presented in the next reference. Later a second conference paper describing specific results about the meter reading applications using polling services was published in IEEE COLCOM 2012.[6]

- Castellanos, G.D.; Khan, J.Y.; , "Performance of WiMAX packet schedulers for multi-class traffic," *Communications (LATINCOM), 2010 IEEE Latin-American Conference on* , vol., no., pp.1-6, 15-17 Sept. 2010

- Castellanos, G.D.; Khan, J.Y.; , "Performance analysis of WiMAX polling service for smart grid meter reading applications," *Communications Conference (COLCOM), 2012 IEEE Colombian* , vol., no., pp.1-6, 16-18 May 2012

CHAPTER 2.

SMART GRID

Smart grid is a new concept that will support development of advanced electricity distribution network architecture, which is the focus of researchers, industries and governments in last few years. The smart grid, also known as the intelligent grid, is presented as an evolutionary process towards the development of the power distribution grid into an intelligent and self-healing architecture that could fulfil the requirements of future electricity distribution networks. Smart grids systems are considered as a multidisciplinary technology where the control mechanisms, communication networks and information technology elements are mapped on the top of an electricity distribution network, in order to provide good balance between energy generation and consumption in a reliable, efficient, economical and environmental friendly manner[7, 8].

A communication network is overlaid on the energy distribution network, which should offer adequate transmission capacity to exchange information across all the devices in the electric distribution network, supporting fast responsive control mechanisms that maintain normal operation of the electric distribution network. However, in the current electricity grids, the communication networks deployed are not widely spread across the entire energy network. Some of the devices across the network have unsatisfactory access to communication channels or simply no communication is used at all. In response to that, a communication architecture that provides full connectivity to all the devices across the network fulfilling all the information traffic needs to be developed[9].

In the following section, a brief introduction of the smart grid architecture is presented. It introduces the relationship of future energy networks with control, communication and information technology solutions and explains how these technologies could increase the operational performance of a smart grid network. Then, the needs and challenges of a smart grid are presented by focussing on a telecommunication network based solutions. After that, the proposed smart grid models including the National Institute of Standards and Technology (NIST) and Institute of Electrical and Electronics Engineers (IEEE) IEEE P2030 architecture are explored from the point of view of the telecommunication network architecture and smart grid applications. Next, a review of several communication technologies that can be used in smart grids is presented. Finally, the role of a wireless network based on the WiMAX standard is introduced. The WiMAX network could be used in a smart grid environment to serve large number of smart meters as well as other devices and sensors distributed throughout an electricity network. Hence, it can be seen that the WiMAX network based smart grid communication system could be used in future electricity networks.

2.1. INTRODUCTION TO SMART GRID

2.1.1. WHAT IS A SMART GRID?

The smart Grid is a modern conceptual architecture that will transform the power grids delivering electricity in a more efficient, reliable and environmental sustainable way. The contemporary power grids are described as a one-way energy delivery system where feedback information from final entities is almost none. Energy consumption information is measured in non-real-time methods or over a longer duration, so there is no real knowledge of energy consumption in a finer details level. The load information in current systems is available, but these measurements are very coarse. Power usage over a large area is available at any time; however, lack of fine details of the energy usage makes it difficult to accurately predict the load. Moreover, most of the current control mechanisms used in electricity grids are electromechanical in nature having slow response times that could lead to massive blackouts in case of overload. Consequently, the smart grid technologies are currently investigated to solve some of the problems of electricity networks in order to improve its efficiency, quality, and reliability. New system architecture will offer flexibilities to electricity consumers and support distributed power generation from renewable energy resources.

Initially, it is important to describe the electricity network structure and energy delivery process to consumers. A model to explain this process is divided in four major domains namely, generation, transmission, distribution and consumption. The present model has evolved very little during past hundred years. The current model is seen as a one-way energy deliver process where demand management system (DMS) is very basic in nature and provides a very little feedback information to the centralized controller.

In the generation domain, commonly known as the generation nodes includes electricity generating sources such as hydrological resources, thermal generators including coal, gas, geothermal or nuclear resources, and the new renewables like solar photovoltaic panels and wind turbines, micro-turbines etc. Originally, the energy was generated in central power plants and the energy was sent to diverse consumers from the generated plant which is referred as a 'centralized generation model'. The evolution of technologies in power generation created the needs of locating the power plants in different areas creating a 'decentralized architecture', which requires an efficient transmission network to support a large distribution area. This model is used in most of the countries where numerous power plants feed energy to a distribution networks. However, this scenario has been known to introduce the so called 'domino effect' that could lead to massive blackouts; taking out of service of many power plants and millions of users from the grid [10, 11]. As an answer to this problem, a new model is being developed for future power grids using distributed network architecture. This architecture is supported by the inclusion of smaller power generators from renewable resources in or near to the customers' premises. The introduction of distributed generators (DG) will help to avoid the 'domino effect' using the islanding capabilities to the network. Islanding refers to a segment network that has unexpected behaviour leading to an outage, in case of an outage the island disconnect itself from the network creating a micro energy grid island expecting to be able to serve localized users[9].

The transmission domain, usually known as the bulk power transmission or the high voltage electric transmission system includes an 110kV or higher voltage lines. It connects the power generators with substations in the distribution sites inside cities, urban and industrial areas. In order to avoid power losses, transmission lines conduct energy using high voltage lines across long distances in the order of hundreds of kilometres. There are three ways of connecting those transmission lines; overhead, underground and submarine. Current days, the vast majority of the systems use the overhead lines. In addition, three-phase AC is widely used; however, single-phase AC lines can be used for railway electrification and high voltage direct current (HVDC) for very long distance or interconnection among asynchronous grids. The uninsulated nature of the overhead high voltage power lines, create the risk of outages if the three-phase lines get close enough to generate electric arcs resulting in loss of power supply [12]. These assets are considered usually as passive but have grand importance in the energy network because their elevated voltage and high power transmission capacity leading to a high level of reliability and resilience.

The distribution domain is becoming an important part of an electricity infrastructure because the ability to connect millions of consumers to a power network is a difficult task.

Typically, it uses medium and low voltage power lines, electrical substations and pole-mounted transformers. There are two main ways to connect distribution systems, namely: radial and interconnected. Radial distribution system are used for rural and suburban areas where just one transmission power line delivers the power to a central substation that reduces the voltage and distribute electricity to final distant customers. Meanwhile, interconnected distribution systems are common in urban areas where several substations are connected in a grid mode, creating redundant electricity paths in order to increase the reliability of the network. This part of the network has becoming more complex since the introduction of distributed generators in the household premises. This characteristic has transformed the distribution network from a unidirectional flow to a bidirectional flow of energy from users to substations, requiring power flow controllers.

The transmission and distribution domains used could be the property of the same company. However, the evolution of the energy market has created a division, where transmission infrastructure belong to a company and the distribution infrastructure belong to a different one, allowing competition between companies thus reducing the price of energy and avoiding monopoly in the power supply market [13].

The consumers' domain is one of the important components of the whole network, because it is driven by the necessities of daily users and its demand diversity is growing exponentially as the technologies of homes and range of appliances are expanding. The majority of the infrastructure inside the consumer domain belongs to the residential and industrial users, different from the other three domains where infrastructure belongs to companies. This makes this domain very different because the implementation of some technologies is driven by the users believes and needs, making every household or premises different thus creating a very diverse domain. The four domains; generation, transmission distribution and consumers, are depicted in Figure 1 where energy generation is the first step in the electrical energy flow process, continuing with transmission and distribution domains to deliver energy to customers.

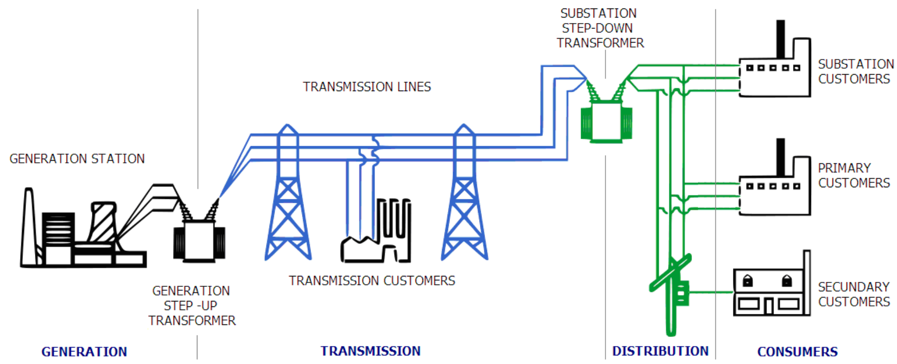

Figure 1. Domains of the traditional energy network.

Most of the energy delivery networks forms a national or regional grid by connecting number of cities, towns and locations, which may contain millions of consumers. A network of this size could include millions of devices that need to be controlled in perfect harmony to maintain reliable electricity delivery. Hence, some sort of control mechanism that needs to be implemented over the network, in order to maintain uninterrupted flow of energy. The level of control depends on the domain design; with each domain having specific requirements. Control algorithms are widely used in the generation domain because the importance of the process of generation. The actual generation process generates only the energy that the network is consuming, it means that no energy is stored; instead, it is sold to other networks where energy is used or needed in high demand. New generation plants based on renewable energy are weather-dependent and generation could not be controlled in the same way as done in conventional plants. New control algorithms need to be created in the new power grids in order to manage the generation, distribution and demand control processes.

These control algorithms need to have real-time information from the entire network and process them in a timely manner to manage the electricity grid. Information should arrive on time to the control equipment to take the proper decisions on time to avoid failures in the delivery process.

In an electric network, a control system is overlaid on the electricity grid to make it a functional grid. A basic control system could be divided in four important blocks: i) the sensor system, ii) the plant and distribution system, iii) the communication or feedback loop and iv) the control block. Figure 2 illustrates the blocks of a closed-loop control plant. In this case, the plant block is consider as the evolving electric grid and need to be controlled [14]. Legacy electric networks works based on an open control loop where no information from final users is generally taken into account in the control process. In fact, no information from customers is available in real time to be able to be used in the control process. The evolution of the electric network will transform the electric network (the plant) in a more dynamic system requiring real time control, where information from the final user needs to be transmitted to the control mechanisms in real time. As is shown in the Figure 2, the communication technologies are used to support the feedback loop of information flow.

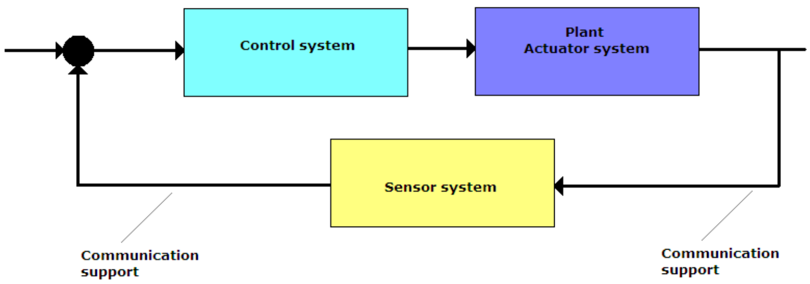

Figure 2. An electric grid model using a feedback loop using sensor data.

The communication support is needed to collect information in real time from the users about their consumptions and demands; from the distribution equipment and their power information; from the status of the transmission lines; from the generation plants and from others external sources like weather agencies. Information from a range of services is sent to the control servers for processing. On the reverse direction, control messages are transmitted to customers, distribution and transmission equipment as well as to power generation sites. The quality of the communication links depends on the nature of information that is transported, involving some levels of QoS that need to be assured.

As discussed above, the smart grid can be seen as an integrated control and communication system overlaid on top of the electricity network, in order to fulfil the challenges and needs imposed by the future electric network and the new generating sources such as renewable generations.

2.1.2. *WHY ARE THE SMART GRID NEEDED?*

The need of a smart grid resides in the answer of 'what happened if we don't do anything?'. It is a fact that demand of electricity has increased in the past decades driven by grow in population and the introduction of new home and office appliances among other electricity consumption equipment. In U.S. this increase is almost 25% per year since 1982 [15].

The risk of not implementing modern control infrastructures for an electric grid where demand is constantly increasing, could lead to massive blackouts that could affect millions of consumers. Massive blackouts affect the countries' economies, bringing losses of order of thousands of millions of dollars per hour during an outage. For example, the northeast U.S. blackout of 2003 resulted in USD $6 billion losses for the region. Analysis performed to the three massive black outs in the U.S. in the past ten years, conclude that those were caused mainly by a lack of on time ‘situation awareness’. That means that the network operators did not know the real time status of the network, while the energy demand increases leaving controllers without the proper information to act accordingly. In addition, the electromechanical actuators are too slows to react on time to the excess of energy demand [15].

On the other hand, power demand needs to be controlled from the consumption side. In specific, customers’ premises have to be more efficient in order to maintain the balance between generation and consumption. The actual electric network capacity is designed to supply power in peak hours, but the reality is that the consumption profile has peak hours just between 6 am and 8 pm, the rest of the time consumption is under the average capacity. If utilities want to use their grid more wisely, the consumers should be encouraged to use some house appliances, like the washing machine or the dishwasher, in off peak hours. This problem could not be solved with the actual networks having no real time information of the consumption. Without real-time system information, no control over the household electricity usage could be made.

Finally, introduction of green technologies and reduction of the carbon footprint could be hard to achieve if no modern controllers are implemented. Green distributed energy generators (DG) will need to send generation information frequently to the central controller so that the controller can implement an adaptive demand management system using the real time information.

Finally, to improve the efficiency of electricity generation and distribution system by incorporating variety of energy generators it is necessary to develop a smart grid architecture, which will deliver energy to users in a fail-safe manner.

2.1.3. NEEDS AND CHALLENGES FOR FUTURE ELECTRICITY GRIDS

Smart grids present a series of requirements and challenges that have to be satisfied to achieve a good network performance. In literature, many definitions of the smart grid exist. Beidou *et al*, describe the challenges of a power network based on the functions of the smart grid, namely; self-healing capabilities, renewable energy integration, usage of energy storage systems, reliability, power quality and motivation to customer for an intelligent consumption. The self-healing systems are preferred, which can take actions when a contingency occurs, gains importance and raise the necessity of a controller application in every device of the network supported by a consistent communication infrastructure. Moreover, the introduction of renewable energy solutions, like wind turbines and solar panels, changes the energy deliver model. These models are; the *demand model*, where energy is generated based on the consumers demands, and the *climate model*, where energy is generated according to weather conditions. The smart grid requirements could be described in terms of connectivity, effectiveness, efficiency, QoS and cyber security [7].

A proper management of the increasing electricity demand is one of the challenges that a smart grid need to face. As mentioned before, that increasing demand of electricity could create problems that may lead to massive blackouts. The power grid infrastructure should support a smooth and progressive integration with new and diverse energy sources, taking into account the safety and reliability of the network itself. Gungor *et al*, describe some of these challenges for the electric power distribution network and support their research based on the need of reliable information as a key factor to an optimal network performance [16].

The smart grid, as a communication solution, faces a series of challenges. Some of these challenges include the development of communication protocols, which are able to interoperate with the existing ones across different domains. Next, the identification and classification of telecommunication technologies those could serve inside every domain of a smart grid network in best possible ways. Third, define the security protocol inter and intra domains to maintain the privacy of customers. Parikh *et al* in [17], present these challenges for the communications in smart grids.

The requirements of end-to-end communications are very important for the smart grid. One of the principal characteristics of a communication network is the need of QoS segregation for different applications of a smart grid. The first requirement is high reliability and availability of the network where all the nodes could be reached within a specific delay, this is very important issue when a wireless network is used. Second, automatic management of redundancies is needed if a connection is not available, where a desired device needs to find the path to connect. Third, high coverage area and longer transmission ranges are important to cover in an electricity transmission grid. Fourth, large number of communication nodes needs to be supported due the fact that substations as well as millions of meters and sensors need to be connected to the network. Fifth, the appropriate communication delay and system responsiveness is very important to support QoS management between low priority and high priority traffic sources. Sixth, the security of information is necessary since the nature of the control information used to maintain the quality of energy delivered. Finally, easy deployment and maintenance is necessary to reduce the cost of installation and maintenance of the infrastructure. Authors Sauter and Lobashov in [18] made an analysis of these requirements. They designed a large communication network by the insertion of tunnelling mixed with gateways for real-world scenarios, connected with power line communication (PLC) technology and a protocol stack that supports this mixture called ‘REMPLI protocol stack’ by including PLC communications and the Internet. They found that there is a need for new transport layer protocols equivalent to the REMPLI but appropriate for the particular network communication technology.

As mentioned before, the communication architecture needs to be deployed on top of the smart grid networks existing in order to enable the usage of advance applications. These application aims to fulfil interoperability goals for the communication infrastructure. These goals are divided in three groups: connectivity, effectiveness and efficiency. Connectivity refers to the ability of a network to connect devices to exchange information. Effectiveness refers to the need of transmitting proper information and messages provided by the competent format, protocols and interfaces in the particular network devices. Finally, efficiency refers to the ability of the network to support its real time nature, taking into account the number of devices in a smart grid network and the amount of information that needs to be transmitted [19].

In addition, cyber-security is another topic that needs to be considering for the implementation of a smart grid networks. The support of critical infrastructure in the countries, and the protection of the information from attacks is the main concern. For that reason a tight security scheme able to protect, detect and respond on time to attacks, is a must in the implementation of smart grids communication networks [19]. This particular issue is not further considered in this work.

Table 1, compile the requirements and the proposed goals of a smart grid need to operate properly and they are mapped onto communication interfaces. These goals are connectivity, effectiveness, efficiency, QoS and cyber-security. Connectivity is referred to the capacity of the network to establish and maintain connection with all the devices in a smart grid. Effectiveness concerns to the capacity of the communication network to deliver all information according to application-specific requirements. Efficiency refers to the ability of a network to deliver such information in between the periods defined by the application. Quality of service is related to all the interfaces and parameters of diverse technologies used, including QoS assurance, and end-to-end delivery mechanisms. Finally, the cyber-security is in charge of developed mechanisms to protect the information, assure that this one is reliable and belongs to the device that is sending it.

Requirement	Key communication interfaces
Connectivity	• Cyber-physical interfaces that allow power system equipment to interact with the cyber system • Network interfaces that allow entities to establish connectivity • Network interfaces and APIs for libraries and/or services that allow entities to establish connections with appropriate naming, addressing and routing
Effectiveness	• Software interfaces, service interfaces and APIs that allow entities to exchange messages with appropriate naming and addressing functions (at the Application Layer) • APIs for protocol libraries that allow exchange of messages satisfying application-specific information requirements
Efficiency	• Network interfaces that provide access to high-bandwidth, high-performance, low-latency networks • APIs and software interfaces that allow protection/monitoring/control applications and devices to use the advanced networks • Service interfaces and APIs to establish common time reference for the grid-wide system as well as to gauge the timeliness of data and events
Quality of Service	• Hardware and software interfaces that support QoS assurances (e.g., real-time, reservations and scheduling, prioritization) at computers/devices • Network interfaces that support QoS assurances (e.g., real-time, reservations and scheduling, prioritization) in the network • Middleware interface that provides end-to-end QoS delivery mechanisms (by building on multiple underlying transport and network protocols across the wide area system) • Software interfaces and APIs that allow software applications to use Middleware capabilities
Cyber Security	• Hardware interfaces for protecting secret keys and passwords • Network interfaces and hardware/software interfaces for maintaining cyber security in the network (e.g., intrusion detection systems) • APIs, service interfaces and software interfaces for use of cryptographic algorithms as well as for key management • Middleware interface that provides end-to-end cyber security mechanisms • User interfaces for cyber security monitoring

Table 1. Key interfaces for the Smart grid communication according to [9].

2.1.4. SMART GRID PROPOSED ARCHITECTURES

The National Institute of Standards and Technology (NIST) from the U.S. Department of Commerce, defined a conceptual model for smart grids, where they are divided in seven part or domains. These domains describe, not only technical function of the electric network, but also the stakeholders involved in the business of power delivery. These seven are *generation*, *transmission*, *distribution*, *customers*, *markets*, *operations* and *service providers* [3].

Figure 3 shows the framework proposed by NIST and presents a set of communication paths that need to be developed for the optimal behaviour of the network. In this Figure, the model is defined the communication paths, the electricity flows and the domains that are interconnected. The four bottom domains; generation, transmission, distribution and customers; are similar to the domains explained in section 2.1.1. this describes the power delivery stages and the flow of energy. It is important to recall that these energy flows are bidirectional especially in the distribution to customer path. The *market* domain is in charge of the negotiation of the electricity market with other electric networks defining the price of energy for users according to the offer and demand of energy. The *operation* domain is in charge of applications like billing, consumer consumption, and management of users' accounts and diverse operational aspects of the power company. Finally, the *service provider* domain is in charge of developing services and applications for power companies and consumers to enable intelligent control of the electricity usage. These seven domains need to be interconnected by specific communication paths with diverse communication requirements in order to fulfil particular communication requirements like real-time communications, end-to-end QoS long range connectivity and cyber-security among others.

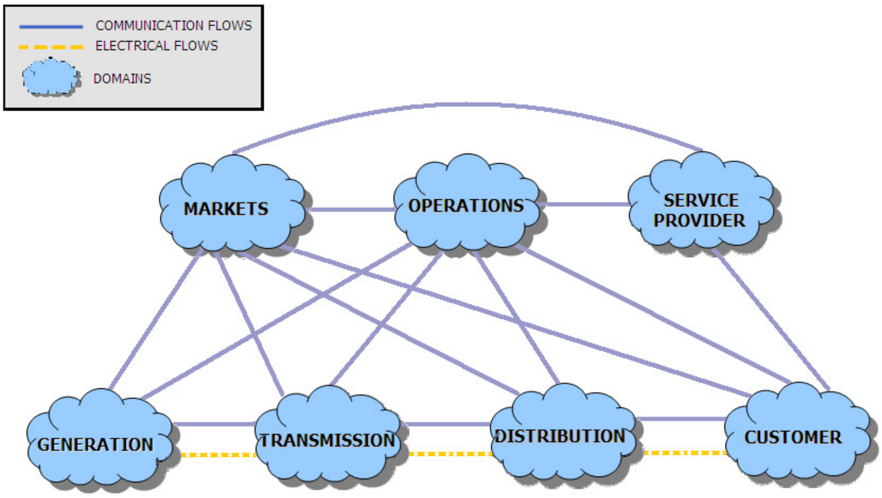

Figure 3. Smart Grids Framework according to NIST [3].

According to the NIST model, a number of area networks have been proposed to support communications between devices, databases and controllers within a smart grid. Because each domain has a different purpose, their devices use different applications that have different QoS requirements hence; the networks being chosen are different as well. Local Area networks (LAN) and Wide Area Networks (WAN) are examples of the network that are chosen for the diverse network requirements. Every domain has an intra-domain network that supports the communication across the devices of the specific domain. Also, secure communication channels should be created to transmit information across different domains.

For the bulk generation domain, a set of industrial Local Area Networks (LAN) are deployed to serve communication inside the generation plants. Additionally, transmission and distribution domains share Wide Area Networks (WAN) and Field Area Networks (FAN) that connects substations, transformers, data collectors and field devices among others. The FAN refers to those ubiquitous wireless networks deployed in urban and suburban locations serving field equipment and field mobile workers in utilities companies like the power company [20]. These networks are long range by nature, because the long distance where the electricity is delivered. Moreover, in the customer domain, a premise network is implemented with several communication technologies including the ZigBee, the Wi-Fi and the Bluetooth.

The reference model of the NIST is divided into several categories; namely the domains, the information networks, the actors, the gateways and the communication paths. The seven domains represent the electricity delivery process plus the markets, operations and services described previously in section 2.1.1.

The information networks present a level of abstraction where the information is transmitted to serve the electricity delivery process. Different aspects of the grid are represented by different information networks. First, the Internet/e-Business networks comprehend the networks based on internet that are designed for business. Their architecture includes corporative LANs with business servers, Virtual Private Networks (VPN), firewalls and security protocols. Second, the enterprise bus network describes the networks inside the utility company or its affiliated companies. These ones are typically LAN or WLANs. Third, the substation LAN is a network with industrial capability able to support the harsh environment of the substations that present high levels of electromagnetic contamination. Wireless LANs are not common but could be used for specific applications inside substations. Fourth, Wide Area Networks and Field Area Networks are to support the communication needs of the transmission and distribution domains. One of the characteristics of the WAN and FAN is the ability of long-range communications in the order of tens of kilometres. Finally, the premises network, also known as Home Area Network (HAN) is defined to support communication information among the electric appliances inside the house. The clouds in the Figure 4 represent different information networks that support a smart grid. These can be enumerated as follows: Internet/e-business, enterprise bus, substations LANs, WAN, FAN and HAN [21].

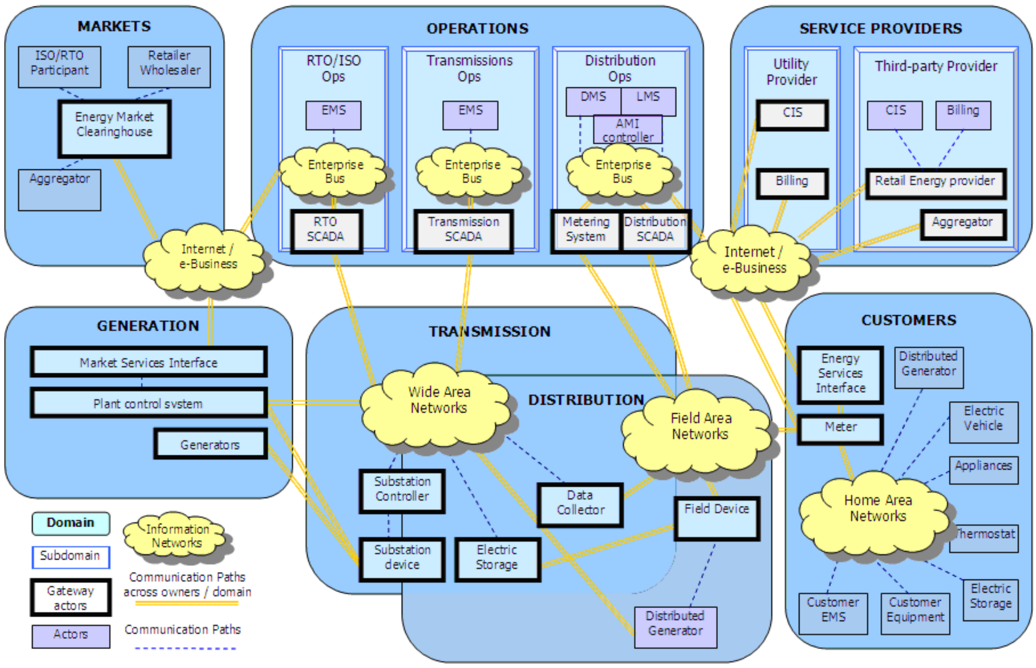

Figure 4. The Smart Grid conceptual reference diagram based in NIST[21].

The inter-domain gateways help the network to communicate across domains providing specific application solutions for the particular domain. For the market domain, the energy market-clearing house provides connectivity between the markets and the e-business network, collecting information from aggregators, retailers, wholesalers and regulator organisms. For the operations domain, four gateways maintain the operation running; these are the Regional Transmission Organization (RTO), supervisory control and data acquisition (SCADA) system, transmission SCADA system, distribution SCADA system and the metering system. For the service providers' domain, there are two important gateways the billing system and the Customer Information System (CIS). For the generation domain, the three are gateways with the information of the plant control system and the generators that allows the system to exchange particular information of the generation process. For the transmission and distribution domains, there are common and shared gateways; these are substation subsystem, substation controller system, data collector system, energy storage system and device information system. These systems collect information of the transmission and distribution process, and act according to the control procedures. Finally, in the user domain, the meter and the energy services interface, collect information of all the appliances in the consumer premises and provides the information trade between the markets, the services and the needs of the user. Table 2, presents the mapping between the actors, the gateways and the domains; and their relation between the smart grid task force and the NIST architectural model [22].

Domain	Related NIST diagram Actors	SG Network Task Force reference Actors
Generation	Bulk generators	Generators
	Plant control system	Plant control system
Transmission	Distributed generator	Distributed generator
	Field Area Network Gateway	Field Area Network Gateway
	Field device	Voltage regulators
		Field sensors
	Storage system	Distributed storage
	Substation controller	Distribution Application Controller (DAC)
	Substation device	Substation device
Distribution	Distributed generation	Distributed customer generation
	Field device	Capacitor bank
		Circuit breaker
		Recloser
Customer	Appliances	Smart Appliances
	Customer EMS	Customer Energy Management System (EMS)
	Customer equipment	Heating, Ventilating and Air Conditioning (HVAC)
		In Home Device (IHD)
		Load Control Device (LCD)
	Distributed generation	Distributed Electric Resources (DER)
	Meter	Smart Meter
Markets	Aggregation Retail Energy Provider	Retailer Wholesaler
	Aggregator	Aggregator
	RTO/ISO	Regional Transmission Operator (RTO) / Independent System Operator (ISO)
Operations	Demand Response	Demand Side Management (DSM)
	Distributed SCADA	Distributed SCADA Front End Processor (FEP)
	DMS	Utility Distribution Management System (DMS)
	EMS	Utility Energy Management System (EMS)
	RTO SCADA	Regional Transmission Operator (RTO) SCADA
	Transmission SCADA FEP	Transmission SCADA Front End Processor (FEP)
Service Provider	Bill Payment / Bank organization	Bill Payment
	Internet external gateway	Internet Gateway
	Utility billing	Utility CIS Billing
	Web portal	Web portal

Table 2. Mapping of actors between the smart grid task force and NIST architect model [17]

2.2. SMART GRID COMMUNICATIONS

In this section, a close focus on the communication aspects related to the implementation of smart grid requirements is presented, exploring the needs and requirements of the communications network, the proposed communication models, services and applications that will be incorporated in the model.

2.2.1. *NEED FOR A SMART GRID COMMUNICATION NETWORK*

As described in section 2.1.1, communication networks will serve as a feedback loop in the control scheme in the energy generation and distribution process. This is a simplistic definition outlining the communication network role in smart grids, but it helps to explain in an easy way the operational need of communication networks in smart grids. In addition, communication networks help to collect information from customers about their consumption, how much energy is produced by distributed generators and exchange electricity market data to help customers to make decisions about the energy use. Ultimately, communication networks will support the optimal delivery of information to controlling energy generation, distribution and load management process.

2.2.2. *THE IEEE P2030 COMMUNICATION MODEL*

As presented in Figure 5, the NIST is a smart grid conceptual reference model that provides guidelines of the components in a smart grid including the energy delivery control process, the telecommunication infrastructure and the application information related with it. Meanwhile, the IEEE P2030 standard refers to the smart grid as a large complex 'system of systems', and discuss the interoperability components of the communication, power system and information technology architectures based in the guidelines of the American NIST model and the European IEC model.

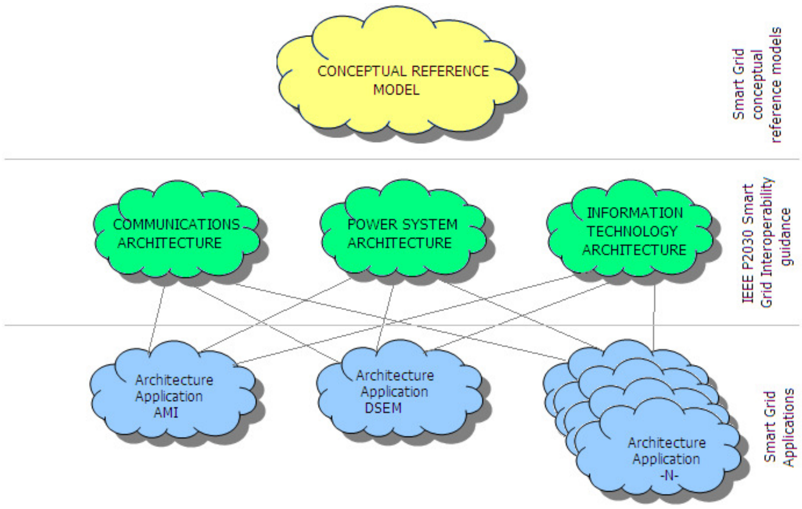

Figure 5. Evolution of the smart grid interoperability according to IEEE P2030 standard[4].

The end-to-end communication capabilities are one of the critical parameters in the design of the communication architecture. The IEEE P2030 standard proposes a layered structure to provide end-to-end communication channels. The layers consider in this model begin with a top security layer that provides protection to the data that is transmitted in the network. Next, a network management provides control of the communication links fulfilling the QoS requirements. Finally, it defines a series of area networks that are superposed over the energy/power domains. Each area network provides connectivity for devices across the entire smart grid network. Figure 6, presents the end-to-end communication model proposed by the IEEE P2030 that includes the public internet as an interface on top of the area networks[4].

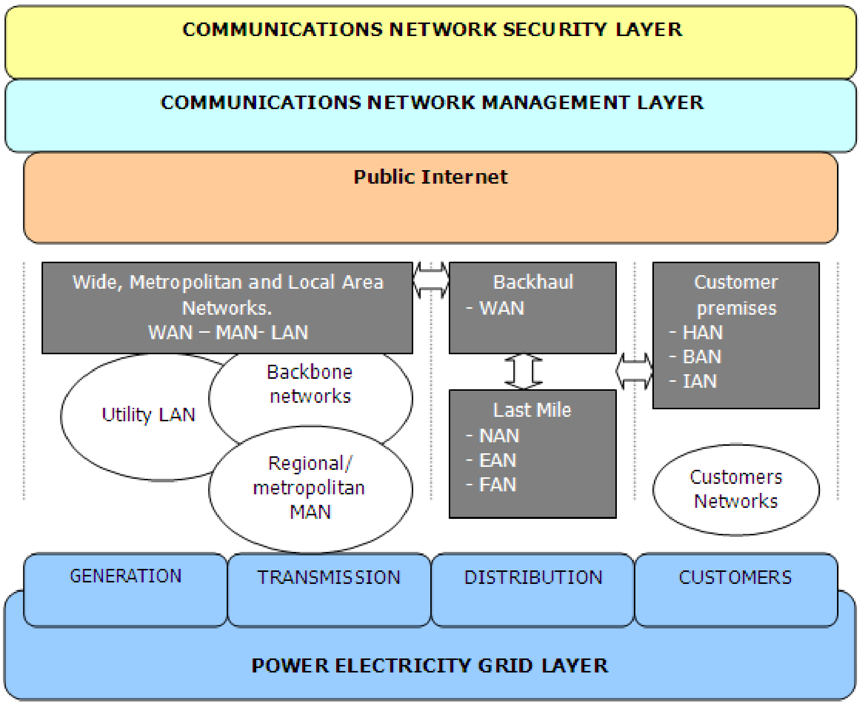

Figure 6. End-to-end smart grid communication model based on IEEE P2030 standard[4].

One of the principal concerns about communication models in the legacy electric networks is the unidirectional flow of information and the lack of service differentiation in the communication channels. These evolving energy grids need more efficient, fast and bidirectional communication network that reaches every corner of an electricity network. In order to solve these issues, a new architecture has been proposed by the IEEE P2030 task force and the NIST.

The IEEE P2030 standard is a guide for the smart grid interoperability between the power systems with the user applications and the electrical loads. It also defines that integration of the energy technologies with the information and communication technologies (ICT) should be compulsory for the proper operation of smart grid networks and its interoperability. The interoperability is divided in three levels; the power, the communication and the information technology systems. These three aspects aim to fulfil the interoperability needs of the smart grid domains. However, each aspect addresses specific issues using diverse technological solutions. In each aspect of the reference model there is a definition of actors and interfaces between them that are laid over the seven domains of the NIST model. First, actors are defined as all the devices, communication networks, computers, software and other equipment that is located inside each domain. Last, interfaces are those logical relations between the actors supporting data flow. In particular, inside the communication technology interoperability section of the reference model, there is a description of 24 entities/actors across the seven domains and 71 communication interfaces. In Figure 7, the grey boxes represent the entities and the lines marked as CTxx represent the interfaces. Details of these entities and interfaces are explained in the Tables 7-1 and 7-2 of the IEEE P2030 standard [4] respectively, also presented in the Annex A.

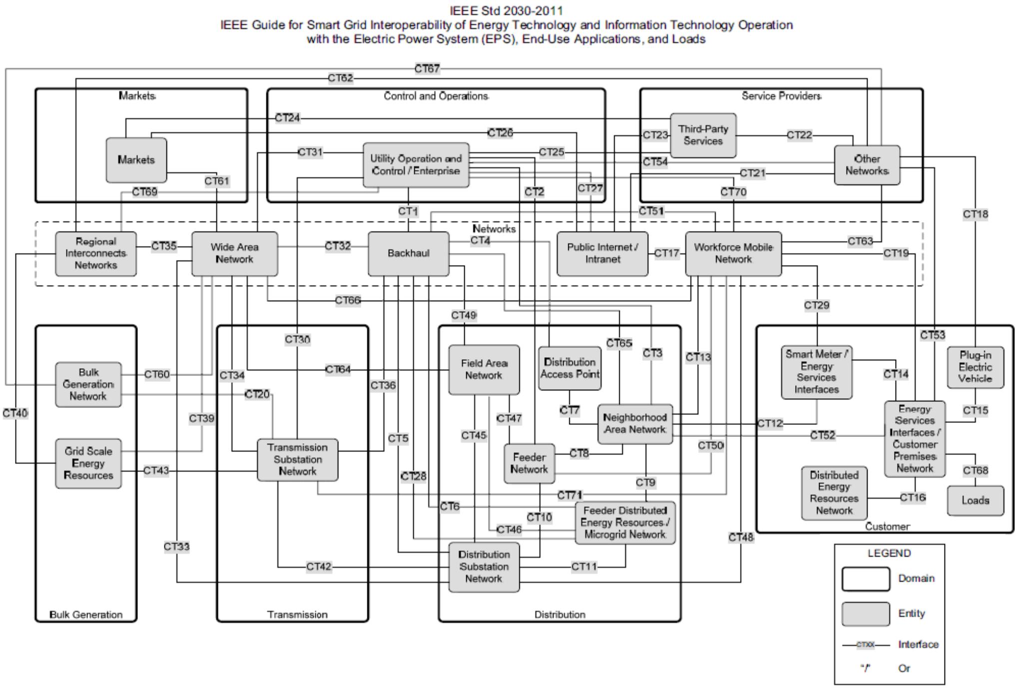

Figure 7. IEEE P2030 Communication technology interoperability architecture[4].

Figure 8 present the current architecture of a smart grid encompassing the communication network. The reference architecture of the IEEE P2030 describes the current stage as a one-way communication system from a utility backbone network to the customer domain using very limited wireless network to connect feeder devices and substations. In the utility side, a fiber based optical backbone connects diverse substations with application serves in charge of the operation of the energy delivery. Parallel wireless communication channels are used to communicate feeders, capacitor banks and substations with control and operation servers.

Finally, one-way paging mechanisms are used to send control messages to premise devices in order to perform Direct Load Control (DLC).

The vision of the IEEE P2030 describes a mixture of wired and wireless interfaces to connect the defined actors inside the smart grid. In Figure 9, a cloud representing the energy utility groups the markets, operations, service providers and generation domains of the NIST model. This cloud is characterized by a fibre optic backbone that includes the LAN connecting service application servers, firewalls and wireless management services. Outside the cloud, are the transmission, distribution and customer domains. The transmission domain is connected by fibre optic networks, private point-to-multipoint (PMP) wireless or cellular data networks. These connectivity options aim to create communication channels between the core network and devices like feeders, capacitor banks, regulators, substations and access points for the transmission and distribution domains. The vision of the IEEE P2030 standard also contemplates mesh networking for the distribution domain, for example, it considers this domain as an automatic metering infrastructure (AMI). Finally, the home area network (HAN) is proposed to connect home appliances using the ZigBee technology. ZigBee is a low transmission power, low speed wireless network which is an important component of the smart energy home networks. These provides low speed communication channels for electric devices in a mesh networking fashion [23]. Electric appliances could create a ZigBee mesh networks where all data is collected by the meter reader and retransmitted to the core network through the mesh network [24].

Further analysis of the IEEE P2030 standard includes a wireless overview of the framework architecture, in which some key features need to be emphasised, namely access technologies and the transition from legacy technologies. A whole infrastructure is proposed using several access technologies - such as cellular and wide area data networks, private Line-of-Sight (LoS) networks, relayed access points, and wireless multihop networks. Figure 9 illustrates the wireless network model proposed by the IEEE P2030 working group [24]. The capabilities of the IEEE 802.16 WiMAX standard and its amendments [25] will allow implementation of

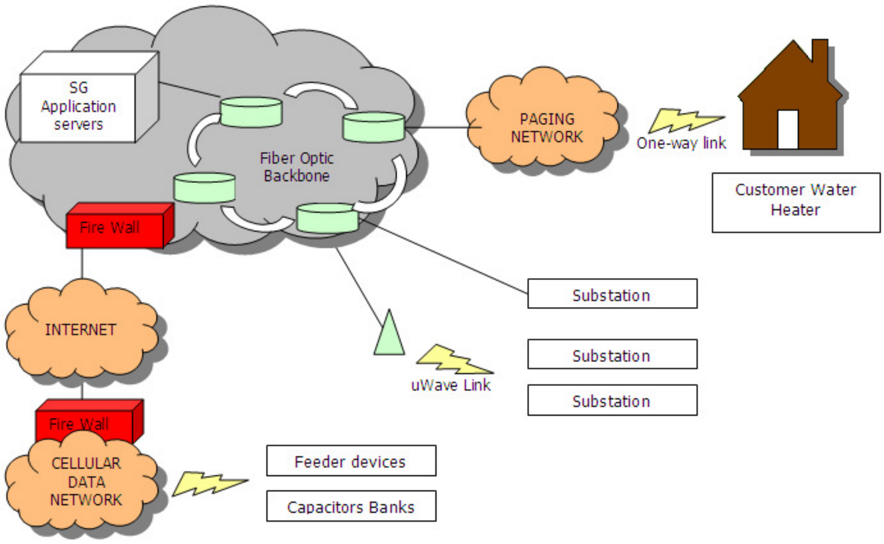

Figure 8. Current stage of the communication network in the electricity grid (based in IEEE P2030) [24].

different communication scenarios of the smart grid. First, the WiMAX standard could serve as a backhaul or a PMP access network; this configuration application has been successfully used for some time in electricity networks and is represented in Figure 9.

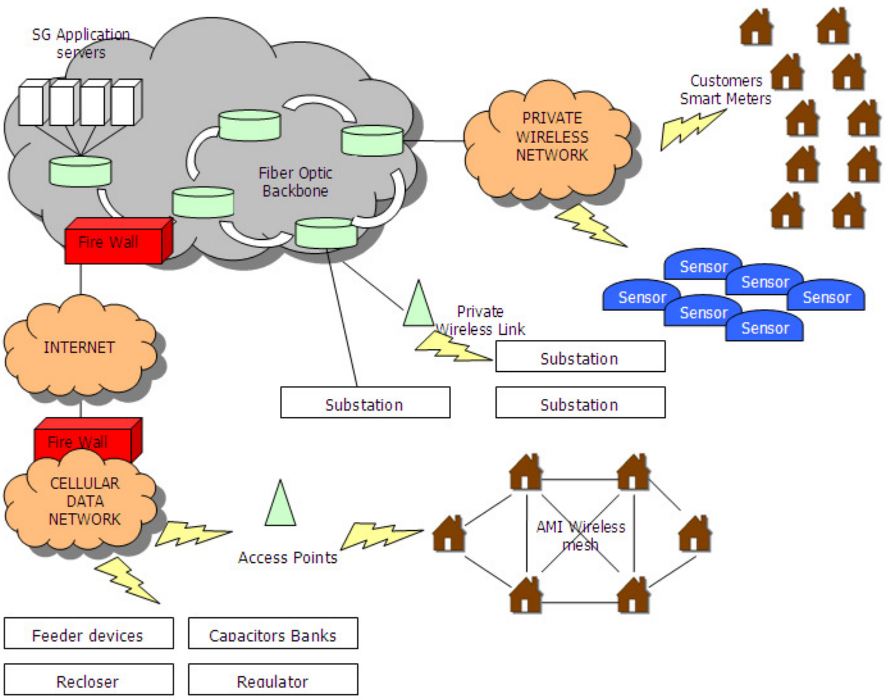

Figure 9. Future vision of the Smart Grid using wireless communications (based on the IEEE P2030 Architecture) [24].

In order to understand the interoperability integration of the three aspects of the IEEE P2030 model, an example of the implementation of distributed automation (DA) systems is presented. In Figure 10, a description of the distributed automation system is presented integrating the three interoperability perspectives of the IEEE P2030 standard, namely the power system, the communication system and the information technology system. The power system level is the one related with the energy, from the substation, through the distribution domain to the customer premises. Second, the communication system level includes private and commercial wireless networks. In the private wireless networking architectures such as the mesh and the PMP are used. For commercial wireless networks the Code Division Multiple Access (CDMA), Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and WiMAX standards, are used. Finally, in the information technologies level, management servers are used to control the DA using SCADA and AMI management services [24].

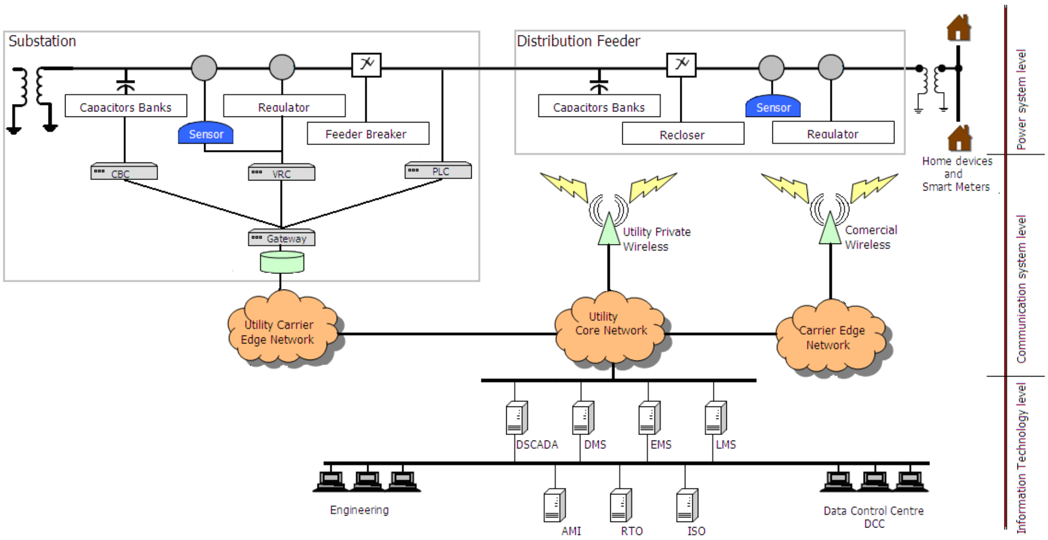

Figure 10. Example of an IEEE P2030 Distributed Automation Technology deployment and the relation with the interoperability infrastructure [24].

2.2.3. SERVICES SUPPORTED IN A SMART GRID COMMUNICATION NETWORK

The services provided by the smart grid communication networks are divided in the network devices and the end user known as Demand Side Energy Management (DSEM).

The first group provides the services to the utility network. These services are related to the measurement and control of the generation, transmission and distribution devices'. Such services are: load management, security service, power quality, meter reading, grid monitoring, among others [26], and offer the support for energy deliver processes. These services are usually working in the operation and service providers' domains.

The second group is related with the energy management at the households. The DSEM aims to serve and control the electric appliances connected in the HAN, usually through a web service application. This service is installed in the service providers' domain, and a controlled by a hub inside the house premises. However, the connectivity to this hub could be done by the household internet connection or through the smart grid communication network. It depends in the type of information used for the application. Ideally, this information needs to be sent in the smart grid network because it contains information about the energy use of various appliances that affects directly the performance of the grid [27]. The services in the end users are divided in two groups: First, measurement of in house electric appliances and second control of electric appliances. In both cases, control of the distributed generation could be installed, depending on the home infrastructure of distributed generators and energy storage banks.

2.3. WIRELESS NETWORKS FOR THE SMART GRID

The design of different area networks that supports the needs of smart grids has its own technical challenges. One of the most significant requirements in fulfilling the data traffic requirements is to connect all the sensors and actors as well as other communication devices across every corner of the smart grid, either in rural areas or in dense urban centres. The particular requirements of smart grids networks are quite different from the actual broadband mobile networks deployed or the point-to-point networks currently used for the power energy networks. This critical problem is going to be explored in this research.

Among researchers, there is an agreement that the best way to support the above requirement is using a Wireless Networks (WN) rather than using a fixed network [9, 17]. A WN provide connectivity for large-coverage areas with a required bandwidth capacity and QoS maintenance including for low latency connections. The advantage of using wireless communications resides in the cheap deployment cost of WN in large areas compared to wired channels, especially when smart grid data traffic requirements are low compared to multimedia applications. Moreover, wireless networks provide scalability and easy upgrading feature without the need of changing the whole architecture.

Two wireless networks are currently considered by the industry for future implementations in smart grids are the WiMAX and Long Term Evolution (LTE) standards. The IEEE P2030 standard, in the communication interoperability section, recommends both technologies should be taken into account when designing the last mile access for the distribution domain and for the WAN, to support applications in the transmission and distribution domains. In the past, there has been a lot of research on the WiMAX standard as a solution for the wireless broadband network applications. In addition, the WiMAX is known to provide full end-to-end QoS specification, based in the IEEE 802.16 standard, which gives a good solution for smart grid applications using private networks compared to the LTE which is typically a public network [9, 21, 22, 28]. So far, no major works have been carried out to investigate the performance of a WiMAX networks for smart grids applications which is the focus of this work.

2.3.1. WiMAX in the Smart Grid

The WiMAX is wireless network technology is based on the IEEE 802.16 standard [1, 2]. The WiMAX uses point-to-multipoint (PMP) connections that are designed to support different types of QoS in a long-range connectivity mode. The QoS is sustained by the usage of appropriate resource allocation mechanisms, scheduling schemes and definition of service classes. Each scheduling class performs packet scheduling using various algorithms that analyse the incoming traffic and the transmission channel status, and maps the information onto frames to be transmitted on the wireless channel. The IEEE 802.16 standard do not define the algorithms used in practical implementation, this leads to opportunities for researchers to develop appropriated resource allocation methods for diverse applications like smart grids. Moreover, at the time of this literature review is made, there are no proposed algorithms for smart grids applications, like low latency and sporadic bandwidth requests which will be the focus of this research.

The WiMAX standard is an evolving technology known to be effective for reaching distant users. Long-range connectivity is achieved by the use of adaptive transmission techniques provided by the selection of Modulation and Coding Scheme (MCS) to users that achieve high SNR connections. Terminals with low SNR conditions are offered appropriated MCS values to reduce the packet losses [2, 29]. Using the WiMAX standard to reach a large number of customers and electrical devices is a challenging issue for wireless networks because of the dynamic characteristics of the wireless channels and the variability of the network users' distribution patterns. Initial simulation results of a WiMAX network using the smart meter traffic sources show that when a large number of meters is served by a single network its efficiency is affected by the number of connections admitted and the quality of the links. Two main problems arise for low SNR users, due to the use of the Adaptive Modulation and Coding (AMC) schemes in a low SNR condition; higher MCS values are used resulting in more symbols used to transmit the same amount of data compared to a good SNR connections leading to exhaustion of the WiMAX frame capacity rapidly. The second problem is for terminals with very low SNR. Bandwidth request (BWReq) from low SNR terminals will not arrive at the BS; hence, no resource allocations are made. Hence, these terminals will not receive any mapping information on the Downlink Map (DL-MAP) and will not be able to transmit any data. This parameter is heavily affected by the receiver sensitivity on WiMAX radio transmitters.

2.4. SMART GRIDS APPLICATIONS, REQUIREMENTS AND CHARACTERISTICS

The smart grids applications have a vast number of parameters and requirements to make a smart grid work in an optimal way. These parameters depend in particular characteristics of each application. The IEEE P2030 introduces a framework of characteristics where each application could be classified according to certain values range or qualitative consideration. These characteristics vary from coverage, end-to-end delay, packet size, data generation characteristics and reliability to security aspects. The classification helps to determine which is the best communication technology to use for a particular application, according to its parameters.

Table 3 presents the data characteristics and the classification values related to each category. The first characteristic is the range of coverage and it could support from short communication range of under ten meter to coverage of more than a kilometre. Latency of application could be grouped into four ranging from seconds to a few milliseconds that also represent real time or non-real time communication links. Synchronization needs are divided in two groups, those applications that need to be synchronized with others within the entire network and those not requiring any synchronization. The next characteristic groups the data generation parameters from the applications which includes, the data burst size, the occurrence interval the broadcast method and the priority. In this category, the data burst size varies from small byte packets to gigabytes of information; the occurrence interval include values of milliseconds, seconds, minutes and even hours; the broadcast method could be unicast, multicast, broadcast or all of them; and the qualitative priority level could be grouped in none, low, medium or high.

The next group compiles the qualitative parameters of the information reliability such as quality of information, availability of information and the impact the particular information in the smart grids. The quality of information could be informative, important or critical; the availability is divided in low, medium or high; and the impact of not having the information is defined in limited, serious, severe and catastrophic. Finally, the last group cover the security aspects of the information including confidentiality, integrity and availability. These three parameters are divided in none, low, medium or high values.

Despite that the IEEE P2030 provides this framework, it does not define particular values for the applications discussed in this document; hence, a study of these parameters in each application needs to be made to select the optimal communication network to support the application requirements.

<table>
<tr><th colspan="2">Data Characteristic</th><th colspan="12">Classification/ Value Range</th></tr>
<tr><td colspan="2">Coverage</td><td colspan="3">< 10m</td><td colspan="3"><100m</td><td colspan="3"><1Km</td><td colspan="3">>1Km</td></tr>
<tr><td colspan="2" rowspan="2">Latency</td><td colspan="6">Real time</td><td colspan="6">Non-real time</td></tr>
<tr><td colspan="3">Low-low
< 5 ms</td><td colspan="3">Low
< 20 ms</td><td colspan="3">Medium
< 1 sec</td><td colspan="3">High
> 1 sec</td></tr>
<tr><td colspan="2">Synchronicity</td><td colspan="6">Yes</td><td colspan="6">No</td></tr>
<tr><td rowspan="4">Data generation</td><td>Burst Size</td><td colspan="3">Bytes</td><td colspan="3">Kilobytes</td><td colspan="3">Megabytes</td><td colspan="3">Gigabytes</td></tr>
<tr><td>Occurrence interval</td><td colspan="3">Milliseconds</td><td colspan="3">Seconds</td><td colspan="3">Minutes</td><td colspan="3">Hours</td></tr>
<tr><td>Broadcast method</td><td colspan="3">Unicast</td><td colspan="3">Multicast</td><td colspan="3">Broadcast</td><td colspan="3">All</td></tr>
<tr><td>Priority</td><td colspan="3">None</td><td colspan="3">Low</td><td colspan="3">Medium</td><td colspan="3">High</td></tr>
<tr><td rowspan="3">Information reliability</td><td>Quality</td><td colspan="4">Informative</td><td colspan="4">Important</td><td colspan="4">Critical</td></tr>
<tr><td>Availability</td><td colspan="4">Low</td><td colspan="4">Medium</td><td colspan="4">High</td></tr>
<tr><td>Impact</td><td colspan="3">Limited</td><td colspan="3">Serious</td><td colspan="3">Severe</td><td colspan="3">Catastrophic</td></tr>
<tr><td rowspan="3">Security</td><td>Confidentiality</td><td colspan="3">None</td><td colspan="3">Low</td><td colspan="3">Medium</td><td colspan="3">High</td></tr>
<tr><td>Integrity</td><td colspan="3">None</td><td colspan="3">Low</td><td colspan="3">Medium</td><td colspan="3">High</td></tr>
<tr><td>Availability</td><td colspan="3">None</td><td colspan="3">Low</td><td colspan="3">Medium</td><td colspan="3">High</td></tr>
</table>

Table 3. Data classification Table for the IEEE P2030 reference model [4].

2.4.1. *DEFINITION OF THE SMART GRID APPLICATIONS*

The most important information of the distribution domain in the smart grid is the residential and industry energy consumption. The knowledge of this information will help the control systems to develop accurate control mechanisms in order to manage the loads for the users and the renewable energy sources that reside in the user premises. Knowing this data in to the latency parameters is vital importance to avoid overloads and blackouts. Several techniques developments have been developed in terms of the automation of the energy reading like Automatic Meter Reading (AMR) and Advance Meter Infrastructure (AMI). The AMR is a simple unidirectional communication network designed to avoid the manual reading of electricity that was the common way to make energy reading for almost a century. On the other hand, AMI is a more advance communication network that provides information of the electricity consumption as well as information for distributed generation and, in some cases; it provides a bidirectional channel for control purposes for application like the demand side management (DSM). [26, 30, 31]

For the proposed communication model in this work, three different applications will be consider, namely Meter reading, Demand Side Management and Sensor reading. These application and their characteristics are explained below. Based on the framework provided by the IEEE P2030 standard, the proposed applications are mapped into the application characteristics using a WiMAX network.

Above applications requires a minimum radio coverage area of 1Km, where smart meters and sensors are distributed. In our model we allowed high latency for smart meters reading applications, medium for demand management and low latency value for sensor data. Synchronization is only considered for some sensor reading applications. Data burst applications was limited to kilobyte value. The occurrence interval of these data is in the range of minutes for all applications. Unicast packet transmission technique are used for the smart meters and could be unicast or broadcast for the sensor applications. Finally, for the priority allocation; low priority smart meter reading, medium for demand management and high priority is used for the sensor reading.

Reliability requirements for these applications are variable. Relaxed reliability requirements was allocated to smart meter reading, medium requirements for demand management application and very high for sensor network application. The availability is considered medium for the smart meters and high for the sensors. In addition, the impact of the information is limited for the smart meter reading, serious in the case of the demand management and catastrophic for the sensor reading application. In the last category, security, the smart meters are categorized in the medium risk scale and the sensor in high-risk scale. Table 4 presents the mapped characteristics for the applications used in this work.

Priority of different applications is mapped on the ToS (Type of Service) field of the IP packet header. This parameter is related to the data characteristics of various applications. The IP ToS flag offers datagrams certain level of priority in a mixed application traffic environment. This flag is eight bits long where the ToS field is placed between the 3rd and 6th bits giving only 8 usable types of service. Initially this four-digit field defined in the RFC1349, describes the semantics for particular performance such as to minimize delay (1000), maximize throughput (0100), maximize reliability (0010), minimize monetary cost (0001) and the normal service (0000) [32]. However, the above RFC has been superseded by the RFC2474, where the four bit definition is leaved to use for full range of services and provides differentiated services shown in Table 5[33].

Data Characteristic		Classification Of Applications		
		Smart Meter Reading	Demand Side Management	Sensor Reading
Coverage		> 1Km	> 1Km	> 1Km
Latency		High (Non-real time) > 1 sec	Low (Real time) < 20 ms	Low-low (Real time) < 5 ms
Synchronicity		No	No	Yes
Data generation	Burst Size	Kilobytes	Kilobytes	Kilobytes
	Occurrence interval	Minutes	Minutes	Minutes / Hours
	Broadcast method	Unicast	Unicast	Unicast / Broadcast
	Priority	Low	Medium	High
Information reliability	Quality	Informative	Important	Critical
	Availability	Medium	Medium	High
	Impact	Limited	Serious	Catastrophic
Security	Confidentiality	Medium	Medium	High
	Integrity	Medium	Medium	High
	Availability	Medium	Medium	High

Table 4. Data characteristics mapped to the application used in this work.

Type of Service Number	Type of Service
0	Best Effort
1	Background
2	Standard
3	Excellent Effort
4	Streaming Multimedia
5	Interactive Multimedia
6	Interactive Voice
7	Reserved

Table 5. Type of service (ToS) values available.

In order to map the data characteristic values proposed by the IEEE P2030 standard in the Table 3 on the RFC2474 ToS flag, the author propose the following parameter mapping Table as is shown in Table 6.

As discussed in section 3.2.1, each application and its traffic flows should be assigned to a unique service class. This assignment will create an allocation Table inside the WiMAX MAC layer thus allowing differentiated traffic flow from different applications and provide different levels of QoS for each one of them.

Data generation Priority	Type of Service
None	Best Effort (0)
Low	Excellent Effort (3)
Medium	Streaming Multimedia (4)
High	Interactive Multimedia (5)

Table 6. Relation between data priority and type of service.

In addition, each application has different latency requirements which should be supported. In this work, the delay values of real time or non-real time applications are selected and mapped onto the WiMAX QoS management techniques as explained in section 3.2.1. Table 7 presents the application QoS and WiMAX parameters mapping process used in this work. The following sections discuss smart grids application characteristic and requirements used in this work.

Application	Type of Service	Service Class Name	Latency	
Metering reading	Excellent Effort (3)	Metering	Non-real time	>1sec
Demand Side Management	Streaming Multimedia (4)	Demand	Real time	<1sec
Sensor reading	Interactive Multimedia (5)	Sensor	Real time	<150ms

Table 7. Relation between applications data characteristics used in WiMAX.

2.4.2. *METER-READING APPLICATIONS*

Meter reading application refers to the reading of smart meters from different user premises. This application only considers transmissions of Meter Reading data in a periodic manner. This message contains information such as voltage, current, consumed power (incremental and differential), power factor (θ) and user identification ID. Table 8 presents the detail of the packet information and the size of each field in the packet. Figure 11 presents an example of data fields used to send meter reading information. In the second column, the 10byte size is used to support integer and real numbers. As part of the design, it is assumed that an application control and error coding of ½ is introduced, leading a total packet size of 600 bytes. Also, some extra information could be send inside this message that has not been consider in the Meter-reading packet format, hence a reserved field of 145 bytes is allocated. Also in Figure 12 is presented the simple message transaction in the smart meter mode.

Value Name	Value	Alarm
10 bytes	10 bytes	5 bytes
Voltage	221.4 v	N/A

Figure 11. Example of the value field used in the simulation.

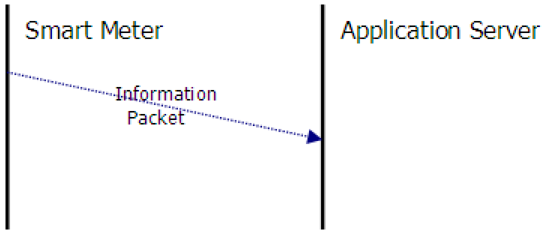

Figure 12. Smart Meter message behaviour

Value	Size
User ID	15 bytes
Type of user	5 bytes
Time and date [1] [34]	30 bytes
Voltage	25 bytes
Current	25 bytes
Power	25 bytes
Total incremental power	25 bytes
reserved	145 bytes
CRC-32	4 bytes
TOTAL	**300 bytes**

Table 8. Meter-reading mode packet information.

2.4.3. DEMAND SIDE MANAGEMENT APPLICATIONS

The demand side management application is designed for users who have green energy generators like solar panels or wind generators; and programmable electric appliances like electric water heaters, air conditioners, dishwashers, washing, dryer machines and more. Also for those users that need extra information from the electricity network like price information, status of the network and electricity market information such as willingness to buy/sell. Such operation will require transmission of different types of packets at different intervals.

Users with these applications enabled, send a request for extra information to the server, including some distributed generation and programmable appliances parameters, as shown in Table 9. These messages could be used as a request of information or as a response to a control

[1] In Table 8 to Table 13 the "*Time and date*" field uses 'Universal supportable date and time pattern' plus fraction time (microseconds) included in ISO-8601 standard as follows: YYYY/MM/DD HH:mm:ss:uuu ±hh:mm

decision. In the first case a Type I field is created by sending information about the willingness to buy or sell power according to the power storage capacity of the user and the intention of purchase or sell energy. In addition, information about programmable appliances is sent in order to change previous configuration parameters or inclusion of new devices or services.

Value	Predefined values	Total Size
User ID		15 bytes
Type of user	DSM	5 bytes
Time and date	2011/09/15 15:43:30:075 -10:00	30 bytes
Type I - Request of info field	Request buy; Request sell; Request controlled appliances; Upgrade configuration data; etc.	50 bytes
Stored power		25 bytes
Power willing to sell/buy		25 bytes
Power willing consume		25 bytes
Controllable appliances		25 bytes
Type of energy	Solar; Wind; Solar/Wind; other	20 bytes
CRC-32		4 byte
TOTAL		**225 bytes**

Table 9. Demand application packet information Type I.

The service provider replies to the user by sending the requested information. The reply message contains the buying and/or selling price of energy; predicted weather parameter like wind speed and direction, cloudy/sunny/rain probabilities and local weather forecast data. This message is 325 bytes long using the same format as the UL message which is coded using a ½ rate error correcting coder generating a message size of 650 bytes. The detail of this server response message is described in Table 10.

Value	Predefined values	Total Size
User ID		15 bytes
Type of user	Server#	5 bytes
Time and date	2011/09/15 15:43:30:075 -10:00	30 bytes
Response message field	Buy; Sell; Control appliances; Upgrade configuration data; etc.	50 bytes
Wind parameters	Average speed and direction, Gust speed	25 bytes
Sunny parameters	Sunny; partially cloudy; cloudy; etc. sunrise and sunset times.	25 bytes
Prices on peak	User-sell price; User-buy price	25 bytes
Prices off peak	User-sell price; User-buy price	25 bytes
Control class message	Heater; Water; Dish-washer; Washing-machine;	25 bytes
Control value		25 bytes
Priority level	Mandatory: optional; User-preference; n/a	50 bytes
Type of energy	Solar; Wind; Solar/Wind; other	20 bytes
CRC-32		4 byte
TOTAL		**325 bytes**

Table 10. Server response mesagge for Demand application.

Finally, the control message from the smart meter is transmitted. The smart meter with demand management capabilities responds with the decision taken and associated parameter values. This decision could be taken by the meter, by the user or by the service application. A Type II message is sent in the case the user decides to change, sell or buy energy, or acknowledge a control requirement made by the service provider. Format of the message Type II is presented in Table 11. Demand management message behaviour is presented in Figure 13.

Value	Predefined values	Total Size
User ID		15 bytes
Type of user	DSM	5 bytes
Time and date	2011/09/15 15:43:30:075 -10:00	25 bytes
Type II – Operation info field		50 bytes
Stored power		25 bytes
Power sold / bought		25 bytes
Power allocated for consumption		25 bytes
Appliance control message		25 bytes
Duration of the operation		20 bytes
CRC-7		4 byte
TOTAL		**250 bytes**

Table 11. Demand application packet information Type II.

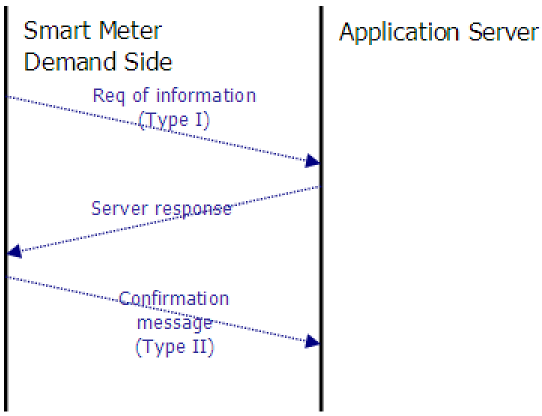

Figure 13. Demand application message behaviour.

2.4.4. *Sensor Data Applications*

The third application is the transmission of the sensor data. Sensor devices are distributed across the network that needs to send measurements or alarms in particular time with a high priority level. Sensors measure information about the status of an electricity network like low voltage transformers voltages, currents, phases and temperature and send that information by including the location of the sensor. This packet is coded using ½ rate error correction coding technique and has a total of 730 bytes to transmit. Table 12 describes the type of information sent by the sensors. An acknowledge message is quickly sent by the server to provide confirmation that the alarm was sent and the message is being processed.

Value	Size	Total Size
Sensor ID		15 bytes
Type of Sensor	Sensor#	5 bytes
Type of message (Regular / Alarm)		25 bytes
Time and date		30 bytes
Voltage	25 bytes / phase	75 bytes
Current	25 bytes / phase	75 bytes
θ	25 bytes / phase	75 bytes
Weather info		25 bytes
GPS information[2] [35]		40 bytes
CRC-32		4 byte
TOTAL		**350 bytes**

Table 12. The sensor application's information packet fields.

After the message is being processed, the server sends an information packet containing the confirmation of the values and necessary actions according to the type of alarm or the data received from sensors. Total payload is 350 bytes which is protected using a ½ rate error correction coder for a total transmitted packet size of 700 bytes as presented in Table 13.

Value	Size	Total Size
Sensor ID		15 bytes
Type of Sensor	Server#	5 bytes
Time and date		30 bytes
Voltage	25 bytes / phase	75 bytes
Current	25 bytes / phase	75 bytes
θ	25 bytes / phase	75 bytes
Action message (Reserved)		85 bytes
CRC-7		4 byte
TOTAL		**350 bytes**

Table 13. The sensor's application server response fields.

Finally, an acknowledgement message is transmitted from the sensor using a payload size of total 500 bytes including the ½ rate correction coding bits. Figure 14 presents the sensor message transmission process.

[2] In Table 12, the position of the sensor devices follows the Geographic Latitude and Longitude Global (GLL) data format of 40bytes. Example: $GPGLL,4916.45,N,12311.12,W,225444,A,*1D Where: GLL = Geographic position, Latitude and Longitude; 4916.46,N = Latitude 49 deg. 16.45 min. North; 12311.12,W = Longitude 123 deg. 11.12 min. West; 225444 = Fix taken at 22:54:44 UTC; A = Data Active or V (void); *iD = checksum data

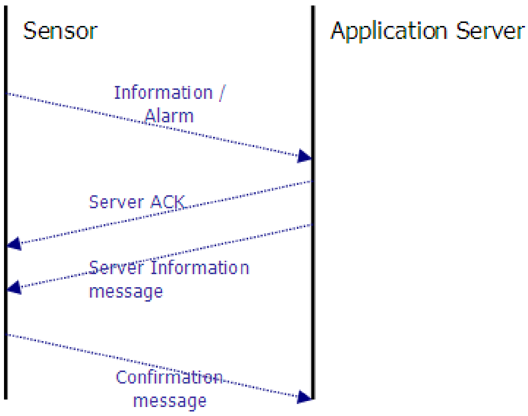

Figure 14. Sensor message behaviour.

2.5. *CHAPTER SUMMARY*

The present chapter introduces the concept of smart grids. A smart grid is a new concept applied to energy power networks that aims provide full connectivity and control over the electric network based in the communication and control of the devices included in the network. Standards like the NIST, describe the network in seven important domains; generation, transmission, distribution, customers, markets, operators and service providers. The last the domains are included from the traditional power grids to include a better performance of the network. Also, smart grids are seen as a multidisciplinary concept where the power systems, the communication architecture and the information technologies are the three important elements of these grids as presented by the IEEE P2030 standard. These two standard bring ideas and present challenges for the described domains and technologies related.

Smart Grids communication network, are getting a lot of importance in the smart grids, and the need to connect all the users places a big challenge for researchers. Wireless communication networks capable to support diverse QoS requirements, are seen as the solution for these challenges. WiMAX is one of the technologies that provide wide area communication, QoS support and multiple users using diverse applications.

Moreover the definition of the application is an important task in this process which also helps to determine the traffic parameters of the communication architecture of the network. In this chapter the definition of these parameters is presented as well as creation of three important applications such as; smart meter reading, demand side management and sensor reading.

Finally, this chapter presents the application basis and requirements needed to create a communication network able to support smart grids applications. In the following chapter, a study of the communication network parameter of WiMAX is introduced based on the application needs presented on this chapter.

CHAPTER 3.

WiMAX NETWORK ARCHITECTURE FOR SMART GRID COMMUNICATIONS

This chapter introduces various aspects of the Worldwide Interoperability for Microwave Access (WiMAX) IEEE 802.16e standard and its relevance in the design of a smart grid communication architecture. The WiMAX technology has been developed for a wireless broadband network (WBN) that can be used to support most of the communications need in the distribution domain of smart grids. This technology is based on the IEEE 802.16 standard [1, 2].It is supported by the WiMAX forum, initially created on June 2001 [36], and the WiMAX 360 community, which consists of many industrial organizations aiming to provide interoperability of the WiMAX products through certified devices practices.

As claimed by the WiMAX 360 community, WiMAX technology could offer similar services to those provided by high performance Wi-Fi networks with long range capacity [37]. Also, WiMAX can support QoS in a cellular network, providing connectivity to thousands of users connected to the same base station. Moreover, the WiMAX standard could support other diverse types of applications like machine-to-machine (M2M) connectivity which constitutes the foundation of a smart grid communication network.

The WiMAX standard also supports the Wireless Metropolitan Access Networks (WMAN) and Wide Area Networks (WAN) architectures. WiMAX networks have been designed to operate in NLOS (No Line of Sight) mode when the carrier frequency is 11GHz or below. The network operates in the LOS (Line of Sight) mode between 10 to 66GHz operating frequency. In addition, it can use two types of channel structure: Single Carrier (SC) and Orthogonal Frequency Division Multiplexing (OFDM). WiMAX network data rates could go up to 70Mbps depending on the radio channel condition and the type of Adaptive Modulation and Coding

(AMC) used, and the coverage radius could go from 0Km to 50Km [29]. This chapter reviews the IEEE 802.16-2009 version of the WiMAX standard commonly known as the 802.16e [2] In addition, some modifications proposed by different researchers are also studied in the following sections

3.1. WIMAX PHYSICAL LAYER SERVICES

The physical layer of the WiMAX standard is first reviewed as it plays an important role in the design of wireless communication networks for the smart grid. The Physical layer controls the performance parameters of a network which determine the capacity and size of a cell as well as the procedures for network entry, power management, and resource allocation in close cooperation with the MAC layer. This section presents the basic aspects of the WiMAX physical layer in relation to the design of the smart grid architecture.

3.1.1. NETWORK ENTRY PROCEDURES

When a device enters in a WiMAX network, several procedures need to be executed before it is considered as an active device. This section explores the first procedure called the ranging process. The ranging process allows the device to synchronize with the timing of the network and perform power adjustments for data transmission based on link quality.

The first issue to consider for a device joining the network is to scan the DL broadcast messages and synchronize the device with the frame timing of the BS. That means it is necessary to find the preamble field in the OFDMA frame by scanning the possible DL channels and then collect the downlink map organization (DL-MAP), uplink map organization (UL-MAP), downlink channel descriptor (DCD) and uplink channel descriptor (UCD) messages of the network. These messages are broadcasted with the strongest modulation and coding scheme, i.e. QPSK with the ½ rate coder.

After the device finds all the configuration data of the DL frame, it proceeds to send an initial ranging message (RNG-REQ) with a null value in the connection ID (CID) in the initial contention ranging slot, using CDMA codes. If the transmission is successful, the BS responds with a RNG-RSP message containing the ranging status, the timing adjustment values, the power adjustment values, an offset frequency adjustment values, basic and primary management CIDs, a MAC address of 48bits, a DL burst profile or a ranging subchannels among other response information.

Then, the users move on to send the initial ranging message called the DBPC-REQ using a selected power level where the transmission power is denoted by Equation 1:

$$P_{TX\_IR\_MAX}[dB] = EIRxP_{IR,\max}[dB] + BS\_EIRP[dB] - RSS[dB] \tag{1}$$

Where *EIRxP* is the maximum equivalent isotropic received power at the subscriber stations, *BS_EIRP* is the equivalent isotropic transmitted power by the BS (this value is transmitted in the DCD message). *RSS* is the Received Signal Strength.

Using Equation 1, initial power corrections are achieved by calculating the path loss based on the received power, the BS transmitted power, and the sensitivity of a receiver. However, the calculation is not precise because the usage of different channels on the UL and DL are different. Hence, the BS responds with a DBPC_RSP message correcting or leaving the actual power transmission level. This process could end in three different scenarios: first, there is a ‘success’; hence, the ranging and the initial ranging processes are over. Second, there is a ‘continue’ ranging process with new tuning parameters for the SS power values. Third, there is an ‘abort’ ranging, when the BS decides to terminate the ranging process unsuccessfully. Although, if the first RNG_REQ message does not arrive at the BS, the SS sent the RNG_REQ message again incrementing the transmission power by 1 dB steps. The retransmission and the power increment processes continue until it reaches the maximum transmission power.

Once a device receives the ‘success’ RNG_RSP message, it is connected to the network. However, the connection stage does not imply an activated stage. In order to activate the device, the following process needs to be completed. A SS authorization and key exchange provide security levels for the data transmission and authentication of the connected device. Following the above process, registration to the network must be completed to identify the device inside the network. A SS should establish the IP connectivity using the Dynamic Host Configuration Protocol (DHCP) services to acquire an IP address. Finally, it establishes a service connection through the Dynamic Service Addition (DSA) service procedure. This last process is detailed in section 3.2.1. which is mandatory for every network entry procedure.

3.1.2. POWER CONTROL MECHANISMS AND QUALITY OF LINKS

Transmission power control in a WiMAX network is an open field of research according to the standard and is up to researchers to explore the best power management techniques. However, the standard introduced three procedures to manage power control: No power control, Open-loop control and Close loop control.

With no power control technique used, the SS uses the transmission power value of the last iteration of the initial ranging procedure and maintains that value for the rest of the SS activity, independent of its status, i.e. whether it is in the sleep or in an active state. The no power control option could be implemented in low complexity receivers which can operate in a fixed radio propagation environment such as monitoring of electricity grid in open or rural areas.

The open-loop control technique is a simple procedure that aims to minimize the SS's transmission power by targeting a specific received signal-to-noise ratio (SNR) at the BS receiver. Using the OFDMA link, this procedure aims to satisfy the link power requirements consistent for UL connections, because it aims at maintaining same received power level at the BS for all UL connections, irrespective of their locations. The BS receiver is configured with a range of receiver sensitivity using typical value of -110dBm/subchannel for the lower limit and -10dBm/subchannel for the upper limit, with a middle value of -60dBm, used as a target value. These values are used in the simulation to maintain low bit error rate (BER). The received SNR is given by Equation 2 and the power received is given by Equation 3.

$$SNR_{rx}[dB] = Pw_{tx}[dB] + A_{gainTx}[dB] + A_{gainRx}[dB] - Noise[dB] - PathLoss[dB] \quad (2)$$

$$Pw_{rx}[dB] = Pw_{tx}[dB] + A_{gainTx}[dB] + A_{gainRx}[dB] - PathLoss[dB] \quad (3)$$

where: SNR_{rx} is the signal-to-noise ratio in the receiver, PW_{tx} is the transmitted power, A_{gain} is the gain in the antennas, *Noise* is the decibel value of the noise and the *Path Loss* is the path loss calculated for a specific distance.

Figure 15 presents the calculated received power for a SS at different distance from the BS using three diverse path loss models: Free space and Erceg with type A and C proposed by the WiMAX group [38]. The path loss models Erceg A and C refers to the propagation of hilly and flat terrains respectively. In addition, the models Type A and C are also used in this thesis to simulate urban and suburban scenarios. Using the path loss value and the receiver sensitivity distance between a BB and a SS can be selected. The author used type A and C variations of the Erceg model including the variations of the shadowing fading expression. Figure 15 shows that the maximum distance is 4.6Km for the Type C configuration when the receiver sensitivity of -110dBm/subchannel is used. This implies that the sensitivity of the transmitter should be decreased or the maximum transmission which is typical used in WiMAX receivers' power should be increased in order to achieve long-range communications. Details of the configured parameters and discussions about the propagation, path loss model and the shadowing fading implications are presented in section 4.3.

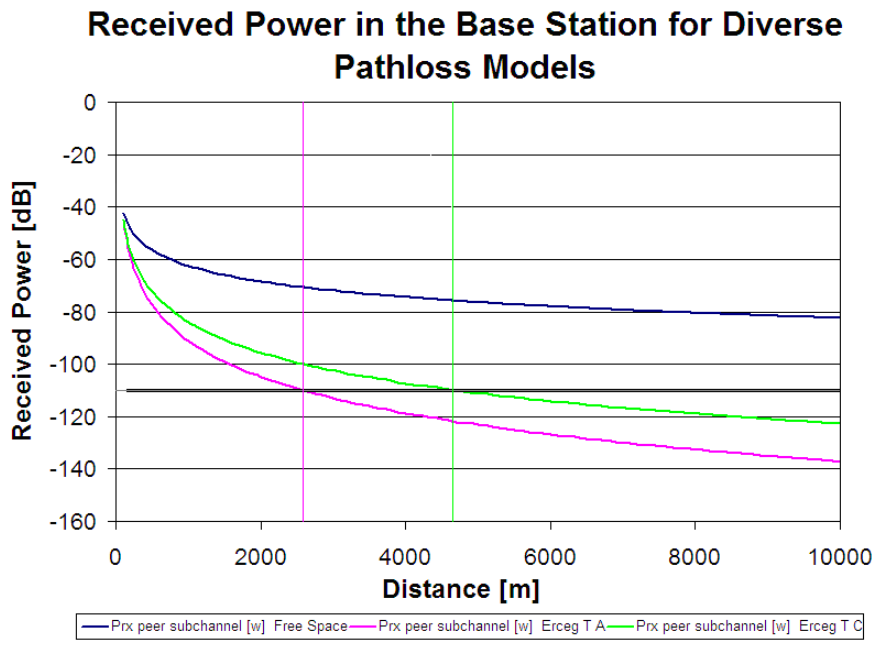

Figure 15. Example of received signal power for different distances using a TX power of 62.5mW.

The power control algorithms are initiated after the ranging process is completed. The control process, that takes place in the BS, uses the path loss reported by the SS in the periodic ranging or in the bandwidth request process to calculate the SS transmitted power. The power control algorithm sets the target value of the received power at the receiver device. If the measured received power in the device is higher than the target value, then it sends a PMC_Req message to reduce the BS transmitted power level. On the other hand, if the received power level is too low then it sends a PMC_Req to increase the transmitted power level at the BS. The transmitted power level is increased in a step-by-step fashion where 1dB is the default step size. Figure 16 presents the SNR measured at the BS for a user with three diverse path loss models using both the no power controller and open loop control options. The results show that the reduction of the SNR in the first kilometre of the graph. The plot also shows the effect of open loop control technique. However, when the received power is out of the limits of the receiver sensitivity, the SS tries to increase the transmitted power but the maximum power level limits the value, so it is automatically reduced to the ranging stage, being half of the maximum power, the default value. This parameter could be modified in the ranging and network entry algorithms.

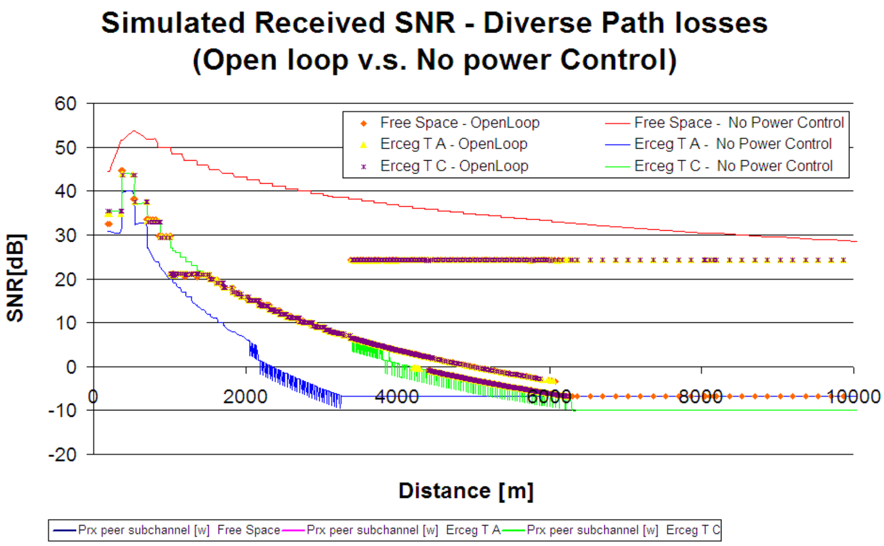

Figure 16. SNR values for different path loss models for different distances.

3.1.3. WIMAX OFDMA FRAME STRUCTURE

The OFDMA (Orthogonal Frequency Division Multiple Access) is a multiple access technique to share the access channel in wireless networks. The WiMAX physical layer could be used either as a single carrier mode (SC) or in multicarrier mode using the OFDM channels. Using the OFDMA access mode sets of subcarriers are divided in equal groups called the subchannels. A block of subchannel/symbols could be assigned to each device, implementing interference free multiple access mechanisms. Figure 17 shows an example of the multiple access capability of the OFDMA.

The number of supported carriers is determined by the Fast Fourier Transform (FFT) size. The supported values of FFT size for WiMAX are 2048, 1024, 512 and 256. These numbers describe how many subcarriers are allocated for the bandwidth of the network. Usually for a 20MHz WiMAX network 2048 subcarriers are allocated. Despite that WiMAX uses subcarriers to send information, power measurements are implemented in a subchannel basis.

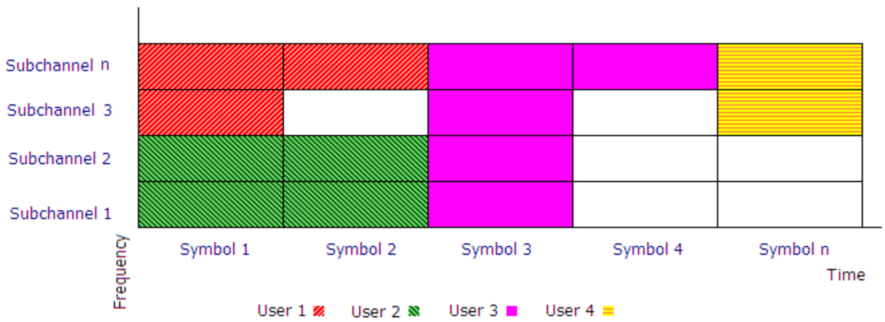

Figure 17. Example of the OFDMA multiple access technique.

The total length of a symbol is determined by the carrier frequency. The symbols are divided into useful duration and the guard time. The useful symbol duration is the inverse of the difference frequency in-between contiguous subcarriers, in this case is 89.6 μsecs. The useful duration of a symbol is determined by the number of subcarriers. In this mode, a sampling factor of 8/7 is applied, it converts the available 20MHz bandwidth into 22.857MHz, and then the bandwidth is divided by the number of subcarriers which gives a delta spacing of 11.160 KHz, which inverse of 89.6μsec for the symbol duration. The guard time is defined as 1/8 of the useful duration which is equals to 11.2 μsecs. Hence, the total symbol time is 100.8 μsecs. Equation 4 present the calculations used to find the total symbol time in the OFDMA frame.

$$
\begin{array}{ll}
AvaiableBw * Sampling = TotalBw & 20MHz * 8/7 = 22.857MHz \\
\frac{TotalBw}{\#Subcarriers} = \Delta Freq & \frac{22.857MHz}{2048} = 11.16KHz \\
\frac{1}{\Delta Freq} = UsefulSymbol & \frac{1}{11.16KHz} = 89.6\mu s \\
UsefulSymb * 1/8 = GuardT & 89.6\mu s * 1/8 = 11.2\mu s \\
UsefulSymb + GuardT = TotalSymbol & 89.6\mu s + 11.2\mu s = 100.8\mu s
\end{array}
\quad (4)
$$

To be able to support bidirectional connectivity, the OFDMA frame is configured in a Time Division Duplexing (TDD) mode, where the first part of the frame is for the DL communication, called the DL Subframe, and the second part is for the UL communication, called the UL Subframe. The number of symbols in each subframe could be variable or fixed. The number of symbols in a subframe is determined by the instantaneous capacity of a channel. This procedure takes place in the mapping and allocation processes. Morsy *et al*, present an algorithm for the dynamic allocation of the DL-UL allocation based on the power and channel allocation algorithms to predict the number of symbols that could optimize the channel capacity [39]. The subchannel allocation algorithm computes resources using traffic information which could introduce large computational load on the BS mapping algorithms that could introduce additional processing delay in the network. This algorithm tries to optimize system capacity by balancing the QoS performance.

In this thesis, a fixed resource allocation algorithm is used where the UL traffic volume is relatively higher than the DL traffic. At the same time it was considered that the DL subframe consumes a fair amount of frame capacity for transmitting the DL-MAP and UL-MAP information. Therefore, to achieve a reduced frame complexity a fixed frame partition structure is used.

The TDD-OFDMA frame structure is presented in Figure 18. The frame size has a length of 5 milliseconds as the value defined by the IEEE 802.16e standard [1]. The total frame is divided into several fields: DL subframe, transmission to reception time gap (TTG), UL subframe and reception to transmission gap (RTG).

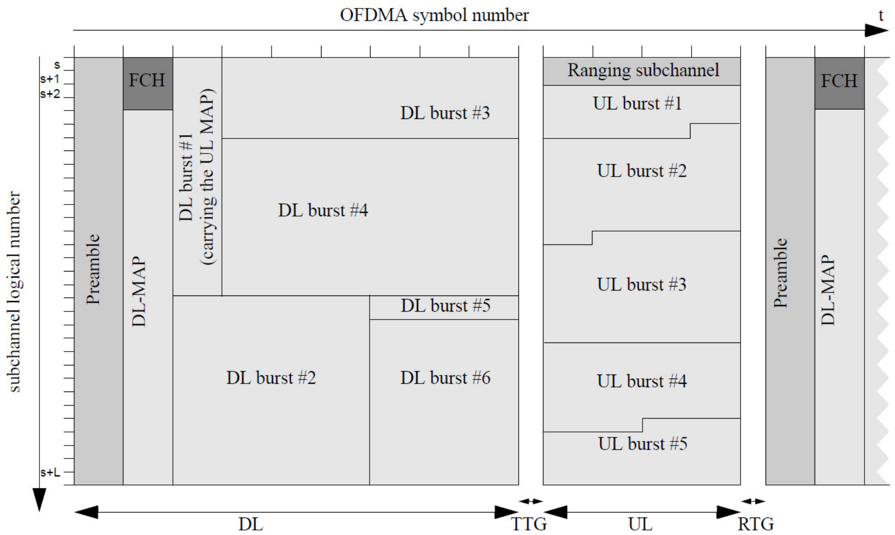

Figure 18. OFDMA WiMAX frame structure. Based in [2]

The TTG and RTG gaps are used to allow the antennas to switch from transmission and reception modes and vice versa. Selection of time values for the gaps is left to the network designers; this information is included in the FCH field of the frame. Using the frame configuration, this work uses 106µsec and 60µsecs for TTG and RTG fields respectively. The specific value of the TTG was selected based on the cell diameter restriction. For a long transmission range some of the SS who are located at the edge of the cell may have to transmit their frame in advance to compensate the propagation delay. This process is accomplished by the timing advancement process. In order to avoid collision between the last DL-frame and the earliest UL frame for the distant user, the maximum distance is determined by Equation 5 and 6.

$$d_{FurthestSS} = \frac{c*TTG}{2} \tag{5}$$

$$d_{FarthestSS} = \frac{3*10^8*106*10^{-6}}{2} = 15.9Km \tag{6}$$

where, c is the propagation speed and TTG is the transmitter to receiver gap.

The DL subframe structure

The DL subframe is composed of a preamble, frame controller header (FHC), DL-MAP information slot, UL-MAP information slot and the DL data bursts. The preamble is a one-symbol message transmitting one of 128 distinct patterns, transmitted using all subcarriers which are BPSK modulated. This preamble is used for the initial and handoff synchronization of users, cell/sector identification and channel estimation purposes [40]. The frame control header (FCH) contents the information of size and position of the DL-MAP and UL-MAP messages. It is transmitted in four adjacent subchannels at the beginning of the DL Subframe using QPSK modulation and ½ rate coding rate.

The DL-MAP contains information about the DL subframe structure. First, it defines multiples zones in the frame. Then it defines the position of each data burst through the inclusion of the DL-MAP IEs (DL mapping information elements). This information element contains the symbol offset, subchannel offset, number of OFDMA symbols, number of subchannels, CID of the destination user and transmission power boosting information. Figure 19 depicts the relevance of these parameters in the DL subframe. The UL-MAP in OFDMA contains the information on the UL subframe. It has the same configuration as the DL-MAP, but it uses the UL-MAP IE instead. The size of the DL-MAP and UL-MAP is increased with the number of users which could be a typical scenario in a smart grid network; hence it is important to minimize these fields in a network to optimize data capacity.

The UL Subframe structure

The UL subframe contains the initial ranging zone, the periodic ranging zone, a contention zone, a fast feedback channel and the UL data bursts. The definition of positions of each zone and data bursts are in the UL-MAP.

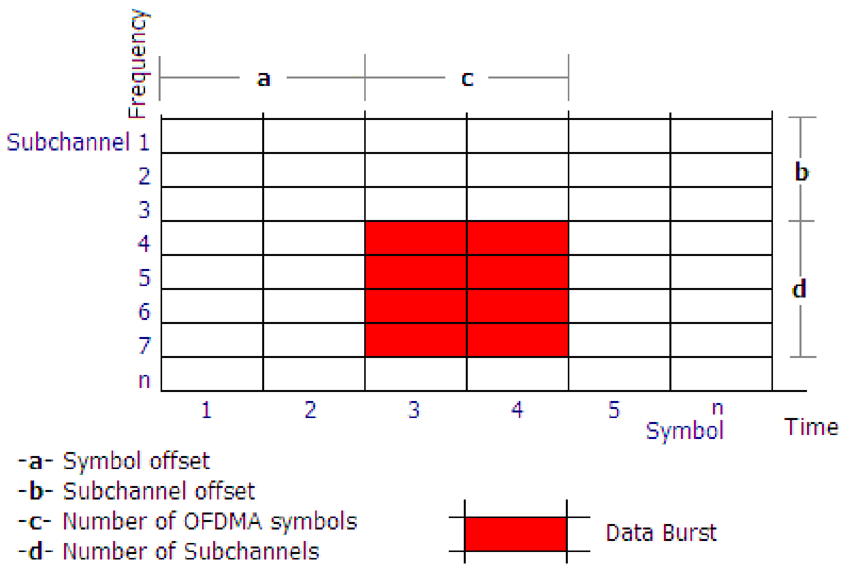

Figure 19. The OFDMA channel Mapping information elements.

The ranging zones are defined for those devices that are entering the network and need to send information to the BS, or for those who have lost synchronization. The contention slot is used for the devices that are polled in the multicast/broadcast mode (see section 3.2.3). The fast feedback channel is used to provide channel quality information from specific users in order to adjust transmission power characteristics through the CINR reports. Finally, the UL subframe contains the UL data burst from the allocated users.

3.2. WiMAX MAC LAYER SERVICES

The WiMAX MAC services in a WiMAX network are in harmony with the physical layer that provides access to users and maintain their QoS requirements. This section explains the data transmission process following the network entry process. When a terminal enters a WiMAX network, it is accepted after following the network entry procedures. Then the terminal requests the BS to admit it in order to be able to send and receive data according to different QoS parameters. Following the admission of connections, if the terminal wants to send data it has to send a resource request with the size of the information it wants to transmit. The BS receives the request and delivers it to the schedulers. When the schedulers grant the required bandwidth, a transmission space is allocated to the specific SS in the UL-MAP. The SS uses the allocated space to transmit the desired data and the transmission is assumed to be successful.

WiMAX technology supports QoS in the MAC layer through the definition and utilization of techniques that are described in the following sections. Services classes, traffic classifiers, service flows, bandwidth request, scheduling, mapping and allocation are the basic techniques that support QoS in the network.

3.2.1. TRAFFIC SERVICES CLASSES

A number of service classes are used in a WiMAX network to offer flexibility to different services across several BSs. Thus the WiMAX network removes the task of generating service classes at the servers; instead, these classifications are generated at the BS. The aim of these service classes is to define different levels of QoS for different traffics sources. Specifically, the priority level is an important service parameter which defines how a particular class will be serviced. The priority level is served by the schedulers, which allocate the maximum sustained traffic rate (MSTR), minimum reserved traffic rate (MRTR), Maximum latency, Maximum traffic burst, and the Unsolicited Grant Interval (UGI) and Unsolicited Polling Interval (UPI) which are relevant for smart grid applications.

Various schedulers define the procedures used to support various traffic flows. According to the WiMAX standard, the scheduler uses the next service classification to allocate resources. These services are: unsolicited grant service (UGS), extended real time polling service (ertPS), real time polling service (rtPS), non-real time polling service (nrtPS) and best effort. However, if different applications need the same class of service with different parameters, then they can be differentiated by other service parameters depending on the scheduling algorithm used.

Scheduling algorithms are used to describe how the traffic of a certain application is going to be handled by a BS. The UGS is designed for constant rate video applications because it serves a constant traffic rate of fixed packet sizes in a periodic manner. The ertPS class is used for voice calls with silence suppression because this class is designed for variable burst sizes with periodic allocations. The rtPS class is used for delay sensitive applications that do not need frequent allocations like error and alarm messaging. The nrtPS class provides a minimum QoS support for delay sensitive applications with low data traffic rate. Finally, best effort connections do not support delay constrains and it resource allocations could be done based on the network’s resource availability.

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 upper layer protocols. The MSTR parameter is calculated based on a long term average of transmission bursts rather than using the instantaneous burst size. Finally, this parameter provides an upper limit of the data transmission but the BS it is not obligated to serve at this rate. Instead, the MRTR presents a lower limit to the traffic rate that the scheduler needs to guarantee to the particular connection.

The maximum burst parameter, similar to the MSRT, defines the maximum transmission rate of an instantaneous burst. This value is configured in bits per second and the size of the burst in a frame is calculated according to the size of the OFDMA frame.

The maximum queue latency, represent 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 a transmission.

The Unsolicited Grant Interval (UGI) and the Unsolicited Polling Interval (UPI) are considered as the same parameter used for deferent scheduling types. The UGI is defined as the time between consecutive grants for UGS and ertPS connections. It is calculated dividing the configured average burst size by the UGS_{MRTR}, and is only used for UGS and ertPS connections. The UPI or Inter-polling Time (IPT) is used for rtPS and active nrtPS connections. It is defined as the time between consecutive polls. The last parameter is discussed in detail in section 3.2.4.

As examined in section 2.4.1, the service classes for smart grid applications relate to the priority of the data generation with the type of service and latency used of these applications. Table 14, presents the most relevant nrtPS and rtPS parameter values of the service classes used for smart grid applications

Service Class name	Scheduling type	MSTR	MRTR	Maximum burst	Maximum latency	Interpolling time
Metering	nrtPS	40bps	40bps	1kbps	N/A	500 sec
Demand	rtPS	100bps	100bps	1kbps	150 sec	120 sec
Sensor	rtPS	200bps	200bps	1kbps	150 msec	100 msec
Default	BE	1kbps	NA	NA	NA	NA

Table 14. Service class definition for smart grid.

The traffic classifiers used in the SSs and BSs are responsible for allocating packets from users/server to a particular service class and posterior service flows. They use the IP type-of-service (ToS) field in the IP header of the packet that is going to be delivered and already assigned to a service class, as described in section 1.4.1. The classifiers are mandatory and are an essential part of the QoS differentiation procedures in the network. According to the data generation priority of the defined application, and the ToS defined in section 1.4.1. Table 15 present the classifier Table used for smart grid applications, showing the relation between the IP ToS flag assigned to each packet and the service class that should be assigned to the packet. If some packets do not match with the IP ToS in this Table, then the packet is assigned a best effort connection, which is the default classification.

IP ToS	Service Class name	Scheduling type
Excellent effort (3)	Metering	nrtPS
Streaming Multimedia (4)	Demand	rtPS
Interactive Multimedia (5)	Sensor	rtPS
Rest	Default	BE

Table 15. Classifier definition for smart grid.

3.2.2. SERVICE FLOWS

A Service Flow (SF) is a unidirectional traffic connection that offers particular QoS levels described by the service class attached to it [6]. A device can have many SFs, and each SF is described by a Service Flow ID (SFID), QoS parameters and a connection label. The QoS parameters are divided in four steps representing the four stages of a SF: Provision, Authorization, Admission, and Activation. The provisioned SF is a connection that is created in a SS but has not been reported to the BS. The authorized SF is categorized for those SF that change the QoS parameters and requires a new allocation. In this case, the SF is considered authorized but not operational. The admitted SF is used in two different scenarios. The first one is when a user has a connection but is not transmitting data on it. The second one is when the user is attempting to send information, but the whole end-to-end connection is not completed. This is the typical stage of all SFs in this work, because this stage protects the SFs from bandwidth stealing. Finally, for a user to transmit data needs to activate its SF. In this case, the SF has allocated recourses to transmit information. Each active connection has a Connection Identifier (CID) that has a unique value in the network and is used only for the admitted and active SFs. The set of messages that change the SF from different stage are called the dynamic service allocation (DSA).

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 Controller limits the number of connections in a network by examining each configured SF bandwidth parameters and compares them with the available capacity to decide whether to accept or reject a particular connection. This process is made when the user enters in a network after the user has been accepted in the network subsequent to the completion of the ranging process (See section 3.1.1). Notice that users could be accepted in a network but its connections could be rejected because network capacity is already exhausted. All the users in the network should create a Basic connection used for data exchange between a BS and the SSs.

All SFs are described by its parameters including the service class. Also, they select the modulation and coding scheme (MCS) values used for this SF, the size of the queue, the average service data unit (SDU) or the packet size, the idle timer applicable for nrtPS connections and the retransmission methods like automatic repeat request (ARQ) or hybrid automatic repeat request (HARQ).

Table 16 presents the service flows configured into the applications used in a smart grid model. It is important to recall that not all service flows are configured on all the devices. Only the service flows for devices' specific applications are configured. Specifically, a simple meter configures two metering SFs for UL and DL respectively. Instead, the smart meter with demand capabilities configures four SFs: two for metering and two for demand. Additionally, for sensor application just two sensor SFs are configured. Each SF is mapped onto the one of the service classes presented in Table 16 according to the application's needs. The MCS is constant using the QPSK modulator and a ½ rate FEC coder the strongest modulation and coding scheme to support long distance transmissions. The Average SDU size is set to 1 Kbyte which is the average value of packets generated by the application layer. The buffer size is configured to 128Kbytes to allow up to 128 connections within the same frame. In this case, a large number is considered for DL connections from the BS to different SS's. Finally, the retransmission parameter is set to zero for the meter reading application because the low priority can tolerate certain packet losses implementing retransmission for this class of traffic will unnecessarily increase the network traffic load. Instead, the 'important' and 'critical' values for demand and sensor applications requires a level of retransmissions to assure that the information is properly communicated, that is why the ARQ is set up for these connections.

Application	Device	Service Class name	MCS	Average SDU	Buffer Size	Retransmission parameter
Meter reading	Meter	Metering	QPSK+½ rate coder	1Kbyte	128kbyte	None
Demand management	Meter	Demand	QPSK+½ rate coder	1Kbyte	128kbyte	ARQ
Sensor reading	Sensor	Sensor	QPSK+½ rate coder	1Kbyte	128kbyte	ARQ

Table 16. Service class definition for meters and sensors in smart grids.

The WiMAX standard defines dynamic service flows that could change QoS parameters according to the traffic class of a particular SF. In this case Dynamic Service Addition (DSA) protocol is used. The DSA protocol aims to manage efficiently the resources of a WiMAX network by changing the state of a SF according to its usage. It characterizes the SF to be in one of these three states: Provisional SF (when the SF is created but there are no resources allocated), Admitted SF (when the SF is admitted but there is no traffic to be sent) and Active SF (transmitting data). The DSA protocol works on a management-messages basis. The initialisation of the protocol could starts at the BS or in a SS. The BS initialisation process is explained below. The BS sends a DSA-Req message to a SS. The SS replies with a DSA-Rsp message containing information about the new SF. Then the BS sends the acknowledgement message DSA-Ack. When the traffic on a flow changes, a set of Dynamic Service Change (DSC) messages is exchanged between the BS and the SS containing a new flow information (i.e.: Bandwidth requirements). Finally, a SF could be deleted with set of Dynamic Service Deletion (DSD) messages. Detailed procedural description can be found in the section 6.3.14.7 of the IEEE 802.16-2009 standard document [6].

3.2.3. BANDWIDTH REQUEST TECHNIQUES

For smart grid applications the nodes need to request transmission opportunities to transmit their data on the air interface. These bandwidth requests (BWReq) are defined when a UL connections from a SS request for opportunities to transmit their data. The resource allocation mechanism depends on the service class of the traffic as well as on the connection and the configuration of the services. The allocation process works in the following way. First, users enter in a network and get connected to a BS where all the connections are initialized. Second, if the user wants to send data, it sends a resource request with the size of the information it wants to transmit. The BS receives this request and delivers this request to a scheduler based on the traffic classification. Third, when the schedulers grant the requested bandwidth, a transmission space is allocated to the specific SS on the UL-MAP. Finally, the SS uses that allocated space to transmit the desired data. However, there are three variations for this mechanism defined in WiMAX namely: i) Unsolicited Bandwidth Grants (UGS), ii) Unicast Polling and iii) Contention-based Polling which are explained below.

Unsolicited Bandwidth Grants

Unsolicited Bandwidth grants are just defined for UGS connections and are described from the initialization point of view. The main advantage of UGS connections is compared to the other methods is that the SS does not need to ask for resource allocation afterwards. Instead, periodic allocations are made based on the Minimum Reserved Traffic Rate (MRTR) and the Maximum Latency (ML) period parameters. Defining the parameter B as the size of the allocation in a specific frame and N as the number of frames between allocations, the values of B and N can be calculated using the Equations 7 and 8 which are listed below.

$$B[bits] = MRTR[bps] * ML[\sec] \tag{7}$$

$$N[frames] = \frac{ML[\sec]}{frame\_duration[\sec/frames]} \tag{8}$$

where *MRTR* is the maximum reserved traffic rate and *ML* is the maximum latency.

Equation 8 means that in every *N* frames, the BS allocates *B* bits to the particular SS with an active UGS connection. The value of *N* is recorded in the UGI, a 6 bit code is defined in Table 189 of the 2009 WiMAX standard document [2]. Nonetheless, if the SS does not have any information to transmit, this allocation is wasted.

Unicast Polling

Unicast polling is one of the most common methods for bandwidth request in the WiMAX network and could be applied for rtPS, nrtPS and BE connections. This procedure is divided in two phases; the polling and the BWReq.

By definition, a poll is an opportunity to send a BWReq to the BS. The WiMAX standard defines this opportunity as an allocation in the UL subframe of the size of a MAC Header (48bits). In this case, the polled SS could respond using a MAC signalling header Type I or transmit simply the padded bits if no BWReq is going to be made. The structure of this message is presented in Figure 20. First two bits of the message represents the type of header and the encryption control which should be set to 1, 0 respectively. The type field describes the kind of bandwidth request that is made, like incremental or aggregate among others. The next 19 bits, represent the bandwidth requested measured in bytes. The next field is the users' CID. Finally, the HCS field represent the check sequence which provides the integrity of the information inside the header with a one- CRC.

When a poll is issued, it could be defined as a solicited poll or an unsolicited poll. There is only one way to generate solicited polling which is through the poll-me bit (PM). The PM bit is part of the Grant Management Sub Header (GMSH) and it is only present when there is a UGS connection. This mechanism is a part of the Piggyback request mechanisms and is used in UGS connections to alert the BS that a non-UGS connection needs to be polled.

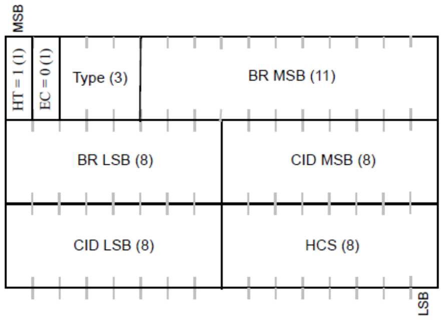

Figure 20. MAC signalling header Type I (BW-Req format) [2].

The unsolicited polls depend on the service class that is configured for connection. For the rtPS, the polling interval is labelled in the UPI and follows the same six-bit code of the UGI presented in Table 17. This Table presents some values of the UPI that are used in this thesis. In the particular case of smart grids applications, the values of the interpolling times could vary from 100ms to 500seconds as defined in Table 14, hence the reserved values should be used because using a 5ms frame time, the defined values set the interpolling times from 5ms to 1 second.

On the other hand, the nrtPS connections are not obligated to use the UGI. Due to the nature of the nrtPS connections, a polling interval is not mandatory for these connections; nonetheless, a way to support the minimum required rate should be provided. In this thesis, the nrtPS connections use the same configuration parameters of the rtPS. The only difference is that the level of priority inside the schedulers is less than the rtPS connections one.

6-bit code (binary)	Interval (frames)	Interval (time for a 5ms frame)
000000	Reserved	Reserved
000001	1	5ms
010010	20	100ms
110100	200	1sec
110101	Reserved (640)	3.2 sec
110110	Reserved (10000)	50 sec
110111	Reserved (20000)	100 sec
111000	Reserved (24000)	120 sec
111001	Reserved (40000)	200 sec
111010	Reserved (60000)	300 sec
111011	Reserved (80000)	400 sec
111100	Reserved (100000)	500 sec
111111	TLV	TLV

Table 17. Selected Unsolicited grant intervals and unsolicited polling intervals used in the project based in Table 189 of the IEEE 802.16-2009 Standard [2]

The UPI or IPT is the time between two consecutive poll generations. There is two ways to define the IPT in a WiMAX network, it could be set during the connection creation or could be calculated based on the Expected Packet Rate Time (EPRT). The expected packet rate time is calculated using the average SDU size as shown in Equations 9 and 10 [41]:

$$ExpectedPacketRateTime[\text{sec}] = \frac{Ave\_SDU\_size[bits]}{mrate[bps]} \qquad (9)$$

$$mrate[bps] = \begin{cases} Max\_Sustained\_Traffic\_Rate \Rightarrow rtPS \\ Min\_\text{Re}served\_Traffic\_Rate \Rightarrow nrtPS \end{cases} \qquad (10)$$

The ratio between the expected packet rate time and the IPT is configured for each connection, which gives an idea of how often polling should be made compared to the traffic need as described in Equation 11. If this relation is too high, it means that the IPT is too long and the connection will suffer from capacity starvation. On the contrary, if the ratio is too low, the IPT will be too short, leading to unused allocation opportunities and wasted UL capacity. To avoid these extremes a minimum and maximum ratio is implemented. In smart grid communication networks, the introduction of these limits helps setting proper values of MSTR and MRTR for admission procedures, and offers some freedom in the configuration of IPT. The maximum ratio, in this case set to 5, avoid packet starvation due to longer poll time. On the other hand, the minimum ratio of 0.01 is set to avoid unnecessary polls that could lead to wasted polls and capacity.

$$MinPollRatio \le \frac{IPT}{EPRT} \le MaxPollRatio \qquad (11)$$

After a user is admitted in a network and its polling services are created after, the connections are established and the polls are started to be issued. The first poll is issued following after the time interval described in Equation 12.

$$first\_poll\_time = Actual\_time + UniformDistribution(0, IPT) \qquad (12)$$

The uniform distribution function is applied for the first poll to help to reduce the chance of poll congestions when a large number of users are entering a network at the same time. Such scenario can be found in a smart grid communication network. After the initial poll, periodic polls are issued spaced by the IPT. In the polling process, the rtPS connections are polled every IPT time, as shown in Equation 13. However, for the nrtPS connections, the polls are only generated if the user is not in a power-saving mode. If a device is in power saving mode, the poll is deferred for another IPT and a counter of deferred polls is increased.

$$next\_poll\_time = Actual\_time + IPT \quad (13)$$

The next poll time usually is not the same time as the OFDMA is created; hence, these polls need to be allocated in a *poll queue*. This buffer contains the UGS allocation for UL transmission and the polls for the rest of the active connections. The buffer is firstly filled with the UGS allocations, then with the rtPS polls, continues with the nrtPS and finalise with the BE polls that have been created in the last frame period. Next, in the frame creation process, this buffer is read in a priority fashion, starting with the UGS allocations, then ertPS allocations, followed by PS polls and finally the BE polls are used. However, some polls could be not allocated, if a UL-Subframe capacity is exhausted. In this case, the polls are postponed for the next frame creation.

Figure 21 presents an example of the time relation between the moment where a poll is generated and the time when it sends on the OFDMA frame is created. In Figure 21, the red bars represent when a UGS allocation time is due. Then the allocation is put in the head of the staging buffer. The blue bars represent every time a unicast poll is due and need to be put in the subframe. This one is put in the tail of the staging buffer. Finally, in every frame during the mapping process this buffer is emptied and allocated in the UL subframe.

Figure 22, shows the resulting subframe allocation after a typical mapping process, where first field represents the UGS allocations followed by the ertPS allocations, then the PS polls, fourth field contains BE polls and finally the allocated BW. The polling mechanism introduces a polling delay, up to five milliseconds that is the maximum time that a poll is in the temporary buffer, considering that all the polls are served in the same frame.

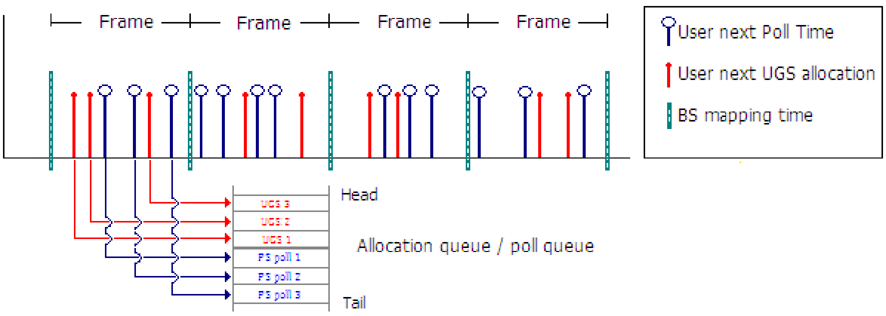

Figure 21. Example of Poll allocation in mapping process.

In the case of best effort connections, they are polled when there is available bandwidth to issue a poll provided the network is not congested. In a network BE polling could be absent for a long time when a network is congested.

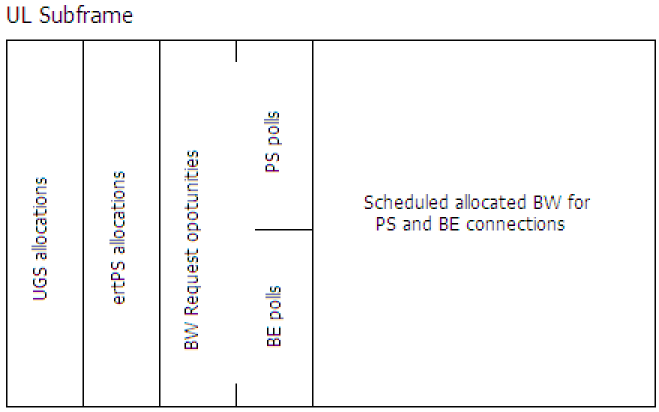

Figure 22. UL Subframe allocations

There are several other proposals defining the polling interval time. Sabri *et al* [42] proposes an adaptive minimum service interval for video application in order to reduce the MAC delay, where the interpolling time is reduced by an opportunistic value derived from the tail of a queue containing PDUs arrival time. Chun *et al* [43] proposed adaptive Polling Service (aPS) is for ON/OFF burst traffic with a variable packet size. This algorithm has a short interpolling time when there is traffic to transmit, but it grows exponentially when there is in idled mode until it reach the T_{max} value. Chun's algorithm reduces the TCP overhead for FTP connections maintaining quite stable the average delay.

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In the analysis of the delay for unicast polled connections, it is important to describe the delay components that could affect the QoS of a connection. The total delay of a successful transmission, i.e. without retransmissions, could be depicted in four different components: *pre-poll delay*, *polling delay*, *scheduling delay*, and *transmission delay*, shown in Equation 14 and depicted in Figure 23.

$$end\_to\_end\_delay = PPoll\_delay + Polling\_delay + Scheduling\_delay + Transmission\_delay \quad (14)$$

The *pre-poll* delay is the time difference between the time a packet arrives in the MAC layer queue of a SS, to time a poll is generated. This delay has a maximum value determined by the IPT. In simulation experiments described in the next chapter, the pre-poll delay is seen as a major component of the total delay of a transmission. Also, in the case of a poll being defer to the next frame due to the exhaustion of the subframe capacity, this delay could grow up to two or more IPT. Such phenomenon is not observed if the average network capacity is higher than the total offered traffic.

The next component is the *polling delay*. It is defined as the time between a poll is being issued by a BS and the time when the BWReq arrives to the BS. This delay could have the values of one or two frame sizes depending on the *burst allocation delay* in the MAP allocation configuration. In order to reduce the value of this delay, the *burst allocation delay* is parameter is configured to be in the same frame having this delay a constant value of five milliseconds.

The *scheduling delay* depends on the congestion level of the scheduler with previous allocations. Its minimum value is one frame size, because the scheduler is not able to process the request in no time to send the allocation in the immediate frame. However, there is a procedure implemented in the mapping process of OPNET's simulation model, that allocates the BWReq as early as possible to allow them to arrive a couple of symbols before the mapping procedures for the next frame by combining the polling and scheduling delay within one frame size. The last delay component is the *transmission delay* and it depends on which block of the ULsubframe is allocated. This delay is typically up to one frame size for short burst transmissions.

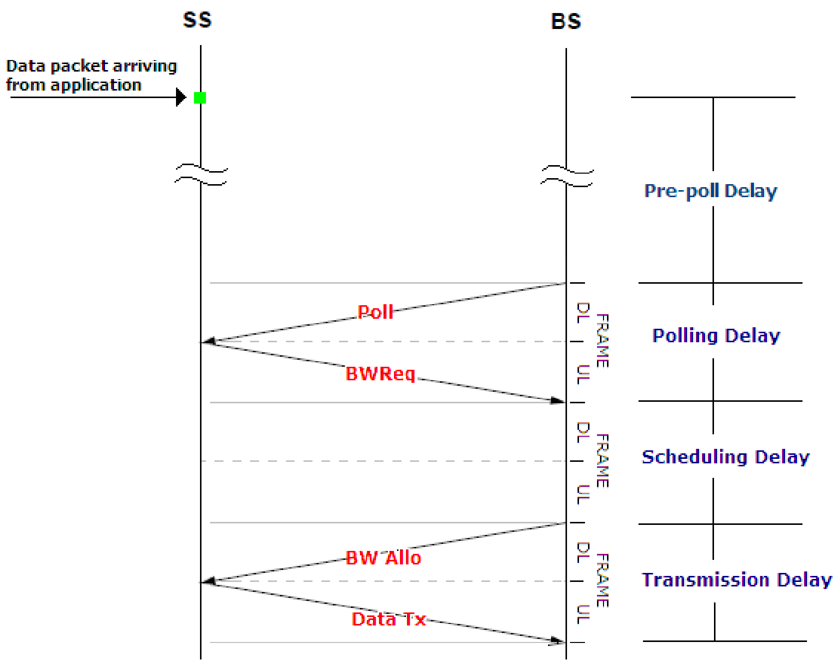


Figure 23. Delay components for allocation using Unicast polling.

Contention-based and multicast/broadcast polling

The contention-based polling is a mechanism used in conjunction with multicast and broadcast transmissions. The principal objective of contention-based polling is to reduce the space used for individual allocations, specifically when the users are idle and do not need to be issued with polls. The BS creates broadcast or multicast groups and assigns users to these groups, creating a group CID. Next, the polling is sent with a group CID of the desired group and is expected that the users in need of transmission to use the allocated space. However, the BS may not be aware of how many users are going to reply and which allocations are going to be used, creating the chance of collisions. In order to solve the issue, the WiMAX MAC protocol proposes that users could respond using the contention area defined for this purpose. There are two types of contention slots in the contention area, namely *initial ranging* and *periodic ranging*. The *periodic ranging* zone is also known as *contention slot* or *Request IE*, because is in this zone where the contention BWReq are sent back to the BS. Due the nature of the contention mechanism, only SS with BWReq needs should respond.

In a WiMAX network, the devices could respond in two ways; first, using only the MAC Header Type I with a stand-alone BWReq as explained in the previous section or; using the CDMA-based contention mechanism, which is explained below.

The CDMA-based contention mechanism uses a series of pseudorandom CDMA codes defined in the standard. The code is selected randomly with equal probability from a set of Periodic Ranging Codes and is introduced in the Ranging Slot Randomly selected. The SS having BWReq to made, sends the CDMA code in the ranging slot waiting for a response from the BS. The SS will wait for that response from the BS. Due to the nature of the CDMA code, the BS is not able to determine which SS has sent the code, hence it replies with a broadcast allocation. The CDMA allocation IE is a broadcast/multicast ranging response message containing the same CDMA code of the requested user. This message, decodes the CDMA allocation IE and use the allocation for transmission. In WiMAX, this allocation is only allowed to send BWReq because has a fixed size of six bytes.

The contention mechanism uses transmission opportunities described as the allocation assigned in the UL-MAP for SS assigned to a particular group. The number of transmission opportunities depends on the size of the allocation made and the size of the BWReqs and should be published in the UL Channel Descriptor (UCD) (i.e. UCD TVL ‘BWReq opportunity size’), Figure 24 shows and example of one Request IE sent in the UL-MAP containing 3 opportunities.

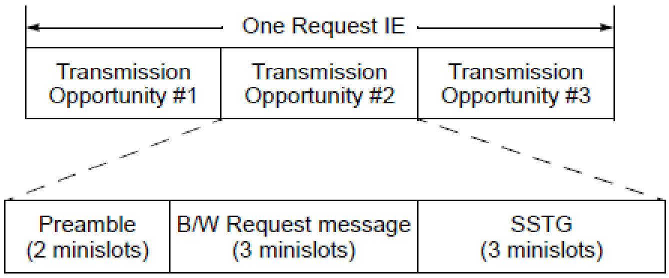


Figure 24. Example of a Request IE.

When a SS connection has information to send through the contention algorithm, it sets an internal back off window equals to the initial size defined in the UCD message. Then, it selects a random number contained in the window. This value represents the number of transmission opportunities that this SS needs to wait prior to sending a BWReq inside a Request IE. Followed by a transmission of the BWReq, the SS have to wait for a response (Data Grant Burst Type IE) within a timeout period. In the case of a contention-based timeout expiry, the SS will assume that the transmission was unsuccessful and collision occurs triggering a reattempt. The SS duplicate the size of the internal back off window up to the maximum size described in the UDC message, and select again a new random value. The reattempt process continues until the maximum Requests Retries value is reached.

Comparison of polling mechanisms

Different types of polling mechanisms need to be analysed according to the characteristics of applications that are going to be implemented. In case of smart grid applications, rtPS and nrtPS are the most common scheduling services used. They could provide the enough resources to support the required QoS without consuming significant network capacity.

According to the WiMAX standard, not all the polling mechanisms could be used for all the scheduling types. UGS connections do not need polling, because they already have fixed allocations. Only they use a piggyback technique to support non-UGS connections to request for unsolicited polls. For ertPS they are allowed any of the polling mechanisms to change the allocated bandwidth. In the case of rtPS connections, unicast and piggyback options are allowed, because they are the only ones that could support real time connections. This is a drawback for the contention polling. For nrtPS and BE connections all of the polling mechanisms are allowed. A list of polling mechanisms is presented in Table 18.

The principal disadvantage of the contention polling is its inability to support real time communications. As explained that a request enters in a random back off window that does not assures a maximum time delay. Hence, delay sensitive applications like emergency sensor or demand meters could not use this technique.

Scheduling type	Unicast Polling	Multicast/broadcast Polling	Piggyback
UGS	Not Allowed	Not Allowed	PM bit for non-UGS connections.
ertPS	Allowed	Allowed	Extended Piggyback
rtPS	Allowed	Not Allowed	Allowed
nrtPS	Allowed	Allowed	Allowed
BE	Allowed	Allowed	Allowed

Table 18. Polling options for scheduling types.

3.2.4. Scheduling Techniques

In a WiMAX network, QoS is managed through the use of packet schedulers. Several numbers of schedulers could be implemented to support the multiclass traffic in WiMAX networks. However not all of them are designed to suit the needs of smart grids applications like low latency, prioritized queuing or high bandwidth in WiMAX networks.

The WiMAX MAC layer, manage the services classes through three different queues (buffers) in the BS. The first queue deals with the granted traffic connections (UGS - ertPS) and usually works in a FiFo fashion. A second buffer is used for the PS (rtPS – nrtPS) connections, serving them with Round Robin (RR) schedulers. In the third queue, the Best Effort (BE) connections are served through another RR scheduler [44]. Finally, between these last two schedulers a priority queue is implemented to serve them. Figure 25 shows the scheduler scheme.

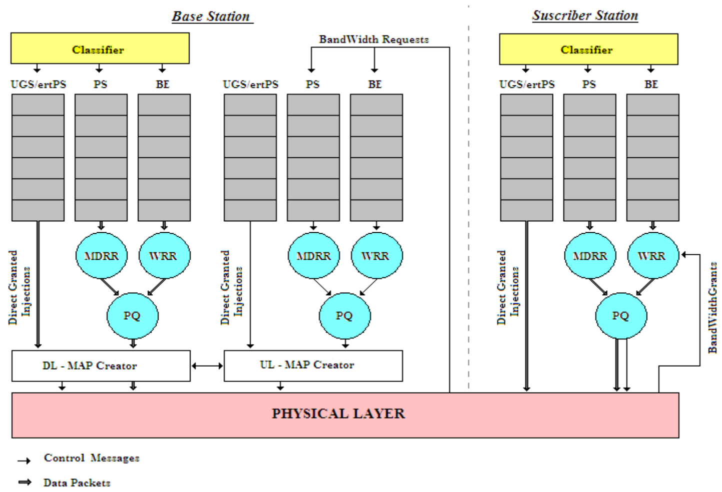


Figure 25. The WiMAX packet scheduler scheme.

Currently there are many scheduling schemes proposed in literature. They can be classified in two groups according to Chakchai [44]: channel-Unaware algorithms and channel-Aware algorithms. Channel-Unaware schedulers use traffic and QoS parameters found in the MAC layer and assume an error-free channel to schedule packet transmissions. Most of them deal with the fairness of the scheduling process, but do not take account of the quality of the wireless channel. First-In First-Out (FiFo), Round Robin (RR)[45], Deficit Round Robin (DRR) [25], Weighted Fair Queuing (WFQ) and the Deadline First family (EDF, LWDF and DTPQ) are examples of channel-Unaware scheduling algorithms. These algorithms are able to work only inside one type of service class. For the ones that work across diverse service classes, Weighted Round Robin (WRR) and Priority Queuing (PQ) are examples of the algorithms used [44].

Channel-Aware scheduling algorithms use traffic and channels information as input parameters in the scheduling process. There are four key objectives to pursuit: i) fairness, ii) QoS guarantee, iii) system throughput maximization and iv) transmission power minimization. A set of advanced Round Robin based algorithms could be found in the literature: Wireless Deficit Round Robin (WDRR), Uniformly-Fair Deficit Round Robin (UF-DRR) [46], Deficit Round Robin with Fragmentation (DRRF) [47] and Customised Deficit Round Robin (CDRR)[48]. Finally, for the utility scheduling algorithms like the one studied by Nascimiento

[49] that is mainly based on the Dynamic Resource Allocation (DRA) technique proposed for the IEEE 802.16e standard.

Round Robin Based Algorithms

For multimedia and machine-to-machine (M2M) communications traffic, it is assumed that each user has a FiFo queue and the queue will be served in a sequential fashion. The RR scheduler may not be able to offer fairness to packets of different lengths in different queues. In order to solve that problem, the WRR algorithm is introduced which assigns a weight to each queue that represents the portion of the available bandwidth for that specific queue. Hence, the number of packets served is proportional to the weight value assigned to a queue. Nonetheless, it still has an unfair behaviour because the value of the weight is proportional with the size of the queue instead of QoS requirements of the queue [45].

The Deficit Round Robin (DRR) proposed by Shreedhar, introduced a deficit counter. The deficit counter is initialised by a value called *quantum*, which reflects the shared bandwidth reserved to this flow. The DRR scheduler visits each queue, adds the quantum value to the deficit counter and compares its value with the size of the first packet in the queue. If the size of the packet is smaller than deficit counter, the packet would be transmitted and the size of the transmission queue would be deducted from the deficit counter. If not, the packet will be held for subsequent rounds until the deficit counter exceed the size of the packet [50]. This behaviour leads to two scenarios. First, if the arriving packet is smaller than the *quantum*, the transmitted data rate will be smaller than the allocated bandwidth, leading to an under-utilised channel. On the other hand, if the packet size is much larger than the *quantum*, the packet will be held in the queue until enough bandwidth is granted leading to increased packet delay. A proper size of the *quantum* should be selected to achieve the connection QoS requirements and an optimal channel usage.

In a WiMAX network, this *quantum* parameter should be directly related and proportional to connection QoS parameters, i.e. Maximum Sustained Traffic Rate and the Minimum Reserved Traffic Rate values. Lailas described the value of the *quantum* = Q_i as shown in Equation 15. The r_{min} represents the lowest reserved rate and r_i the reserved rate for the flow i [48]. Moreover, the values of reserved rates should not exceed the channel capacity as shown in Equation 16

$$Q_i = \left(\frac{r_i}{r_{\min}}\right) * MaxSizePacketInTheRound \tag{15}$$

$$\sum_{i=0}^{n} r_i \leq AvailableChannelCapacity \quad (16)$$

The MDRR is a variation of the DRR algorithm. The MDRR adds a low-latency queue, which is useful for real time connections. It could work in two modes: *Alternate Mode*; when the queue is alternated between the no-low-latency queues, and *Strict Priority Mode*; where no other queue is served until the low-latency queue is fully served. Another important modification of the MDRR is the definition of a Maximum Transmission Unit (MTU), which is the maximum packet size that could be dequeued. In the MDRR the *quantum* value is calculated using Equation 17, where w_i is the weight of the actual queue defined by Equation 18. Equation 19 shows that Q_i should be greater than zero in order to give the opportunity to send at least one packet in the first round. Finally, if the queue is empty, the deficit counter will be reset to zero avoiding a waste of symbols [45].

$$Q_i = MTU + 512 * w_i \quad (17)$$

$$w_i = \left(\frac{MRTR}{TotalCapacity} \right) * 100 \quad (18)$$

$$MTU \leq Q_i \leq \frac{51.200 * MRTR}{TotalCapacity} + MTU \quad (19)$$

3.2.5. RESOURCE ALLOCATION AND MAPPING PROCEDURES

The research on resource allocation for wireless networks includes a wide range of topics. The allocation procedures aim to maximize the capacity of the wireless channel taking into account parameters such as the quality of the wireless channel and the QoS requirements of the packet to be sent. These techniques work in-between the MAC and the physical layer of the WiMAX standard. For these reason, the resource allocation described in this section is based on the OFDMA frame structure of the WiMAX standard. In this case, the OFDMA frame behaves like a two dimensional map where all the packets need to be allocated to be transmitted. On the other hand, the resource allocation works directly with the scheduler to optimize the scheduled packets.

As explained in section 3.1.3, the OFDMA frame structure could be divided in subchannels and symbols across the frequency and time axes respectively. Then, use those divisions to send the data burst. The distribution of the subchannels and subcarriers is part of the mapping process. WiMAX defines in it standard two permutation modes for OFDMA namely *diversity distributed* and *contiguous distributed* [2].

The contiguous permutation aims to use the best channel condition and easy channel estimation. In this mode, the Adaptive Modulation and Coding (AMC) technique is mandatory. It provides the versatility of the diverse modulation techniques according to the quality of the channel.

The diversity permutation aims to provide frequency diversity and intercell interference average based in a pseudo-randomly distribution of the subcarriers. However, the drawback is the channel estimation process becomes more complex. In this permutation mode two mandatory techniques are required namely Partial Usage of Subchannels (PUSC) and Full Usage of Subchannels (FUSC). The first one is mandatory for the UL and DL connections; meanwhile the FUSC is only mandatory for the DL [29]. In the PUSC and FUSC, the minimum data region is called *slot* or *tile*. The definition of a slot depends in the permutation mode and the direction of the link.

The allocation for each request could be described as the upper integer number of the slots used as described in Equation 20. The wastage due to this allocation technique could be express according to Equation 21.

$$Allocation = \left\lceil \frac{BW\_Request}{Slot\_Size} \right\rceil * Slot\_Size \quad (20)$$

$$Allocation\_Wastage[\%] = \frac{Allocation - BW\_Request}{Allocation} * 100 \quad (21)$$

As an example, consider a UL connection with PUSC permutation mode where the slot is 1 subchannel by 3 symbols equivalent to 48 bits per slot. A packet of 964 bits would be allocated 21 slots equivalent of 1008 bits. Hence, 4.36% (44 bits) of that allocation would be wasted just by the usage of this technique.

Permutation Mode	Link Direction	
	DL	UL
PUSC	1 SubCh * 2 OFDMA Symb	1 SubCh * 3 OFDMA Symb
FUSC	1 SubCh * 1 OFDMA Symb	Not supported
AMC	1 SubCh * (1,2,3) OFDMA Symb	1 SubCh * (1,2,3) OFDMA Symb

Table 19. Slot definition for permutation modes in WiMAX[2, 29].

For the purpose of this work, the PUSC is selected as a permutation process due its performance with frequency diversity in a large number of devices scenarios and the reduction of the multipath fading impact. Moreover, the PUSC is known to be very effective with channels where SNR changes slowly, hence needing less regular updating of channel status information [51, 52].

The PUSC should work with a two-dimensional mapper that, in collaboration with the schedulers and the channel information status, allocates the space for data packets into data burst of a WiMAX frame. These data burst are allocated in one or more slots. The shape of the data burst is usually rectangular as is shown in Figure 19 and the position is given by the two-dimensional mapper. This mapper starts to explore the two-dimensional grid of slots from the upper-left corner and search for free space in it. If free space is found, the allocation is made and the packet is erased from the queue. The process continues until the full capacity is exhausted or until the BWReq queue from the scheduler is empty. The location of the allocated data burst is written into the DL-MAP or UL-MAP messages as described in section 3.1.3.

Finally, depending on the objectives of the mapper, an allocation could have different shapes. For example, an allocation of 6 slots could be expressed as 1x6, 2x3, 3x2 or 6x1 being *frequency_x_time* the size described. In the 1x6 the transmission power is maximized but the delay is reduced, on the other hand, the last 6x1 the delay is minimized but the power is divided into 6 subchannels, that in the case of a UL connection, could reduce significative the range of this connection. Figure 26 depicts the four possible allocation outputs.

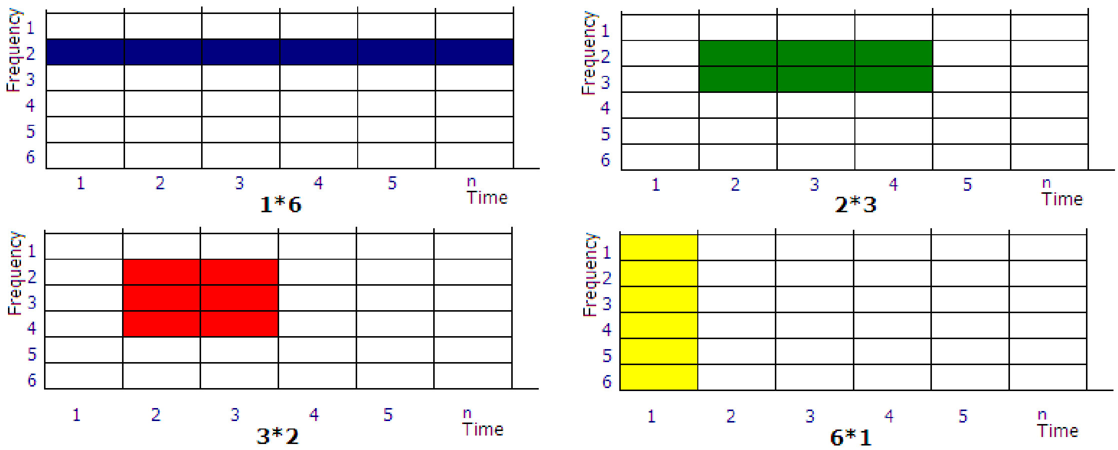


Figure 26. Example of mapping outputs for a 6 slot allocation.

3.3. *CHAPTER SUMMARY*

The present chapter introduces diverse aspects concern to the physical and MAC layers aspects of the WiMAX networks. The chapter start with a brief definition of the WiMAX standard.

In the physical layer, the chapter describes the entry procedures used in OFDMA WiMAX and its relation with the transmission power control algorithms used in the ranging process. It continues describing the power control mechanisms used to maintain the link quality and proposes the effects of the path losses in the link budget. It introduces the Erceg path model used for WiMAX in the frequency of 2.5GHz and compare it performance with a free space path los model and explore the problem of the distributed power in OFDMA frames to maximize coverage. The chapter continues describing the OFDMA frame structure and its parameters related to the WiMAX communication network, the definition of UL Subframe, DL subframe, the gaps between them and the definition of symbol.

In the MAC layer, the chapter presents and explains the parameter relevant to the support and maintenance of the QoS. The concept of service classes is presented and its parameters like scheduling type, maximum sustainable traffic rate, minimum reserved traffic rate, maximum latency and interpolling time are mapped into the smart grids applications described in chapter 2. Next, the chapter continues defining the service flows and how each service flow is a particular connection that is configured to support particular traffic needs depends on the application and service class attached to it. Based on the service flows, the chapter presents and compares the allocation techniques used in the WiMAX standard such as unsolicited bandwidth grants, unicast polling and contention based multicast/broadcast polling. The chapter continues with the definition of the scheduling techniques. In this work the round robin based schedulers are used and modified for the short burst packets of the smart grids applications. Finally the chapter presents the resource allocation and mapping process of data burst into the OFDMA frame. It also explains how bad allocation could lead to capacity wasted.

The parameters of MAC and physical layer presented in the present chapter are the basis for the network architectural design using WiMAX network for smart grid applications. The following chapter 4 presents the simulation model based on the parameter discussed in this chapter for the smart metering application.

CHAPTER 4.

SMART METER READING USING A WIMAX NETWORK

Smart meter reading application is one of the most important applications in the smart grid network. It presents a series of communication challenges that the communications networks should fulfil, such as large coverage network and differentiated QoS management. The WiMAX standard is seen as a versatile wireless network that could handle this kind of requirement in an efficient way. Hence, this chapter introduces a WiMAX network infrastructure used for smart meter reading application for wide area coverage. Several aspects of the network infrastructure are being explored in this work, to design an optimal architecture for the Automatic Meter Reading (AMR) and the Automatic Metering Infrastructure (AMI) services.

The outline of the present chapter presents in first place a definition of the system model which includes the network design distribution and propagation models considered for these scenarios. Next, the chapter presents the smart grid network simulation model based on the OPNET simulator packet designed to validate the proposed network architecture. This section includes the protocols and algorithms used in the MAC and physical layers of the WiMAX standard that support smart grid communications. The chapter then further studies the implication of transmission power constraints and the analysis of different path loss models, cell sizes and user distributions within different cells. Next the capacity of the network is examined using the WiMAX frame configuration, various traffic rates and the admission control algorithm using a single base station model. The impact of different applications and transport protocols is also explored. Next, a study on the polling mechanism, the interpolling time (IPT) and its effects on the delay is carried out. Finally, the chapter finalises with a summary of the findings of smart meter reading applications over WiMAX networks.

4.1. SYSTEM MODEL

In this work we studied a single IEEE 802.16 based TDD WiMAX model with different cell sizes [2]. The smart meters were placed over a large area using three different distribution patterns, namely *circular*; where all the stations are placed at the edge of the cell; *random*, where stations were randomly placed inside a square; and *uniform*, where stations were located uniformly in a matrix fashion as shown in Figure 27. These distribution patterns are used to study different scenarios of smart meters which needs to be serviced by a WiMAX based communication network. The circular distribution is chosen because it represents a constant distance from all the users. The random distribution is used to represent the location of houses in a typical suburban neighbourhood. Finally, the uniform square distribution could be used to represent matrix distributions in cities like Manhattan in New York City.

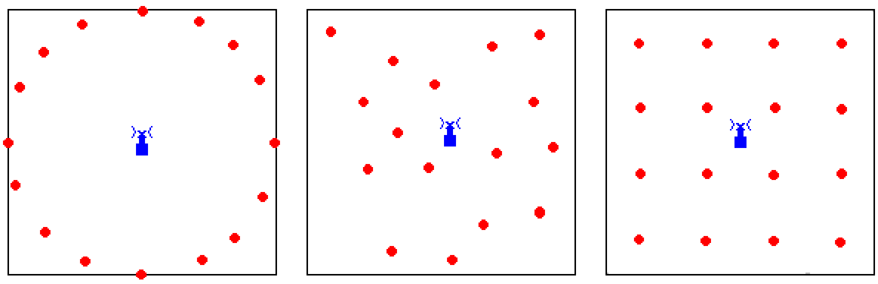


Figure 27. Example of user Distributions a) Circular b) Random c) Square.

The WiMAX air interface bandwidth defined for this system is 20MHz in the band of 2.5GHz as recommended by the NIST [21], is divided into 2048 subcarriers based in a 2048-FFT operation, which are further grouped into 24 subchannels for the DL and 70 subchannels for the UL.

The duration of the frame is set to be 5ms with symbol duration of 100.8µs following the analysis of the OFDMA frame structure in section 3.1.3 Equation 4. This definition provides a total of 47 usable symbols, divided in a fixed boundary of 24 symbols for the UL sub-frame and 23 symbols for the DL one. This frame organization provides a total of 11.6 M symbols per sec, resulting in 5299.2 Kbps for the UL and 6336 Kbps for the DL, which gives an extra 20% capacity in the DL that is used for the mapping allocation. The bps capacity depends on the MCS values used; in this case a QPSK modulator with a ½ rate coder provides a relation one-to-one between symbols per second (sps) and bits per second (bps). For the rest of the document, unless something is specified, the sps and bps are treated indistinctively.

The ranging fields are defined according to the recommendation of the WiMAX IEEE 802.16e standard [2], which values are for 1 subchannel is represented by 6 symbols in the Fast Feedback field, 6 subchannels are represented by 2 symbols in the Initial ranging field and 6 subchannels is represented by 1 symbol in the periodic ranging field that would be used for network entry procedures.

The system model defines the BS maximum total transmission power to 5W, which is evenly distributed among all subchannels; meanwhile the SS transmission power is varied for 500mW, 1W and 2W. The antenna gains are defined as 15dB for the BS one and a range of 5dB to 14dB for the SS antenna. Also, the power control algorithm defined is the open loop which a receiver sensibility ranges of -110dB and -10dB.

Table 20 presents a full configuration used for physical and MAC layer in the system model for the WiMAX network for smart grids.

Parameter	**Value**
Frequency (GHz)	2.5
Duplexing mode	TDD
Bandwidth allocation (Mbps)	Total = 11.635200 UL = 5.299200 DL = 6.336000
Frame duration (ms)	5
Symbol duration (us)	100.8
No of Subcarriers	2048
No of Data Subcarriers	UL = 1120 DL = 1440
No of Null Subcarriers	184 (each side)
No of Subchannels	UL = 70 DL = 24
UL/DL boundary	UL = 24 Symb DL = 23 Symb
UL burst transmission delay	No Delay (UL burst are sent in the same frame of the UL-MAP)
Fast Feedback Area	1 SubCh * 6 Symb
Initial Ranging Area	6 SubCh * 2 Symb
Periodic Ranging Area	6 SubCh * 1 Symb
Subcarrier Usage mode	PUSC UL = 3 Symb DL = 2 Symb
Tile size based on PUSC	UL = 48 bits/slot DL = 48 bits/slot
Antennas	Tx =1 Rx =1
Antenna Gain (dB)	SS = 5; 14 BS = 15
Max Tx Power (W)	SS = 0.5; 1; 2 / BS = 5
Receiver sensibility (dBm)	Max = -10 Min = -110
Power control	Open loop
Modulation and coding scheme	Fixed – QPSK ½

Table 20. System model characteristics

In this model initially the Free space model is used; later the Erceg model is used which is recommended for WiMAX in the transmission band of 2.5GHz [36]. Effect of both models on the smart grid network was evaluated.

The models consider the polling access mode for serving smart meters, in this case all the connections will have their chance to send information about the meter reading within the configured QoS parameters for the service classes as presented in section 3.2.1, Table 14. The application used in the smart meters is the metering application which is configured as an excellent effort type of service with latency higher to 1 second considered as a non-real time connection.

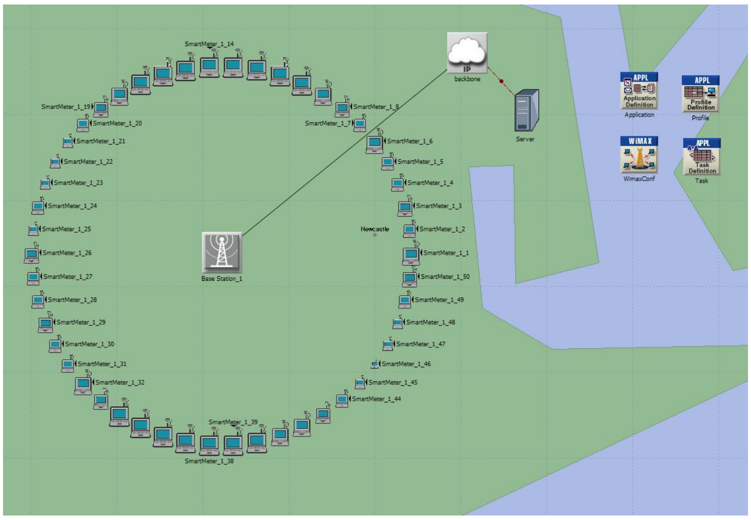
The system analysis evaluates a set of parameters in the smart grid network. The simulations are used to analyse the implication of the propagation model, the cell size, the power restriction, the number and distribution of users, the IPT and the transport protocol used.

4.2. OPNET SIMULATION MODEL

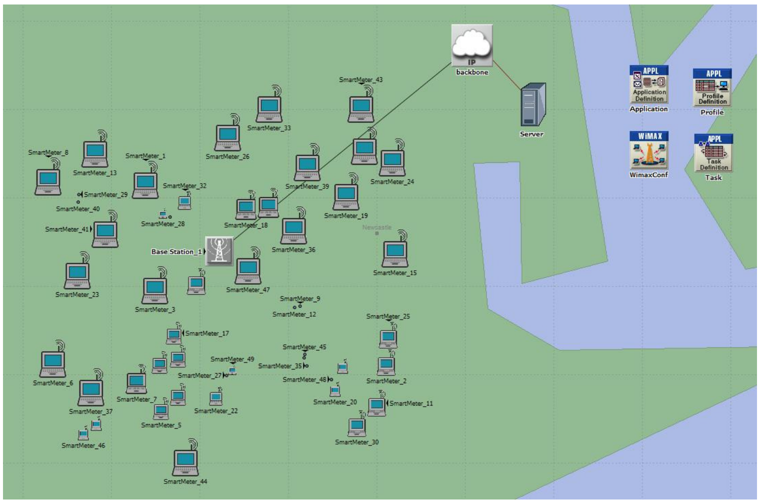
A set of simulation scenarios were developed based on the OPNET simulation package and WiMAX simulation models [41, 53] were used to analyse the performance of the previously described system model. Several simulations were conducted to analyse the performance of the designed smart grid communication network. Figure 28 presents the different traffic distribution models used in the OPNET WiMAX simulation model such as circular distribution, random distribution and square uniform distribution. Figure shows the placements of smart meters in urban area in the Newcastle city in Australia, in network cells of 2Km each. Simulation models also include the WiMAX configuration, application configuration, profile configuration and task configuration files, shown in the upper right corner of the Figure.

In the first set of simulations the total power of the users is divided among all the subchannels as in the BS; however, further analysis shows that the maximum power should be distributed among the used subchannels and then controlled by an open-loop power controller in order to increase the coverage area.

A first set of simulations were run using just 50 stations, varying the simulation parameters such as cell size for 2km and 5km; path loss models Erceg type A, B and C, the user distributions using circular, random and square uniform; and the maximum station transmission power of 500mW, 1W and 2W on the uplink..



a)



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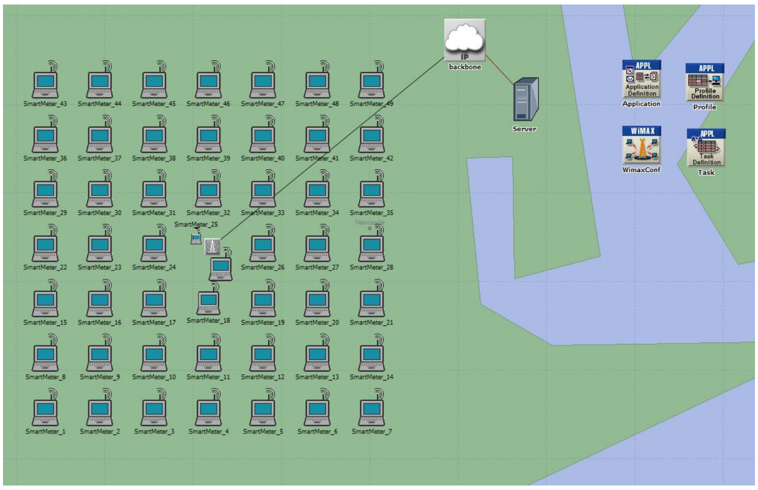

c)

Figure 28. OPNET simulation models for 50 smart meters. a) Circular distribution, b) Random distribution, c) Square uniform distribution.

The three user distribution models were simulated using the OPNET models. The maximum average and minimum distances of the model are presented in Table 21 based on the calculation and the distribution described next. These distances represent the maximum and minimum distance of the deployed smart meters (SMs) from the WiMAX base station. The circular distribution places all users in the same distance; the variations of SNR presented are attributed to shadowing fading. In case of circular distribution all users will experience the same path loss. In case of random distribution smart meters' locations are exponentially distributed with a mean distance of ½ cell size and ¼ cell size standard deviation. The uniform distribution represents a 7x7 grid architecture. However, users with distance under 100m from the BS are moved to 100m to be congruent with the restrictions proposed in the Erceg path loss related with the close-in distance (d_0) parameter [38].

Cell Size		Circular	Random	Uniform
2Km	Max (m)	2000	2745	2828
	Average(m)	2000	1047	1736
	Min(m)	2000	100	100
5Km	Max(m)	5000	6873	7071
	Average(m)	5000	2701	4336
	Min(m)	5000	100	100

Table 21. Distance of user in the different distribution models for a user [population of 50.

A second set of simulations were conducted increasing the number of users from 1 to 500 per cell, in 25 users' steps. Both sets of simulations having 3.2 second as IPT Finally, a third set of simulations were run incrementing the IPT up to 300 second and the number of users up to 1000, in a 2Km cell with random distribution and Type B path loss and 1W of maximum power transmission using a simple UDP transmission mechanism.

The smart meter reading traffic simulation model is defined here. The proposed application model defines two version of the smart meter reading. First, a File Transfer Protocol (FTP) based application is implemented with a packet size of 1Kbytes with a DL confirmation message of 512 bytes from the server. A broadcast message to all users is sent from the server transmitting information about the network status. This message is 5Kbytes size. Second traffic model represents a single User Datagram Protocol (UDP) based application that is used to send the metering information in a 1Kbyte file. In this case, no DL confirmation is implemented. The Message packet size have been changed along the different simulation scenarios to fulfil the application requirements

The packet sizes presented in this section are introductory values to provide information about connectivity, network entry and delay, and not full capacity analysis. Further in the work, the values presented in section 2.4 will be introduced.

The first traffic model represents a connection oriented service whereas the second model represents a connectionless service model. In both models, the generation packet interarrival time is 5 minutes. Table 22 presents a resume of the described parameters.

Parameter	Value
Application protocol	A. FTP over TCP B. Single UDP
File Size (bytes)	A. UL=1000; DL=5000; B. UL=1000; DL=0.
Confirmation Message (bytes)	A. 512 B. 0
Inter-arrival time (sec)	300
Start time (sec)	30-330 Uniform distribution

Table 22. Application parameters used in the simulation.

The smart meter reading application should be mapped into the WiMAX networks services classes as described in section 3.2.1. Table 23 presents the configured service classes in the WiMAX network simulation model. We configured the same value for maximum suitable traffic rate (MSTR) and minimum reserved traffic rate (MRTR) and we vary those values to match the configured interpolling time (ITP) as described in the IPT definition for OPNET model in section unicast polling section 3.2.3 and traffic services section 3.2.1. However, the configured application is using only the *sil_nrtPS* service class. In the SMs, only this service class is activated, because of their implication in the admission control and is explained and analysed in the next section. Variations of the MSRT and the IPT are introduced to analyse the impact of these variables in the system network, in specific, the modifications of the IPT values are defined to investigate the relation of the polling interval into the delay measurements of the network.

The FTP application used in this model is a three step process; 1) opening connections, 2) transmission of data and 3) closing connection, as is shown in Figure 29. In specific, when the metering application generates a packet to be transmitted, the MAC layer put this packet in the UL queue waiting to be sent. Where the poll arrives (a BW request opportunity), the opening connection BWReq message is sent. The FTP server replies almost immediately, which is received by the smart meter after the service and DL transmission delay. Following the connections set up the FTP client (smart meter) is ready to send the packet with the metering load management data. This packet is put in the queue, but is just one IPT later the FTP client gets an opportunity to transmit the packet. When the packet of data is received at the FTP Server, it replies with a 512bytes control message to the SM. 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 IPT becomes very important, because if it's value is too long, the DL will retransmit until an acknowledgement message is received, whereas if the IPT is too short then there will be not enough capacity to poll and transmits data on the UL. Finally, the smart meter has to send a closing connection message that would finalise the communication between the smart meter and the server.

Service Class Name	Scheduling type	MSTR (bps)	MRTR (bps)	Max Latency (msec)	Modulation and Coding	ITP (sec)	Average SDU (bytes)
Gold	UGS	10 000		1000	QPSK+½ rate coder	1	2000
G ertPS	ertPS	5000		1000	QPSK+½ rate coder	1	2000
Silver	rtPS	5000; 320; 160; 80; 54		Not specified	QPSK+½ rate coder	3.2; 50; 100; 200; 300	2000
Sil_nrtPS[3]	nrtPS	5000; 320; 160; 80; 54		Not specified	QPSK+½ rate coder	3.2; 50; 100; 200; 300	2000
Bronze	BE	5000		Not specified	QPSK+½ rate coder	3.2	2000

Table 23. QoS service class configuration parameters used in the simulation.

The UDP transmission is much simpler than the FTP. UDP transmission consists in a simple communication where the communication only includes message with its load management data. In this case, when the smart meter device receives a packet from the metering application, it waits for the polling opportunity and sends a BWReq message with the size of the load information message. After being granted with an allocated space, the smart meter sends the packet and it is finally retransmitted to the server through the base station. No acknowledgement is required from this transmission, leaving the possibility to packet losses and not being able to correct or detect the lost packets. For this situation future analysis of ARQ will be introduced in the next chapter.

[3] Silver-nrtPS is the only used service class configured in the SSs.

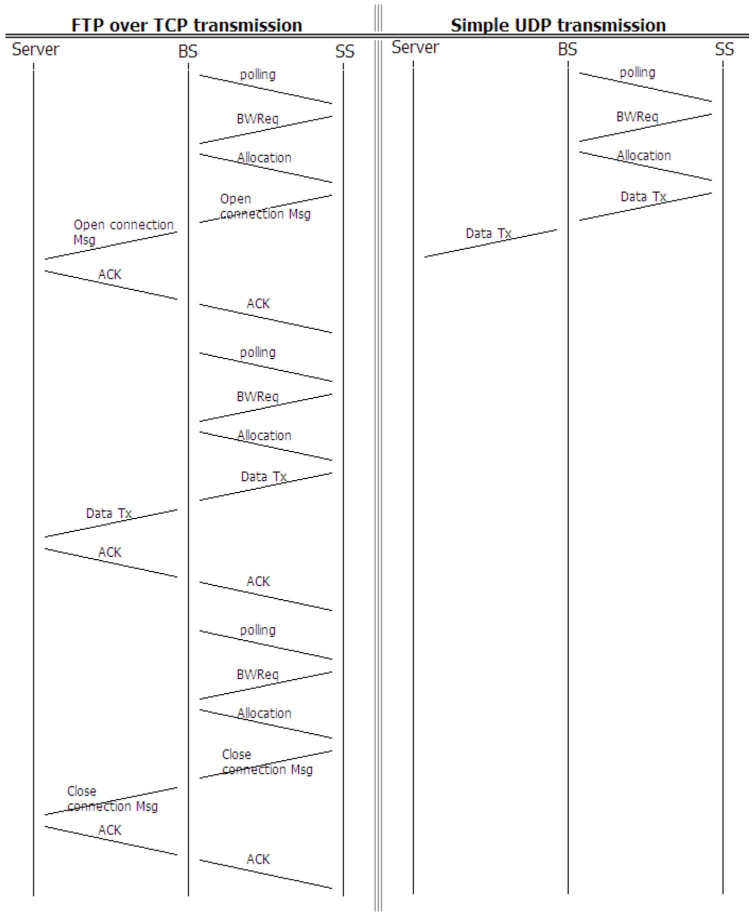

Figure 29. Connection models using of the FTP over the TCP and a simple UDP transmission.

4.3. RADIO LINK DESIGN AND ANALYSIS

In this section the performance of a WiMAX based smart meter service network is evaluated using a number of propagation models. Impact of the propagation models is important because in different deployment scenarios the performance of a smart meter service network will be impacted by path loss and fading characteristics. Also, the propagation issues will be important for transmission power selection.

In this section two propagation models will be explored, first we explore the Free space propagation model and then we develop the Erceg propagation model recommended for smart grid application over WiMAX resembling them within different deployment scenarios. .

4.3.1. FREE SPACE PROPAGATION MODEL

The simple free space propagation model provides a comparison framework for the other advance models which will be used in simulation works. The free space model is based on the propagation losses that an electromagnetic signal experiences when it is being transmitted. The

Equation 22 presents the free space path loss model, based on the Friss free space Equation for a separation distance of d between a transmitter and a receiver. [54].

$$PathLoss_{FreeSpace}[dB] = 20 * Log_{10}\left(\frac{4 * \pi * d}{\lambda}\right) \quad (22)$$

where d is the distance in meters between antennas and λ is the length in meters of the transmitted wave.

However, the path loss model is not the only aspect that affects the received signal. From the same Equation proposed by Friss, the received power is proportional to the antennas gains, having typical values between 10-20dB for the BS antenna and 0 -5dB for the receiver antenna which are determined by the directivity of them [55-57]. In this work, we choose a value of 15dB for the BS gain and 5dB for the SM gain. The effect of the antenna gain in our work is to achieve longer distances because it increments the received power of the distant smart meters. Equation 23 presents the receiver power in decibels. It is the sum of the transmitted power, the antenna gains minus the path loss. According with the configuration, the UL power per subchannel for these sets of experiments is 1W divided in the 70 subchannels 14.28mW/subchannel or 11.54dBs.

$$P_{Rx}[dBm] = P_{Tx} + G_{Tx} + G_{Rx} - PL \quad (23)$$

where P_{Rx} is the received power, P_{Tx} is the transmitted power, G is the antenna gains and PL is the Path loss.

Apart from the received power, the receiver needs to consider the received noise. The importance of calculating the noise determines the coverage and quality of a channel. There are diverse sources of noise, but the one considered in this work, is the related with the electrical components of the receiver, in particular the thermal noise. The aspects related to the noise in the receivers include the noise Figure, the thermal noise of the electronic components, the bandwidth of the channel used and the Boltzmann's constant. The noise Figure (N_0), is related with the effective noise temperature of the receiving device and refers to the noise generated between the input and the output of the device. In this case, the value chosen is 4dB. The thermal noise is the room temperature of the device measured in Kelvin. In conjunction with the noise figure, gives the noise temperature of the device that is different to the actual operating temperature of the device. The temperature selected is 290K. The bandwidth of the channel is calculated for an OFDMA subchannel. According to the selected OFDMA configuration, the 20MHz is divided in 70 UL Subchannels leaving a subchannel BW of 285.7 KHz. The

Boltzmann's constant is 1.38*10^{-23} J/K. Equations 24, 25 and 26 presents the noise Equation and their respective values in dBs[54, 58].

$$Noise[dBm] = TermicNoise[dBm] + N_0[dBm] \tag{24}$$

$$\begin{aligned} TermicNoise[dBm] &= 10\log(\frac{Bz * T * Bw}{0.001}) \\ &= 10\log(\frac{1.38 * 10^{-23} * 290 * 285.7 * 10^{3}}{0.001}) \\ &= 10\log(1.1439286 * 10^{-12}) \\ &-119.7dBm \end{aligned} \tag{25}$$

$$Noise[dBm] = -119.7dBm + 4dBm = -115.7dBm \tag{26}$$

where *T* is the temperature of the receiver, *Bw* is the bandwidth of the subchannel, *Bz* is the Boltzmann's constant and N_0 is the noise Figure.

Finally, the SNR needs to be considered which has a relation between the received signal and the total noise at the input of the receiving device. This relation is presented in Equation 27. In case of the receiver, the SNR value is very important which determines the quality of a received signal. In digital communications, different levels of SNR will bring different levels of bit error rate (BER) use of different modulation and coding schemes could reduce the effect of BER on the received signal. Appropriate measurements of SNR values are necessary to select the proper MCS value that gives the ability to the receiver to reduce the effects of the BER. For smart meter applications fixed MCS values are used because the propagation condition will mostly remain stationary.

$$SNR[dBm] = P_{Rx}[dBm] - Noise[dBm] \tag{27}$$

Other aspects of the propagation condition that are not included in the analysis of a smart meter service network are effects suffered to the propagated wave called fading such as the shadowing fading, multipath fading and building penetration fading. The shadowing fading is an effect generated by the propagated wave that finds obstacles that diminish the energy of the signal. This is a random process defined by the environment of the electromagnetic signal. The obstacles could work also as reflectors that could modify the amplitude, phase and delay of the signal. In some cases the interference effect of the resulting signal at the receiver could be constructive, if the phase shift is close to 360°, or destructive, if it is close to 180°. In order to model this effect, a mathematical model considering the causes previously described, is created represented by a Gaussian distribution. This effect is going to be further included in later simulations.

On the other hand, the multipath fading is an effect produced by the arrival of multiple paths of the same transmitted signal at the receiver. This phenomenon is created because the reflection and diffraction of stationary and mobile objects close to the transmission path. Despite that multipath fading is widely used for mobile transceivers, its effect in stationary devices like the smart meters, is similar to the one in shadowing fading. For that reason we are only considering shadowing fading having the advantage that it reduces computational load compared with the multipath fading process that includes the mobility of the device to calculate the fading. Constructions

Finally, building penetration is the effect produced for those signal entering into building or constructions for devices that are these ones. The analysis of building penetration is quite complex and is affected by several parameters like antenna beamwidth, angle of incidence, outside multipath, indoor multipath, distance from the walls, material of the walls, among others [59, 60]. The complexity of this model is left out the analysis of this thesis due the assumption of the antenna placement for smart meters, i.e. we consider that the entire smart meter had an outdoor antenna positioned in the roof of the house studied.

4.3.2. ERCEG PROPAGATION MODEL

According to the recommendation from WiMAX forum, the Erceg path loss model is the most appropriate for the 2.5GHz band which is used for smart meter service in this work [22]. Models like the Hata-Okumura or the COST 231 are not suitable for the proposed architecture of WiMAX on smart grids. These models are not suitable for this work because the minimum distance of the BS to the users is 1Km, the maximum usable frequency is 1.5GHz and the BS antenna height with moderate terrain is only a couple of meters [61-63]. The Erceg model is an empirical based path loss model widely used for mobile WiMAX network in suburban areas. The model captures different terrain models and cities landscapes, the position of the antennas above the ground level and provides support to multichannel and multipoint services [38, 64]. The model defines three terrain categories and defines the values for these three models. These are Type A which defines the hilly terrain with moderate to heavy tree density; Type B which defines the hilly terrain with light tree density or flat moderated terrain with moderate tree density and Type C which represents a flat terrain with light tree density.

Initially, the Erceg model was created for 1.9 GHz frequency and presented in 1995 based on the experimented data collected at 1.9GHz. The model measures the SNR in a suburban area and generates a formula for the path loss model presented in Equation 28 where there is no specific definition of the shadowing fading (SF) are used[38].

$$PathLoss_{Erceg}[dBm] = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10 * \left(a - b * T_h + \frac{c}{T_h}\right) * \log_{10}\left(\frac{d}{d_0}\right) + SF \quad (28)$$

The Equation was further developed for higher frequency transmissions by using correction factors as shown in Equation 29 [22, 65]. The model also considers the shadowing fading effect by introducing the mean and standard deviation coefficients of a Gaussian distribution modelling the shadowing effect.

$$PathLoss_{Erceg}[dBm] = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10 * \left(a - b * T_h + \frac{c}{T_h}\right) * \log_{10}\left(\frac{d}{d_0}\right) + 6 * \log\left(\frac{f}{2000}\right) - X\log_{10}\left(\frac{R_h}{2}\right) \quad (29)$$

where d_0 represents the minimum distance from the BS of a receiver also called 'close-in distance', λ is the wavelength of the central frequency, f is the central frequency, a, b, and c are constant derived for the empirical model, T_h is the BS antenna height, R_h is the receivers, μ_0 is the standard deviation of the shadowing effect coefficient and X is the shadowing effect at the receiver antenna coefficient.

The values of frequency, wavelength and antennas height are chosen by us and their values are presented in Table 24. Also, in this Table are shown the values found after the depuration of model for each terrain type.

4.3.1. *PROPAGATION EFFECT ANALYSIS*

To perform a radio signal propagation analysis, three different propagation models were used, being Free space, Erceg Type A and Erceg Type C the selected ones. For the first set of simulations, there were no shadowing effect introduced, that means that the mean and the standard deviation values of the shadowing distribution are zero.

Figure 30 presented the mathematical calculations of the SNR per subchannel for the three propagation models in a receiver device that is located at different distances from the BS. In this case the mobility aspects are not included. The calculation follows the SNR defined in the Equation 30, where it includes the values of the transmitter power per subchannel, the antenna gains, the path loss and the noise defined in Equation 23, 26 and 27. In the case of the UL the power is the maximum transmitted power (1W) because there is used only one ranging subchannel. On the other hand, for DL the power is divided among all the subchannels (0.5W, 1W or 2W divided into 24subchannles.)

Model Parameter	Definition	Terrain Type A	Terrain Type B	Terrain Type C
T_h	BS Antenna height [m]	40 m [4]		
R_h	SM Antenna height [m]	2 m		
λ	Wavelength [m]	0.12 m		
f	Frequency [MHz]	2500 MHz		
d	Distance BS – SM [m]	D		
d_0	Close-in distance	100 m		
a	Mean path loss exponent variables	4.6	4.0	3.6
b		0.0075	0.0065	0.005
c		12.6	17.1	20
μ_σ	Standard deviation for Shadowing effect	10.6	9.6	8.2
X	Mean value of Shadowing effect for SM antenna	10.8	10.8	20

Table 24. Erceg model parameters used in the based on references [22, 38, 64, 65]

In Figure 30 the SNR results shows that the results from the free space are much higher from the other two graphs because it only includes the effects of an ideal space without hills or foliage. In the Erceg model, the Type A has lower SNR because it is defined for a hilly terrain with a heavy tree density.

$$\begin{aligned}
SNR[dBm] &= P_{Rx}[dBm] - Noise[dBm] \\
SNR[dBm] &= P_{Tx}[dBm] + G_{Tx}[dBm] + G_{Rx}[dBm] - PL[dBm] - Noise[dBm] \\
SNR[dBm] &= 11.547[dBm] + 15[dBm] + 5[dBm] - PL[dBm] + 115.7[dBm] \\
SNR[dBm] &= 147.247[dBm] - PL[dBm]
\end{aligned} \tag{30}$$

The minimum signal strength that a receiver needs to decode a packet depends on the sensitivity of the receiver. The receiver sensitivity defines the maximum and minimum range of signal that a receiver could decode. In our definition model the minimum value is -110dBm of received power. Under this value the received signal could not be decoded and the user could lose contact with the base station. The value of the minimum SNR related with this minimum sensitivity is given in Equation 31. This value of 5.7dBm is enough to satisfy the OFDMA

[4] The values of antenna height and frequency are configured by the author.

modulation and coding of QPKS ½ requirements for a BER smaller than 10^{-6} used in IEEE 802.16e WiMAX. The minimum received SNR requirement for SS and BS is 5dBm [66].

$$SNR_{\min} = MinRxSensibility - Noise = (-110dBm) - (-115.7dBm) = 5.7dBm \quad (31)$$

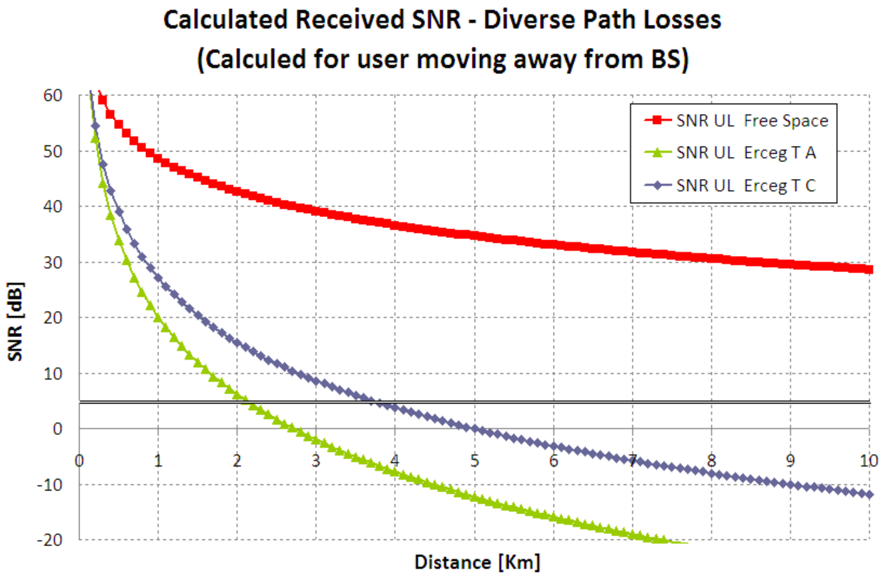

Figure 30. Calculated received SNR for Free Space, Erceg type A and C propagation models.

Figure 31 presents the results of a simulation model in OPNET to validate the performance of the simulator. This scenario presents a device moving away from the BS. Results show that the SNR are quite similar in the area that we call active area. This area is the one where the received power is inside the receivers' sensitivity. Outside this area, the power reduction control and the network entry algorithms modified the transmitter power in order to maintain the device inside the sensitivity ranges. This power modification could be seen at the beginning of the graph, before 500mt, the SNR is affected by the initial ranging power control of the SM, giving lower values of SNR. On the other hand, for the Erceg models, under 5.7dBs of SNR, the sensitivity of the BS receiver is not able to obtain the signal and it enters in a periodic ranging cycle to achieve the needed power. Notice that after some meters, the device is not able to achieve the desired power and it is finally disconnected for the network. At the end, for a device which propagation path loss model is similar to the Erceg Type A, its maximum distance from the BS is around 2Km.

The difference between Figure 30 and Figure 31 is due to the mathematical models used, the network entry procedures and the initial ranging algorithms whose values were not considered.

This could be seen in Figure 32 that shows that the error is zero for the distances where the transmitted power is not affected by the ranging process.

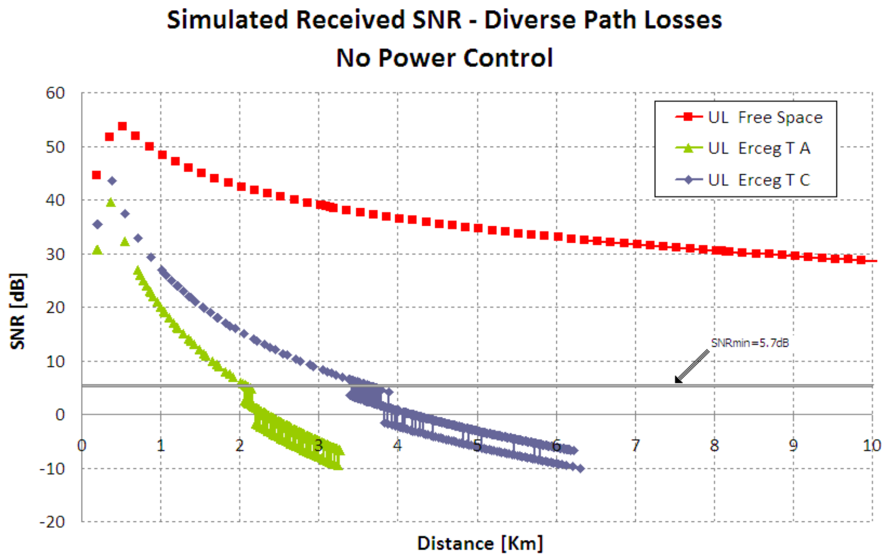

Figure 31. Simulation of received SNR using Free Space, Erceg type A and C propagation models using the no-power control method.

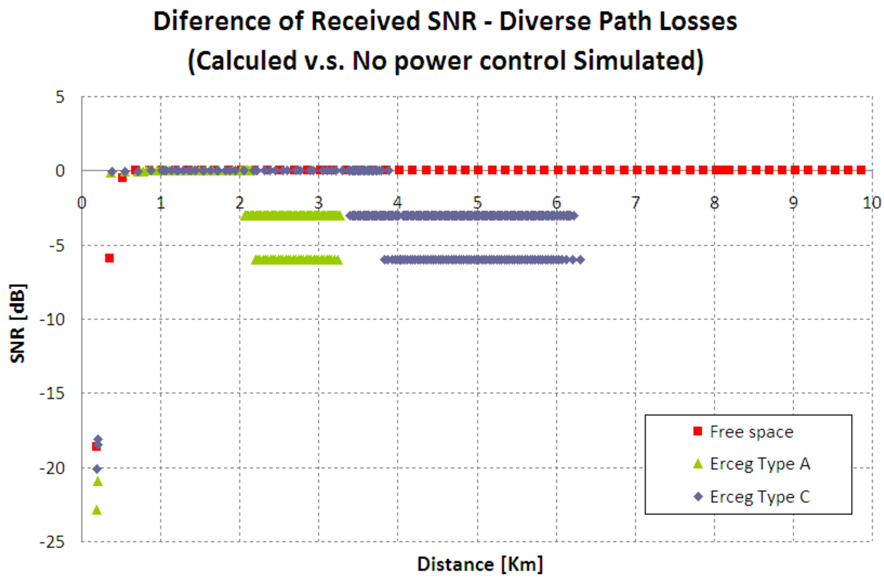

Figure 32. Differences between the simulation and calculated SNR values for different propagation models.

In order to improve the received SNR of devices located after the 2Km limit, the WiMAX network proposes the inclusion of open loop controller. The result of including this algorithm is that the transmission power is controlled by the BS according to the middle range of the sensitivity independent of the path loss model. This is because the aim of the open loop control is to maintain the received power in the medium of that range. In that way the controller is able to compensate the loss values as is presented in Figure 33.

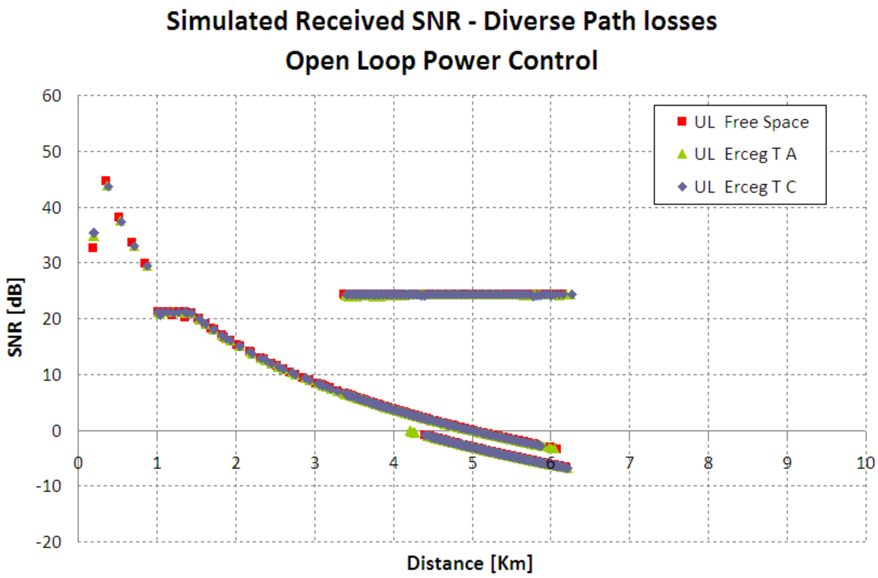

Figure 33. Simulation of received SNR for Free Space, Erceg type A and C propagation models using the open-loop power control method.

Moreover, in the analysis of the transmitted power per user, it was found that the power allocation is made for all subchannels independently if they are used or not, particularly the maximum power is divided in all the subchannels. Hence, the maximum power per subchannel is 14.28mW or 11.55dBm in the DL. In order to improve the coverage, the power control algorithm should allocate the maximum power to the subchannels used. The author implemented this modification in OFDMA power distribution model and in the OPNET simulation model, to realise the full transmission power up to 1W or 30dBm for the UL transmissions and trying to allocate only one subchannel per user to maximize the subchannel transmitted power by device because the total power is divide only in the used subchannels. This simple modification increases the transmitted power by 18.45 dBm increasing the coverage of the UL subchannels. The results of this modification are shown in Figure 34 where the coverage raise form 2.1Km to 5.2Km in Erceg type A and 3.8Km to 10.1Km in Erceg type C.

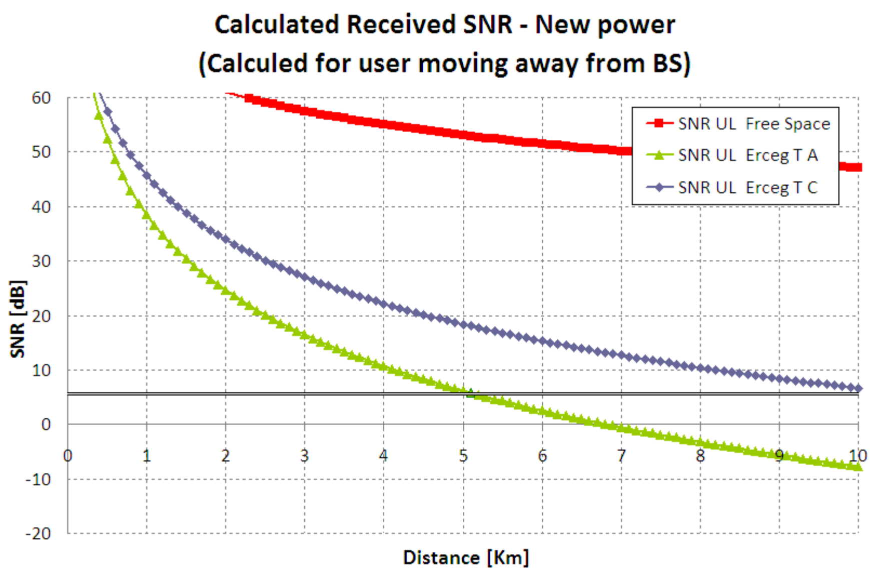

Figure 34. Calculated received SNR for Free Space, Erceg type A and C propagation models using new power algorithm.

Different propagation conditions raise the issue of the uneven transmission power levels for the UL and the DL. In this case, the power per subchannel in the UL is 30dB meanwhile the DL is 17.96dB. This difference of 12.04dB between the UL and DL transmission has an impact to the coverage area, being the DL one smaller than the UL one. For the Type A model the difference is 2.9Km for the DL and 5.1Km for the UL. For the Type C model, the difference is 5.2Km for the DL and 10.1Km for the UL. The results of these differences creates an issue for those users close to the sensitivity floor , that a UL message could be received at the BS but it’s response could not be received by the SM. However, the open-loop controller uses the received power at the SM in the process of calculating the power that is going to be transmitted by the SM. This process reduces the SM transmission power and reduces the difference between the two links.

The introduction of the Shadowing fading modifies the path loss component and the SNR based in the Gaussian distribution model. The Erceg model recommends the shadowing fading as a zero-mean Gaussian with standard distribution of μ_σ shown in Table 24. Erceg *et al*, defines the shadowing fading in Equation 32.

$$SF = N[0,1] * (\mu_\sigma + z\sigma_\sigma) \tag{32}$$

where: *N[0,1]* is the normalized zero-mean Gaussian standard distribution, μ_σ is the mean standard deviation coefficient and $z\sigma_\sigma$ is the zero-mean Gaussian variable of unit standard deviation multiplied by the standard deviation of σ [38].

The shadowing fading modifies the path loss either in a constructive or in a destructive way. As a result, some users in the Type A model could increase their SNR and be further away from the BS and still receive signal. Figure 35 presents the implications of using shadowing fading. In this Figure it is seen that, depending of the variation introduced by the shadowing fading, a user using Type A model could be as close as 3Km from the base station and not have enough SNR to send information or as far as 8.5Km and still be over the sensibility floor. In the case of Type C model, the distances could vary from 6.5Km to more than 10Km. These shadow areas in the Figure, represent the 68.2% of the users in each propagation model.

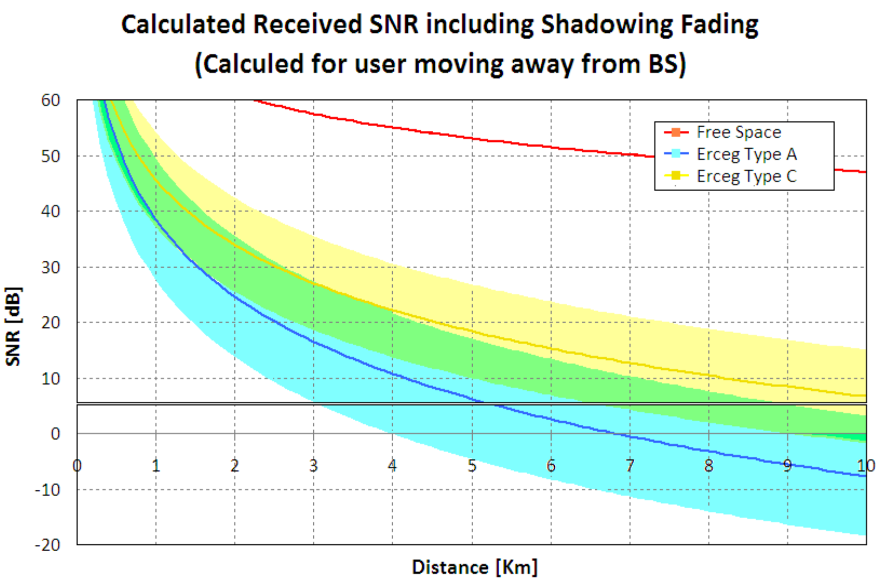

Figure 35. Erceg propagation models with shadowing fading.

Multi-parameter propagation analysis

In this section we examine the effect of user distribution, cell size path loss model and transmission power value on the performance of smart meter service network. Simulation results were obtained by varying three user distribution models: circular, random and square uniform; three maximum UL power profiles in the SMs: 500mW, 1W and 2W, and three propagation models: Erceg Type A, Type B and Type C. In the simulation two different cell sizes 2Km and 5Km are used. Initial simulation model used 50 smart meters.

The implications of the different maximum power could be seen in the UL SNR presented in Figure 36. The results show that the average UL SNR measured at the BS is reduced according to the path loss model. Figure 36 shows that maximum average SNR of 43.9dB is obtained for a 2Km circular cell with a 2W transmitter, whereas minimum average SNR of 13.7dB is obtained for a 5Km cell with a 0.5 W transmitter. On the other hand, the maximum SNR value achieved is 58.0dB representing of -57.7dB of received power, which is the closest value to the target value of -60dB. Moreover, the minimum sensitivity value has a respective minimum SNR value of 5.7dB in which some values are presented. Smart meters whose receiver SNR are below 5.7dB will not be able to decode signal transmitted from the BS. Figure 36 presents the results for the circular distribution model, where all the users are at the edge of the network with a fixed distance to the BS. The average values varies between 43.8dB and 32.1dB for 2K cell and 31.7dB and 13.7dB for 5Km cell, showing that the power distribution by subchannels method provides enough power distribution among the smart meters to serve these cells sizes.

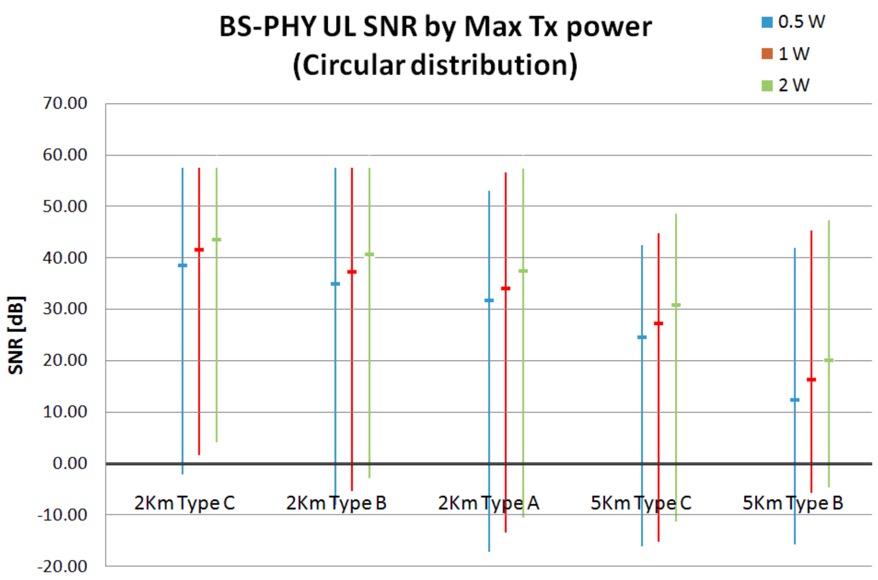

Figure 36. UL SNR by maximum transmission power

Figure 37 shows the average received SNR for three different user distributions with a 1W transmitter. Results show that the average received SNR of random distribution outperforms others distributions by at least 2dB. The maximum SNR value for random and uniform distributions is 61.1dB representing meters closer to the BS and with a positive shadowing fading. Figure 38 shows the probability density function (PDF) of the UL received SNR values. In this Figure, the middle peak of 26.3dB (-88.7dB of received power) represents the first step on the process to achieve the target received power of -60dB for those users with open-loop control configured as described in section 3.1.2 of power control mechanisms. This behaviour is seen also in Figure 33. Also, in random and uniform distributions, the open-loop target value could be seen in the right peak of 58.4dB, which represents -57.7dB of received power, very close to the target value of -60dB.

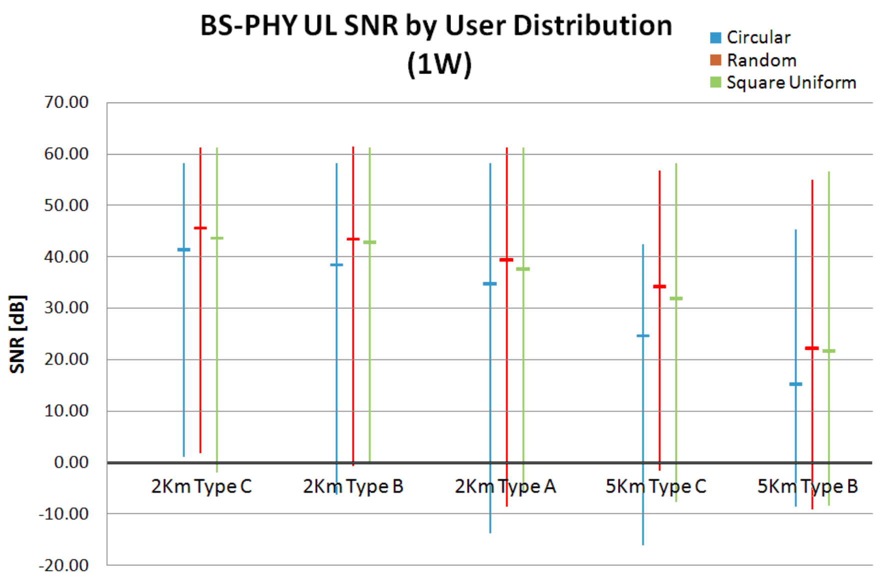

Figure 37. UL SNR by user distribution.

The received power at the BS is very similar to the UL SNR described before. The received power is higher for flat terrains whereas is smaller for hilly terrains with higher tree density. In addition it is inversely proportional to the size of the cell. Also it can be seen that random distribution presents better results to the received power than the circular and uniform distributions. Figure 39 presents a compilation of the received power at the BS.

In the case of the DL channels, the implications of the diverse maximum transmission power in the SM, should not affect the measured DL SNR. As presented in Figure 40, the average values are the same for each scenario, including the maximum and minimum values. This is because the DL power is constant of 5W for the three different scenarios. In addition, the received DL SNR follows the same pattern of the UL SNR shown in Figure 36 and Figure 37 where the SNR decreases in the hilly terrains, whereas is higher in the flat terrains.

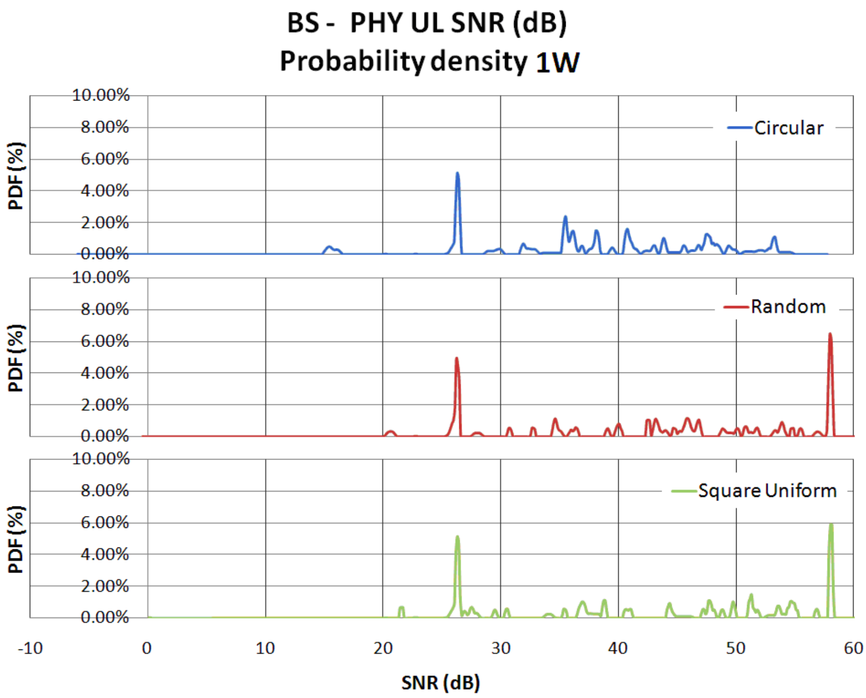

Figure 38. Probability Density of UL SNR for 2Km Type B model for a 1W transmitter.

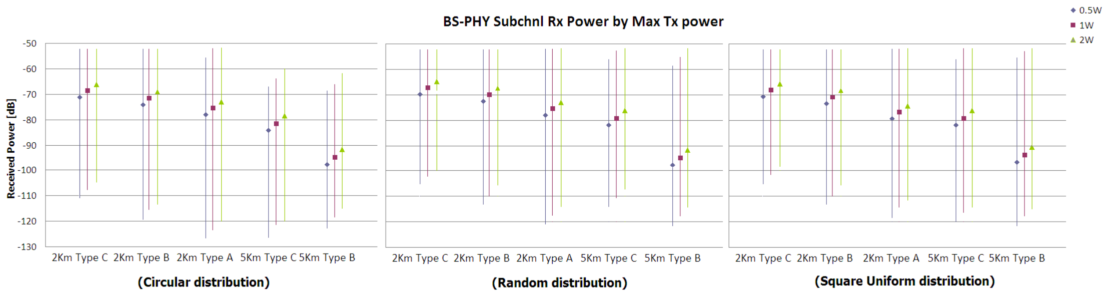

Figure 39. Average received subchannel power measured at BS.

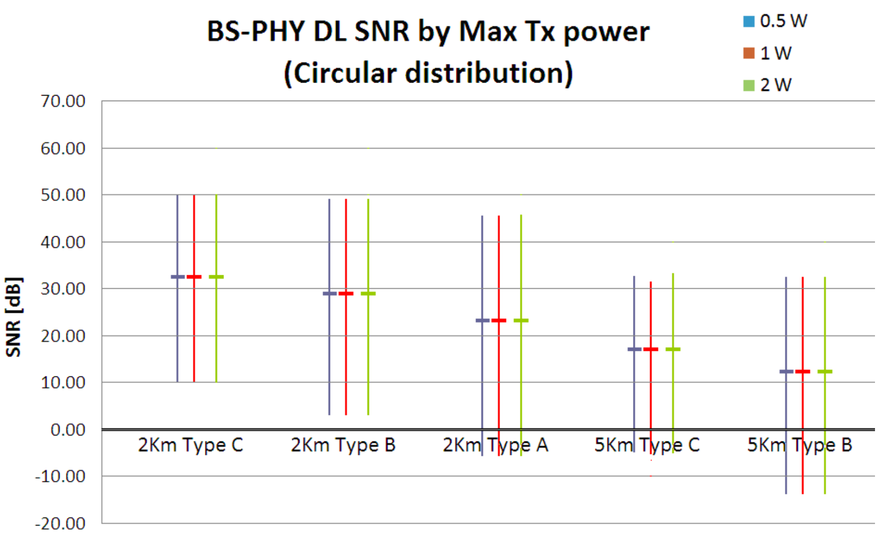

Figure 40. DL SNR by maximum transmission power

The effect of the shadowing fading is shown in the next section. Based on the Gaussian distribution applied to the Erceg path model, the shadowing fading could be described as gauss distribution which standard distribution defines the maximum and minimum values of the distribution. In the normal distribution it is seen that nearly 95% of the values are within- 2 standard deviations on each side, and nearly 99.5% are in- within 3 standard deviations on each side. We defined a delta of SNR ratio values as presented in Equation 33. The definition of the Gaussian distribution used for the shadowing fading is presented in Figure 41.

$$\Delta SNR = MaxSNRvalue - MinSNRvalue \tag{33}$$

In order to prove it, we used the results from the DL SNR transmission power from the circular distribution simulation where all the users are at the same distance, so their SNR variations are due the shadowing fading effect. Table 25 presents detailed results from the simulation presented in Figure 40.

Path loss model	Min SNR Value	Mean SNR	Max SNR Value	ΔSNR
Type A	-5.64	23.05	45.43	51.07
Type B	2.91	28.87	49.17	46.26
Type C	10.23	32.41	49.74	39.51

Table 25. DL SNR values for Circular distribution by transmission power.

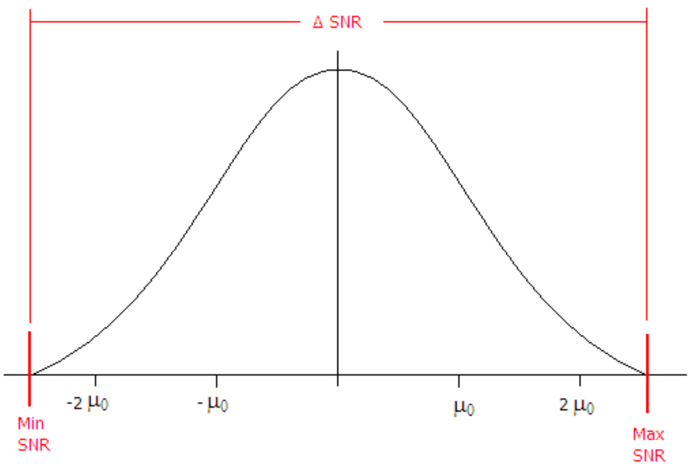

Figure 41. Gaussian distribution for the SNR - Shadowing Fading analysis

The Equation 34, presents the relation of the ΔSNR and the standard deviation (μ_0) of each type of terrain from the Erceg model. From the mathematical analysis we conclude that for 50 users we could cover the 98% of the users in-between 2.4 standard deviations each side. The result shows that for the three scenarios the relation is the same.

$$\frac{\Delta SNR_{TypeA}}{\mu_{\sigma TypeA}} = \frac{\Delta SNR_{TypeB}}{\mu_{\sigma TypeB}} = \frac{\Delta SNR_{TypeC}}{\mu_{\sigma TypeC}}$$

$$\frac{51.07}{10.6} = \frac{46.26}{9.6} = \frac{39.51}{8.2} \cong \qquad (34)$$

$$4.818 = 2 * 2.409$$

However in the case of the other two distributions apart from the circular, the same findings do not apply, because the average distance of the users and its distributions are different, changing the impact of the shadowing fading. In specific, the uniform distribution has a significative large density of SNR measurements that is because there are users as close to the BS as 100m or in the cell edge at 2.83Km in the 2Km cell. These results for the three different meter distributions are presented in the Figure 42.

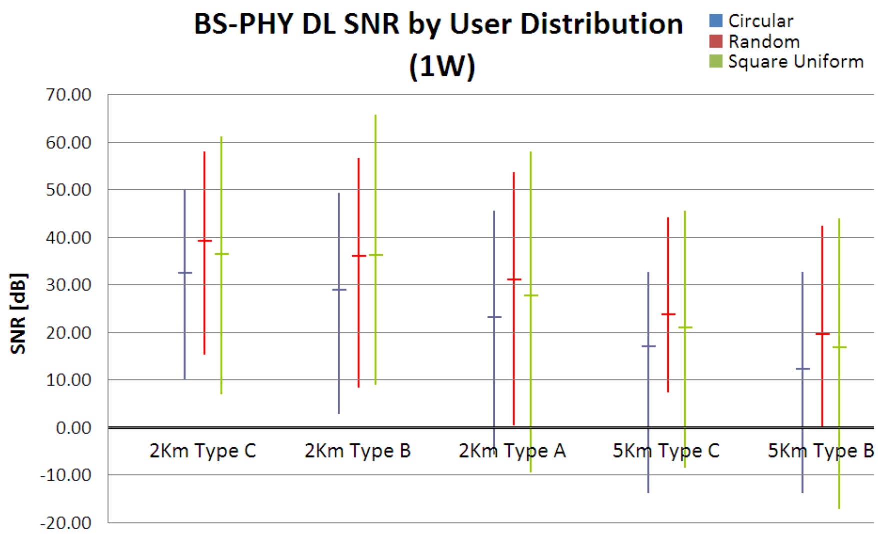

Figure 42. DL SNR by user distribution.

4.4. *PERFORMANCE ANALYSIS OF SMART METER SERVICE NETWORK*

4.4.1. DELAY AND IPT RELATIONSHIP

To analyse the performance of a WiMAX based smart meter service network an OPNET based simulation model was used where both the TCP and UDP based smart meter reading applications were implemented. The first set of simulations used an IPT of 3.2 sec. This value is generated by using the MRTR values of 5kbps and average SDU of 2Kbytes, based on the Equation 9 of chapter 3. The calculation is shown in Equation 35.

$$IPT[\sec] = \frac{Ave\_SDU\_size[bits]}{mrate[bps]} = \frac{16000}{5000} = 3.2s \qquad (35)$$

The result shows that a delay average of 2.198 seconds is experienced when smart meters send packets to the FTP server. Figure 43 present the UL delay distribution for the FTP based meter readings. The delay value was measured in 2Km cell with smart meters randomly distributed. The Figure shows an average FTP packet delay of 2.2, where values are distributed between nearly 11msec to nearly 3.196sec close to the IPT value. For the UDP connection case, the average delay experienced by the smart meters is 1.64 seconds. In Figure 44, the results show a uniform distribution of delay values, very similar to the one experienced by the initial arriving delay of the metering application. In this case, only one message has been sent so the delay value is averaged for that only packet. This delay value consists of pre-poll delay, polling delay, scheduling delay and transmission delay as shown in Figure 23 and explained in section 3.2.3.

The reason the delay values range from near zero to IPT is because the uniform distribution of the application packet arrival time to the queue. In this case, the fact that no delay is above IPT means that all the BWReq are served and resources are allocated into the IPT showing that the scheduling delay is short.

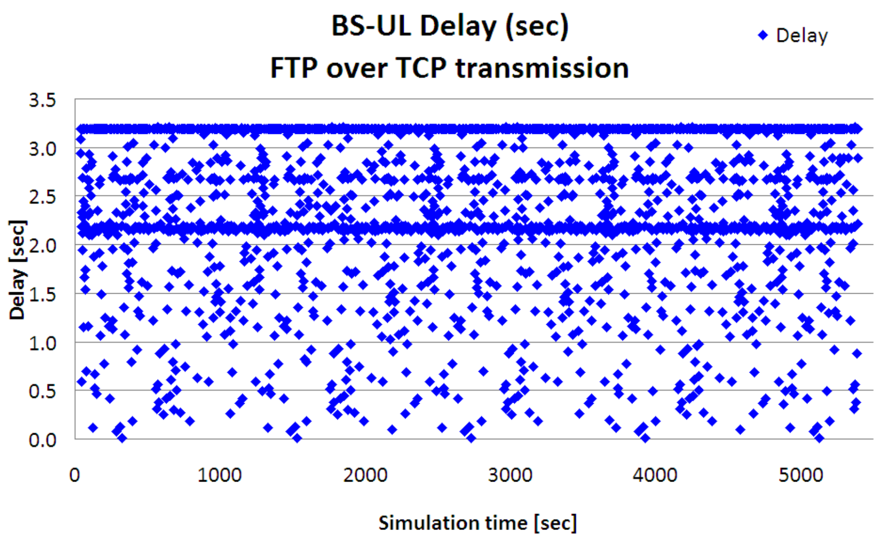

Figure 43. Example of UL Delay for IPT equals to 3.2 sec and random distribution 2Km cell with Type B path loss and 1W of maximum power using FTP connections.

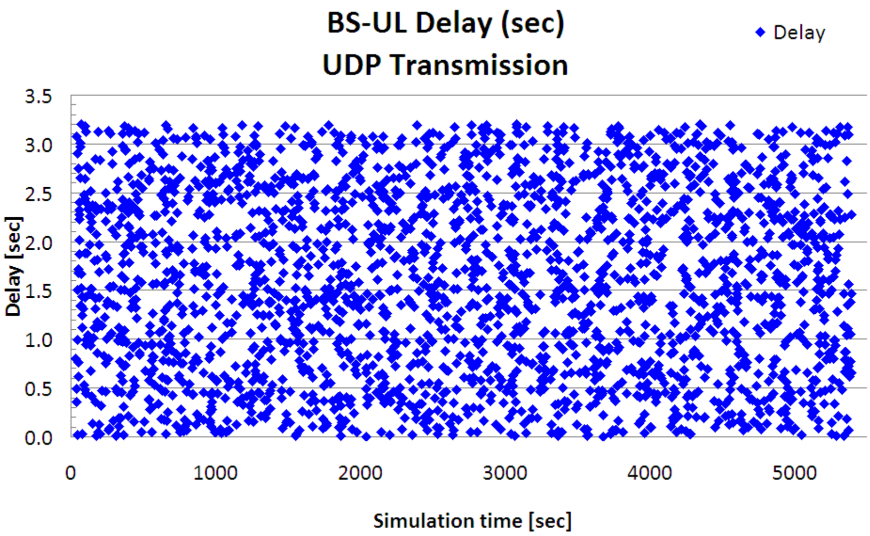

Figure 44. Example of UL Delay for IPT equals to 3.2 sec and random distribution 2Km cell with Type B path loss and 1W of maximum power using UDP connections

The pre-poll delay is the time between packet generation the packet arrival the WiMAX MAC layer, crossing IP and TCP layers and arriving to the queue plus the time while the packets are waiting in in the queue for a poll to arrive. The polling delay is the time between the poll arriving to the smart meter and the time when the BWReq message arrives to the scheduler. Then the scheduling delay is the time which takes the scheduler to serve the BWReq and to allocate the resources. Finally the transmission delay is the time between the moment when allocation message is sent to the smart meter and the moment when packet arrives to the final destination. In these results, the scheduling delay is very short due the small amount of users.

The result of this is a scheduling delay under 5ms for all the packets measured. The minimum scheduling time is considered for the BWReq packet that arrives at the end of the UL subframe of the *n-1* frame and is served immediately at the begging of the frame *n* in the DL-MAP. This packet should wait for the RTG and the preamble time for a minimum delay of 168µsec. In the maximum scheduling delay for the same frame scheduling is for the packet that is received by the BS at the beginning of the UL subframe and is served at the end of the DL subframe. This maximum time is equal to 4.894msec. Figure 45 shows that the results of the scheduling delay have a mean close to 2.47msec which is close to the typical value of 2.76 msec that represent the distance between the beginning of the UL subframe and the next DL subframe where allocations are made.

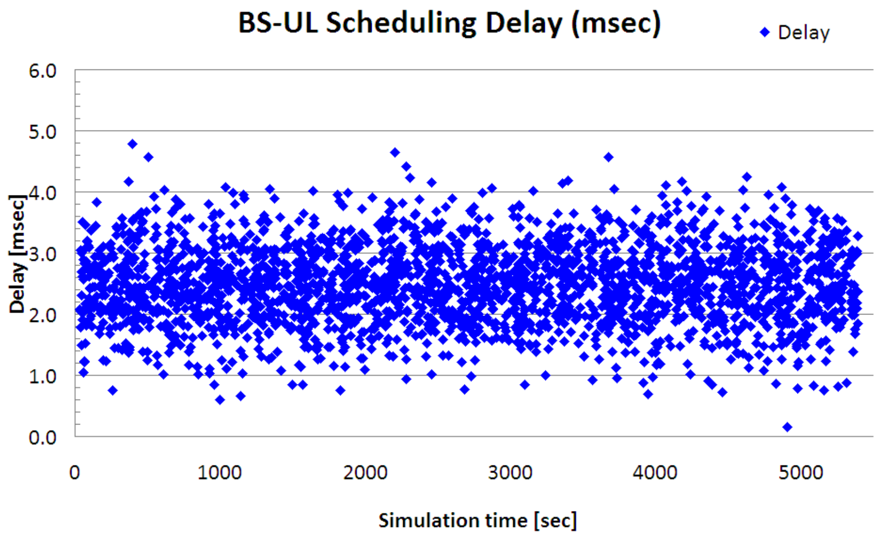

Figure 45. Example of UL Scheduling delay for IPT equals to 3.2 sec and random distribution 2Km cell with Type B path loss and 1W of maximum power.

The transmission delay is calculated since the time when the space for packet transmission is allocated, until it arrives to the receivers queue. In this case it is configured to allocate the packet in the same frame of the UL-MAP message, meaning a delay constant of up to 5ms. These three delays, pre-polling delay, scheduling delay and transmission delay, sum it up to 10ms, leaving a big component to the polling delay.

The polling delay, hence, performs based in a uniform distribution between zero and the configured IPT. WiMAX BSs must poll all the active users in nrtPS and rtPS connections in-between this period. For this reason, the maximum value of end-to-end delay is approximated the IPT if this one is configured in the seconds scale.

The analysis of the end-to-end delay is carried out for all the three path loss models using maximum transmission power. The results show that the maximum delay is constant for all scenarios for the IPT of 3.2sec. The average delay value is slightly different for diverse user distributions due to the proximities of the smart meters.

The different distribution models present very similar results for the delay. In Figure 46 the delay simulation results of the three distribution scenarios are presented. In this Figure the average delay value for all the scenarios is around to 2.5 sec and the same maximum of 3.2sec.

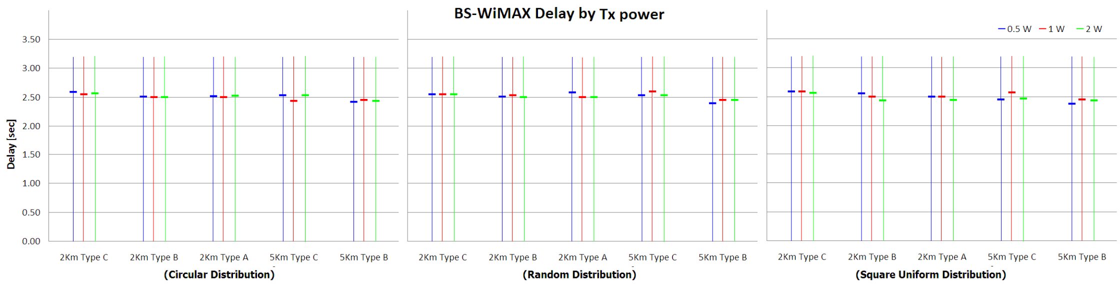

Figure 46. Delay performance for diverse Cell and path loss model for maximum transmission power in circular, random and square uniform distribution using FTP transmission.

The delay performance for a varying number of smart meters in a cell using FTP transmission is presented in Figure 47. The result shows the average delay increases with the number of smart meters mainly due to the increased scheduled packets and the distribution of polls for several numbers of users. The results show that a small increment of the 3.6% is presented. This is attributed to the increment on the first poll time when the users are admitted in the network. Also, a small effect should be appreciated due to the increment of served packets from the scheduler passing from 0.0025 per scheduling cycle 0.05 per scheduling cycle. Figure 48 presents the results for the UDP transmission method. The results show that the behaviour of the delay in UDP is similar to the FTP transmission.

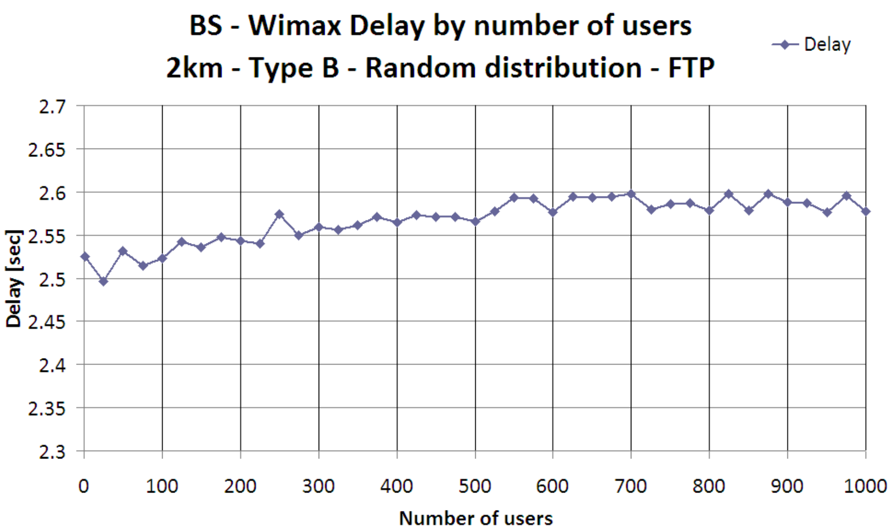

Figure 47. Average delay by number of users with IPT of 3.2s, random distribution in a 2Km cell, max transmission of 1W and path loss model Erceg Type B and FTP transmission.

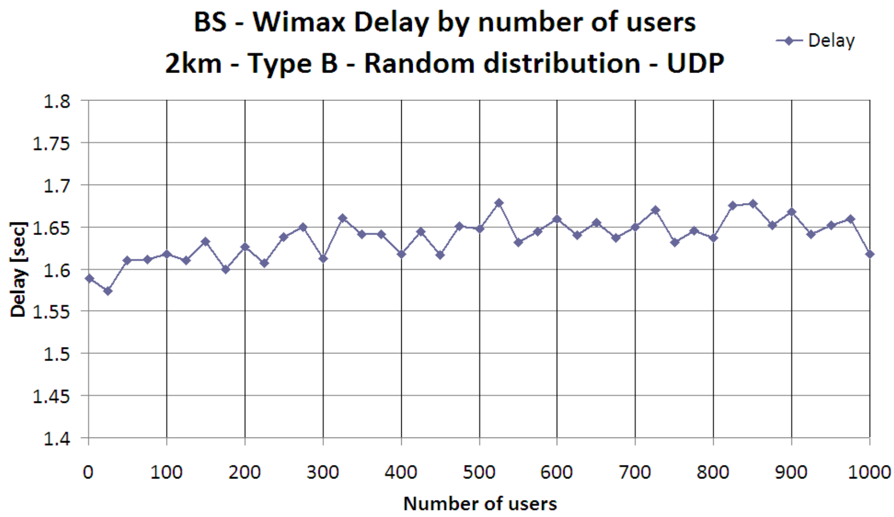

Figure 48. Average delay by number of users with IPT of 3.2s, random distribution in a 2Km cell, max transmission of 1W and path loss model Erceg Type B and UDP transmission

The previous description explains how the IPT is a big component in the average end-to-end delay. However, despite the low delay values obtained, the relation between the unused and the total polls is 96.8%, leaving a big unused space in the UL frame that increments with the number of polled users. Moreover, the average is nearly 78.8% of the IPT (2.517sec/3.2sec). As explained in Equation 36, in a FTP service, the first packet has a uniform distribution which mean value is the half of the maximum polling delay. Each of the consequent packets will have delay equal to the maximum poll delay or equivalent to the IPT. This is assuming that the response for the server is instantaneous. Calculations show that this value is expected to be nearly 83.3%. The small difference shown is because the response from the server is not immediate; instead it could take one or more frames to respond to the SMs' messages.

$$\frac{MaxPollDelay/2 + \sum_{0}^{NoPackets-1} MaxPollDelay}{NoPackets} = \frac{3.2/2 + 3.2 + 3.2}{3} = 2.66s = 83.3\% \quad (36)$$

Next, the UDP smart meter reading algorithm was used to analyse the performance of the WiMAX based smart meter service network. Because it consists in only one packet transmitted with an interarrival time follow a uniform distribution, the expected average end-to-end delay value is the ½ of the maximum polling delay or IPT.

Moreover, a set of simulations incrementing the IPT is presented. The new values are 50s, 100s, 200s and 300s. These values are incremented in order to reduce the unused polls. For the FTP transmission (three messages) system with an application interarrival time of 300 seconds, the unused polls number is given by the Equation 37. The Equation also presents an example for IPT for 3.2seconds, FTP transmission and application interarrival time of 300 seconds. Table 26 presents the relation between the IPT and the unused polls for the FTP and UDP transmission model.

$$UnusedPolls = \frac{APPInterArrivalTime}{IPT} - \# \, packetes$$
$$UnusedPolls = \frac{300s}{3.2s} - 3 = 93 - 3 = 90 \quad (37)$$

IPT	Unused polls (FTP)	Unused polls (UTP)
3.2	90	92
50	3	5
100	0	2
200	0	0
300	0	0

Table 26. Unused polls relation with the inter arrival time for FTP and UDP transmission.

The result of these new sets of simulations show similar results in terms of the slight increment of delay conform the user number increments. Figure 49 shows that the average delay is nearly half of the configured IPT. This confirms the expected 50% of the IPT. Figure 50 shows the distribution of maximum, minimum and average delay values. It shows that the maximum value is still the IPT value, the average is the half of the IPT and the minimum delay value is almost zero.

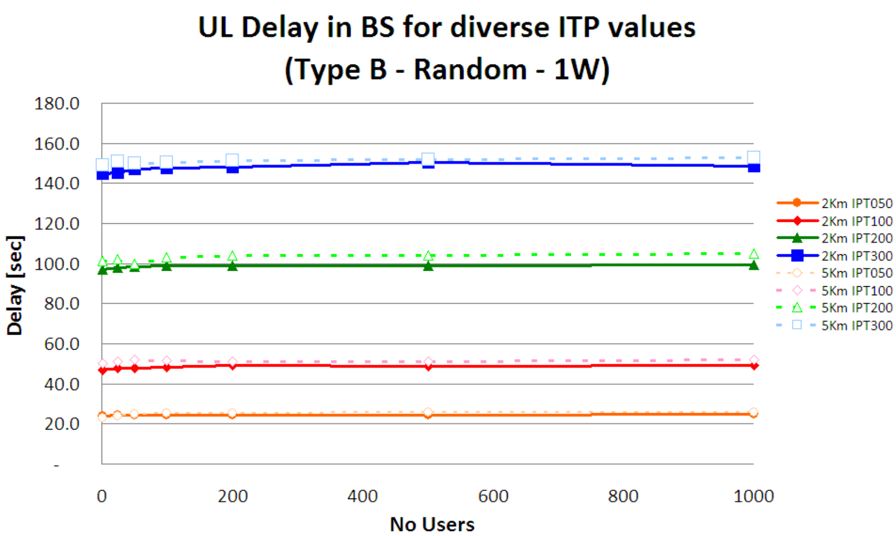

Figure 49. BS Delay for variable IPT (50s, 100s, 200s and 300s) using a random distribution Type B path loss and 1W of maximum power using UDP service.

Figure 51 shows the PDF of and UDP packet delay for different number of users with an IPT value of 100 seconds using random user distribution. Figure shows that delay distribution profile depends on the number of smart meters which are random.

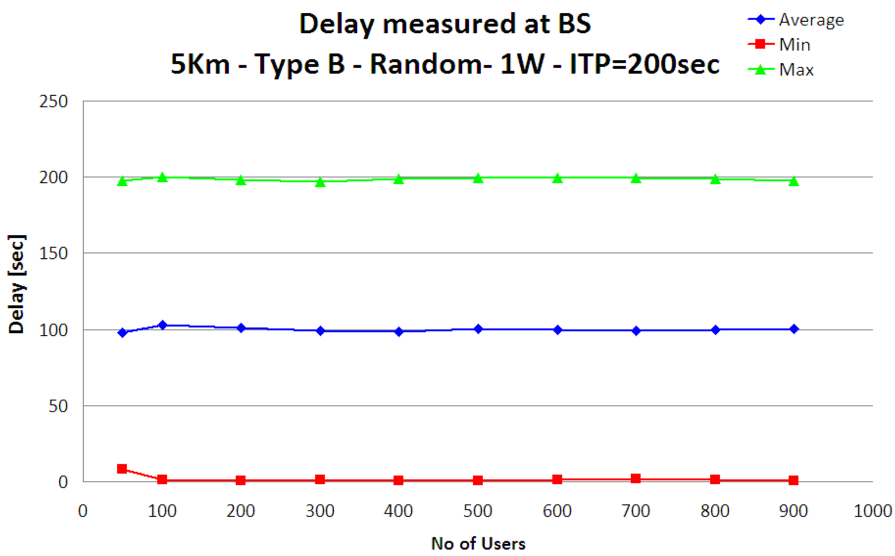

Figure 50. Example of maximum, minimum and average delay for IPT equals 200s in a Random distribution 5Km cell with path loss type B and 1W of maximum power transmission.

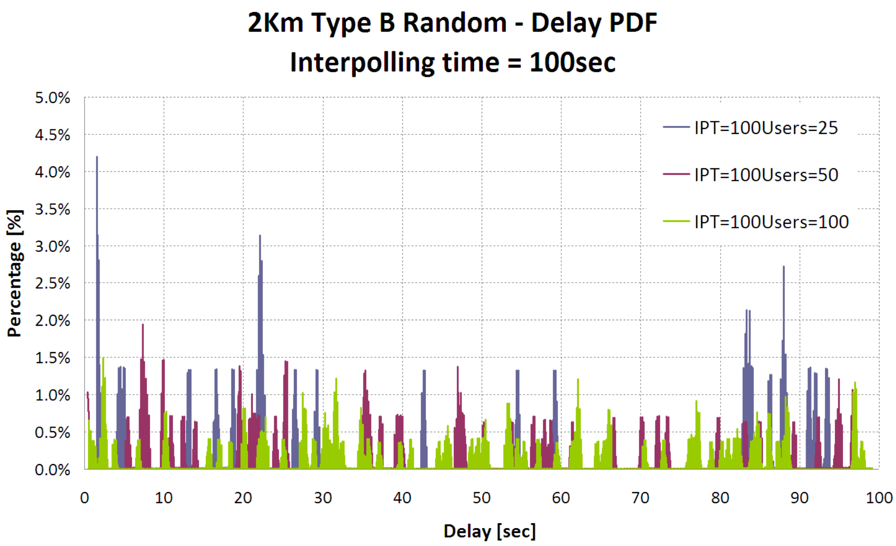

Figure 51. Example of PDF of delay for the UDP single message transmission.

4.4.2. *NETWORK CAPACITY CONSIDERATIONS*

Admission process

To analyse the performance of the network first we examined the number of admitted users. The number of admitted users is close to 100% for most of the scenarios as shown in Figure 52. for larger cells, the number of admitted users is lower, particularly for circular and square uniform distributions. For the random distribution all cell sizes supported 100% of users. In the case of the circular distribution where all the users are located at the same distance, the admission failure is due to the shadowing fading. Admission and entry procedures are described in section 3.1.1.

On the case of diverse maximum transmission power limit, the three values perform equally, because the open-loop power controllers' takeover the maximum power limit as is shown in Figure 52. These Figures present the results of scenarios with 50 users and single nrtPS connection with 5Kbps as MSTR.

In the next set of simulations, increments of the number of users up to 1000 and variations to the IPT with values of 50, 100, 200 and 300, are introduced. The results show that up to 1000 users in a random distribution, the value of admittance for 2Km cell size is has a steady value 100% with a variation of 0.2%, meanwhile for the 5Km cell, the admittance is nearly 95.6% with variation of 1.4%. The results show that the admission process is independent from the IPT because in Figure 54 the values are very similar for the 2Km and 5Km cell radius respectively.

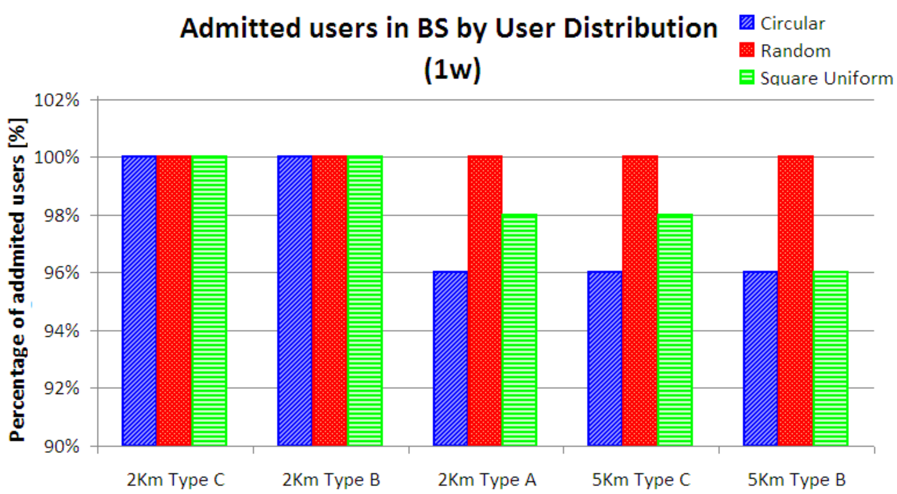

Figure 52. Admitted users for 1W and diverse user distributions.

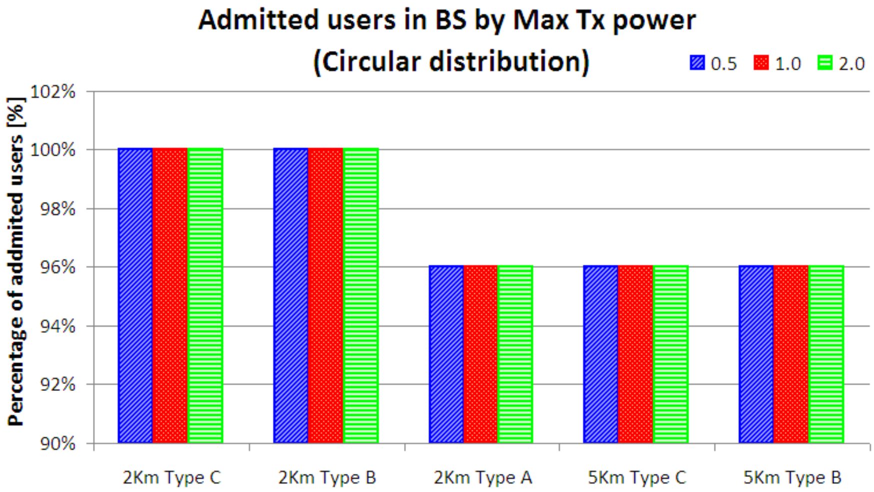

Figure 53. Admitted users in the circular distribution and max transmission power.

Apart from the cell radius, the average admitted value is independent of the number of users and the IPT as presented in Figure 52. Calculations show that the maximum number of admitted users is 1019. Equation 38 shows the relation between the total capacity and the admitted capacity per user. In this case, the value is 5200bps, 200bps more than the actual configured value. This is because the BS assigns extra bandwidth to nrtPS and rtPS for polling purposes, and avoids traffic starvation due the usage of data bandwidth in polling.

$$MaxAdmittedU = \frac{TotalULCapacity[bps]}{CapacityPerUser[bps/user]} = \frac{5299200\,sps}{5200\,sps/user} = 1019\,users \quad (38)$$

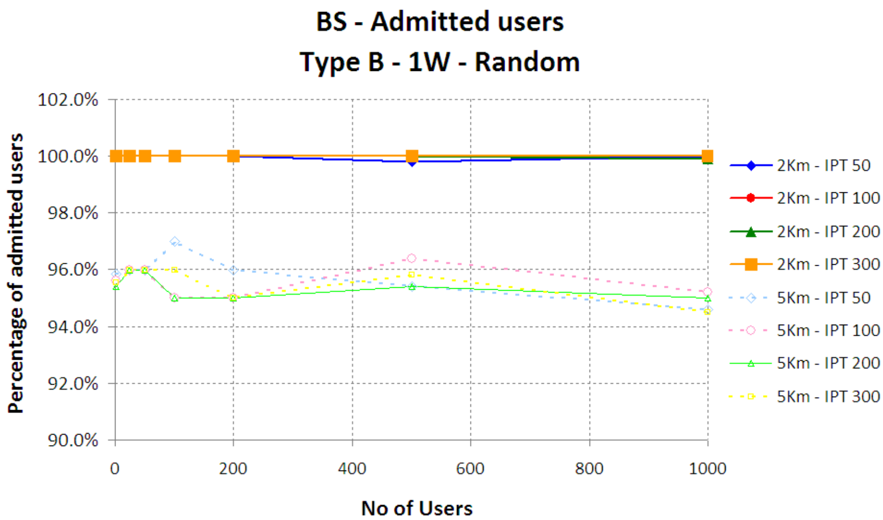

Figure 54. Admitted users for diverse IPT for 2Km and 5KM cells in random user distribution.

Non admitted users are because its transmission power is not enough to overcome the effect of the path loss and the received SNR at the BS is under the sensitivity level. In this case, power control procedures start to increase the transmited power to achieve the desired received SNR . If the SNR sensitivity is not achived the CDMA ranging codes will not be understood by the BS and the connections will be not admitted.

Uplink capacity

The analysis of the UL capacity determines the maximum traffic allowed for the smart grid network and gives the appropiate values for the MRTR and MSTR for the service connections attached to the metering application. According with Table 22, the smart meter application transmits in the UL a 1Kbyte message each 300 seconds. This configuration provides an average traffic rate of 26.66bps per user. Figure 55 presents the average received throughput for a simulation scenario of 100 smart meters with circular distribution using diverse propagation model scenarios. Results show that the througput decreases in scenarios which the users have low SNR due higher path loss such as Ercerg Type A. Notice that for higher transmission power, the throughput is higher, showing that lower values are due to packet losses for low SNR scenarios. Figure 56 shows that the throughput value results from random distribution are more steady through all the propagation scenarios. More over, for this distribution, the average throughput value is higer than the circular distribution. Figure 57 presents the results for uniform distribution.

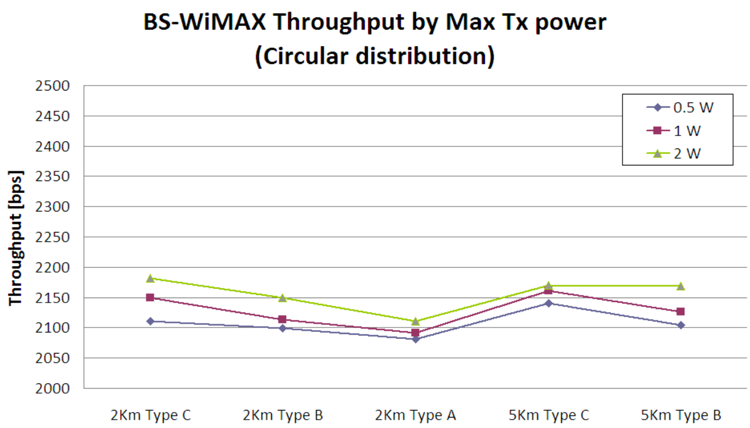

Figure 55. UL Throughput for diverse maximum transmission power for circular distribution.

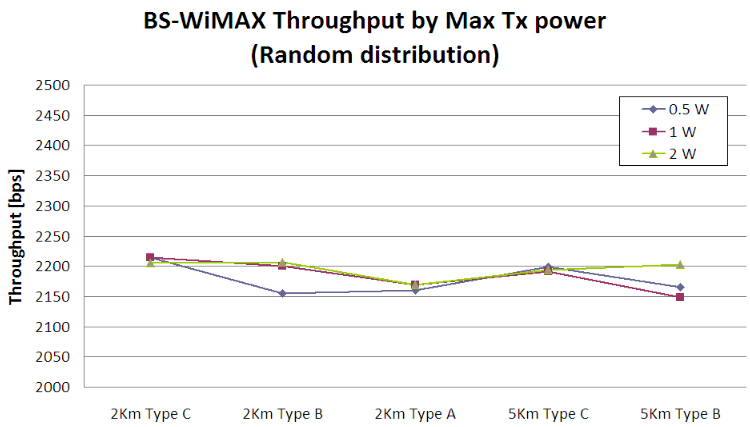

Figure 56.UL Throughput for diverse maximum transmission power for random distribution.

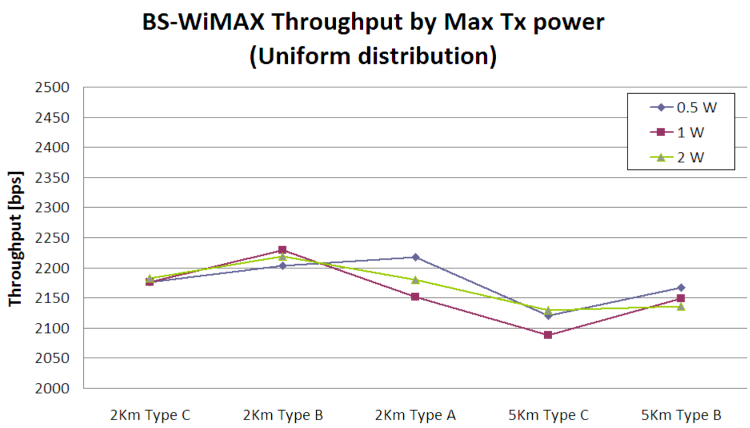

Figure 57. UL Throughput for diverse maximum transmission power for random distribution

The next set of simulations use a random distribution placement of the smart meters with a Erceg path loss model type B in two cell sizes. These two configurations have proven to be having admitted the maximum number of users and transmit the maximum throughput according to the previous section. These new simulations are designed to relate the impact to the throughput from the variation of the ITP. In these ones, we increment the IPT from 50sec until 300sec. Also we increment the number of users from 50 users to 1000 users. Results in Figure 58 shows that the 2Km cell size outperform the average of 5Km cell size. The results are very close to the expected throughput per user of 26.66 bps. Moreover, the Figure shows that the average throughput per user is constant though the number of smart meters. However, higher throughputs are achieved with lower IPT values. This is because in this set of simulations with bigger IPT values, some packets could be stuck in the transmission queue waiting to have a transmission opportunity that never arrived because the simulation ends.

This last asseveration is proven in Figure 59 where the transmission queue is measured. In the Figure the higher queue values are for those simulation scenarios with bigger ITP. This means that at the end of the simulation the queue could be holding some packets to be transmitted, increasing the average queue size. Figure 60 present the value of the smart meter average queue versus the increment on the IPT. In this Figure, the average queue size increments accordingly to the ITP. In addition, the average queue size value increments because the packets stay in the queue for a longer time, making the average increase.

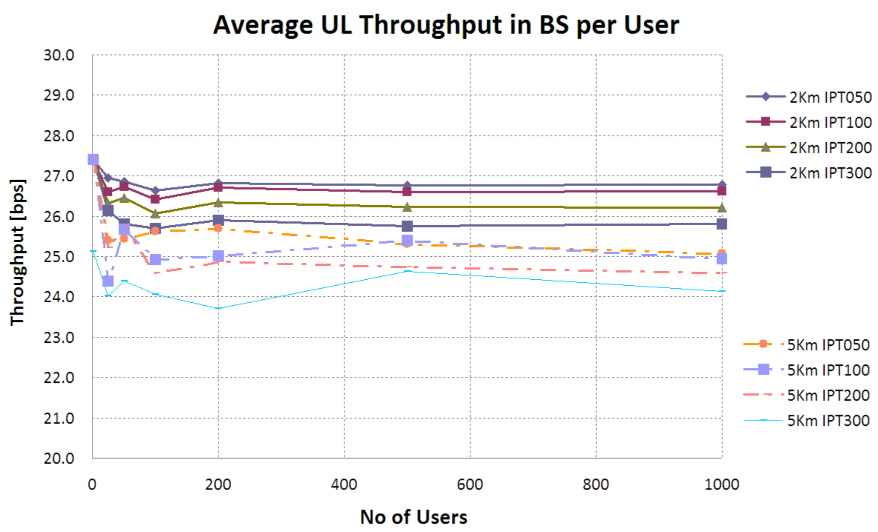

Figure 58. Average throughput per user for type B path loss and diverse IPT.

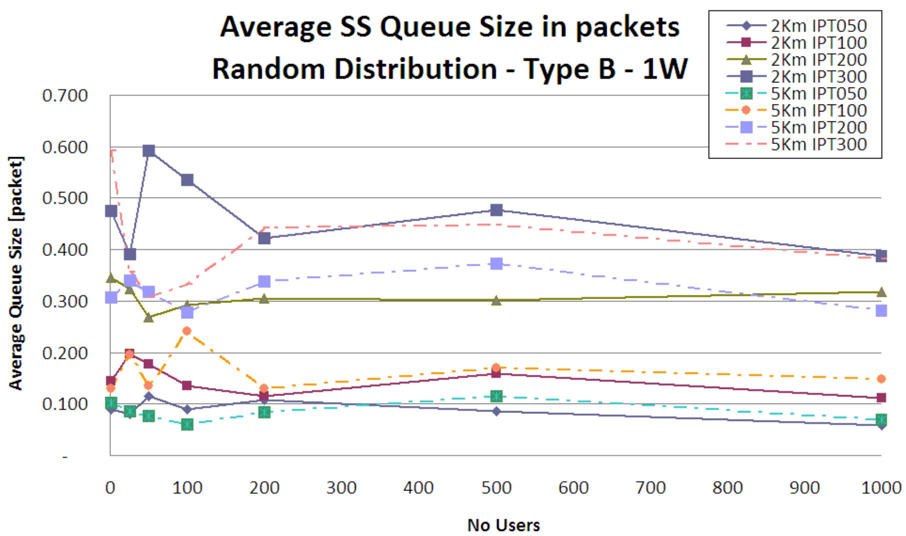

Figure 59. Average queue size for different IPT in a random distribution with path loss type B and maximum power of 1w.

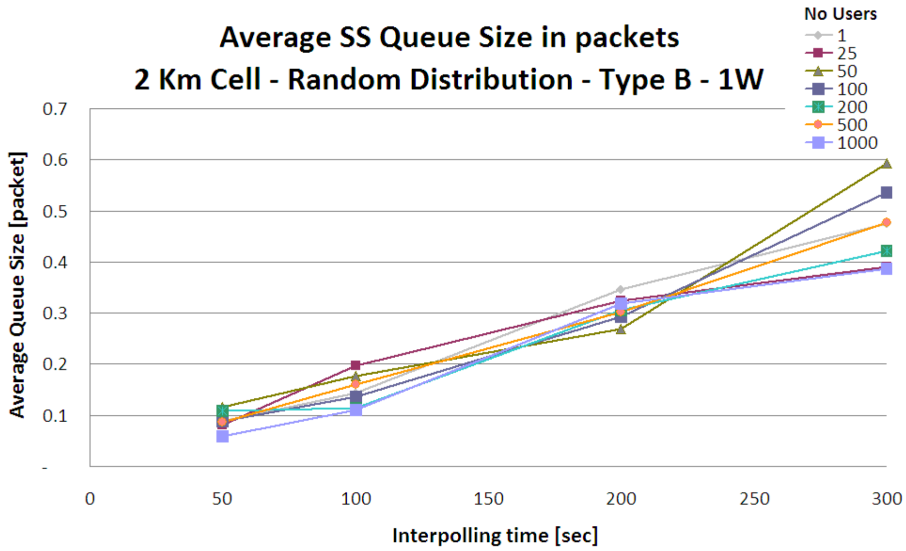

Figure 60. Average queue size for different IPT in a 2Km Cell with random distribution with path loss type B and maximum power of 1w.

4.5. CHAPTER SUMMARY

Chapter introduced the smart grid communication network architecture and the components related to fulfil smart grid applications. First, the chapter presented the distribution placement of smart meters in two different cell sizes, a system model based in the IEEE 802.16 WiMAX standard and the WiMAX physical and MAC layer parameters for the desired system. Next, the chapter presented the simulation model based on the OPNET simulation model, and the application traffic model for FTP and UDP based transmissions. Also the chapter describes the service classes for the smart grid applications in particular the IPT.

The chapter explored the propagation effects in a 2km and 5km cell size for the diverse smart meter distributions. In this section the definition, analysis and relation of sensitivity, received power and SNR is explored for the free space and Erceg path loss model which include the effects of shadowing fading. In order to overcome the effect of path loss the chapter presented the power control algorithms and their implications in the power received and the cell size according to different power transmission profiles. Result show that the best scenario is the 2Km random distribution.

Next was presented the impact of the IPT in the delay performance. Definition of the interpolling time in the simulation model and the relation with the delay per application were described. Results show that UDP based transmissions are more efficient in terms of delay compared with FTP ones. The number of unused polls is also explored to determine the appropriate IPT based in the QoS requirement of the applications. Results show that a network working in normal conditions, the maximum delay was the almost the same IPT.

Finally the network capacity was described. First, the admission process was introduced, and the result shows that the random distribution was able to support the maximum amount of users. Also, the admission results were not affected by the change in the IPT. Last, the uplink capacity was studied. Results showed that the capacity is determined by the amount of traffic and not the admitted capacity of each user. Also, for smart grids, the average traffic was a very small value and outperform with smaller IPT values. At last, the smart meter transmission queue is smaller for smaller ITP.

The next chapter illustrates the performance of the smart grid WiMAX network that serves multiple applications such as metering application, demand management side application and emergency sensor. Those applications have diverse QoS requirements and stipulate diverse network characteristic that will be explored in chapter 5.

CHAPTER 5.

DEMAND MANAGEMENT SYSTEM ARCHITECTURE USING THE WIMAX STANDARD NETWORK

5.1. INTRODUCTION

This chapter analyses the performance of a smart grid network using multiple applications. Compared to the work presented in chapter 4, this chapter presents traffic model for multiple smart grid applications thus realising the demand management system architecture. A Demand Management System (DMS) application and an Emergency Sensor Reading application are the main traffic sources included in the smart grid communication network model to analyse its performance.

These applications were chosen because one of the principal goals of the smart grid network is to manage the energy generation and consumption processes. The inclusion of renewable energy sources in the generation process has created the need for the inclusion of a consumption management system either in real-time or in non-real-time. An application like smart meter reading is a good way to acquire consumers' information, but they do not control their consumptions or offer provisions to appliance controls. Thus, demand management system control applications and sensor reading across the smart grid could provide the control of distributed generators and the consumers' electricity demands.

The smart grid could use a WiMAX network as a communication interface between the customers' applications, the smart grid operational entities and the service domain entities. They are able to support applications related to the household, such as Smart Meter Reading and Demand Side Management applications. On the other hand, sensors across the distribution network could to use the WiMAX communication interface similar to the one implemented for the smart meters. However the sensor could be read by the WiMAX network using a higher priority.

This chapter presents the details of several smart grid applications and their relationship with the WiMAX network. Then, it presents a simulation model used to incorporate the new applications, including the distribution and application models and the appropriate WiMAX network parameters. Next, the chapter presents the performance analysis of a demand site management system and smart reading applications by studying the delay, capacity and packet losses of a smart grid communication network. After the DMS performance analysis, a similar study is performed for emergency data reading applications from a distribution sensor network. Finally, the chapter summarises the results and highlights the communication network design, in order to optimize makes the operational features of a smart grid network.

5.2. *APPLICATIONS DESCRIPTION*

As presented in section 2.4, three applications were defined for this smart grid communication network, which are Metering Reading, Demand Management systems and Sensor data reading. For the sake of simplicity in this work, we refer to those applications as *metering*, *demand* and *sensor* respectively. The applications message behaviour is presented in Figure 61 where differences between the three applications are summarised.

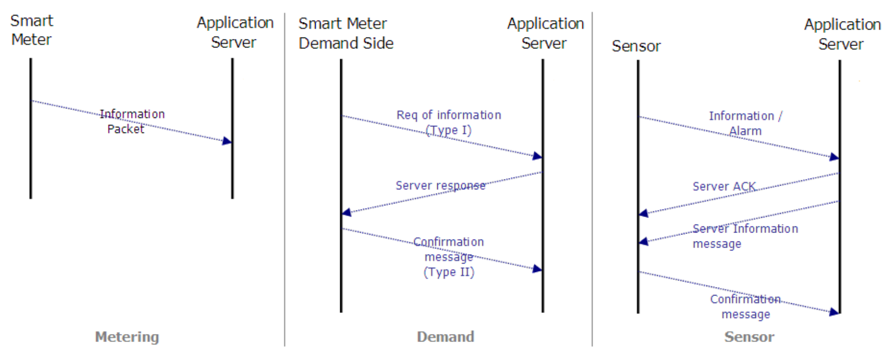

Figure 61. Different message transmission techniques used in metering, demand and sensor applications.

Devices with the demand and metering applications configured in such a way so that diverse priority levels can be supported. In this case, control information from the demand application has a higher priority than the metering information. For this reason, we assigned different service classes to the three sets of messages. The Meter-reading domain has the nrtPS configuration; meanwhile the demand mode and the sensor mode have the rtPS configuration. Table 27 show the different configuration details.

The packet scheduling techniques and services classes which are used in this work have the same parameters as presented in Table 7 of chapter 2. Table 27 below defines those parameters in terms of specific values used in this work.

Service Class name	Scheduling type	Traffic Rate	Interpolling time	Average SDU
Metering	nrtPS	40bps	500 sec	2 Kbytes
Demand	rtPS	100bps	120 sec	2 Kbytes
Sensor	rtPS	200bps	100 msec	750 bytes

Table 27. QoS service class configuration parameters.

In this case the applications are related to the services classes that are also related to the scheduling types. The rtPS type is used to support a connection within a defined range of the maximum delay and the minimum traffic rate. For the case of the nrtPS type traffic, the only supported parameter is the minimum traffic rate, where a minimum delay is not guaranteed. The round robin schedulers, as described in chapter 3, are well known for supporting small size packets like the ones described in Table 27.

5.3. SIMULATION MODEL

5.3.1. TRAFFIC NODE DISTRIBUTION MODEL

The traffic node distribution model explains how the nodes are distributed within the service network coverage area of a smart grid. These nodes are distributed to represent a typical neighbourhood where smart meters and sensor devices are placed within the service area. Based on the findings of chapter 4, the more suitable scenario to represent an average neighbourhood is the circular random which is used in the simulation, where all the smart meters are deployed inside a circle with a random distance from the BS. After distributing the nodes, the simulation model configures different applications on these nodes and then the packet schedulers are configured. The simulation model used is a single cell network with a radius of 2km or 5km for urban and suburban radio coverage area are used as presented in Figure 62. The nodes are distributed randomly within the circular network area. This scenario provides a typical distribution of an average city. The simulation model was developed using the OPNET network simulator as shown in Figure 62.

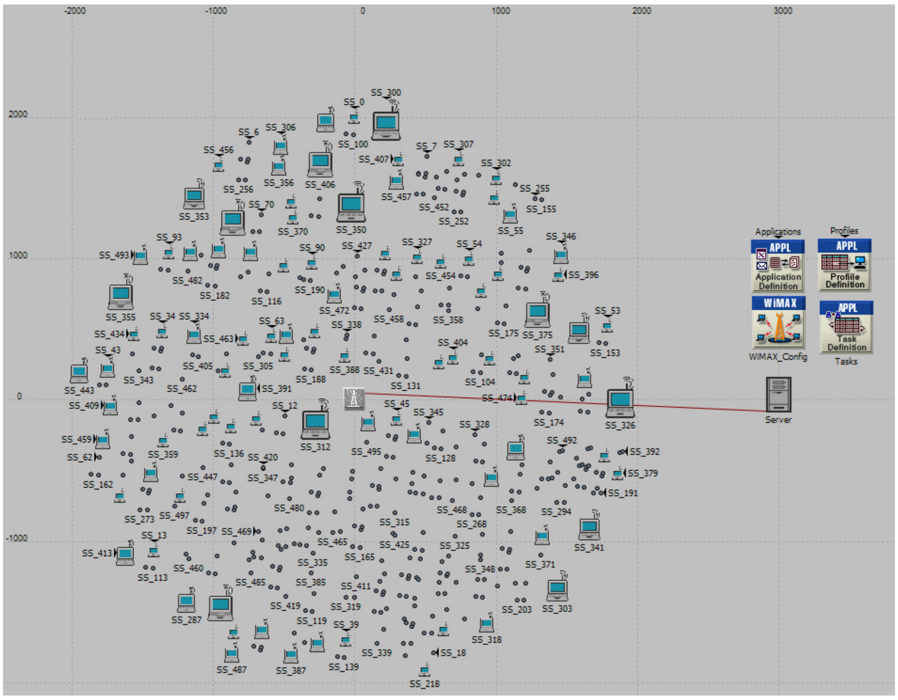

Figure 62. Placement of nodes in a smart grid communication network in the OPNET simulation model.

Within the simulation model various nodes are configured to support different applications such as meter, sensor and demand. Current simulation model assumes that 75% of the smart meters only supports metering application and the rest 25% of user support both DMS and metering applications. Also, an additional 200 devices contained in the network supporting sensor applications across the network are included.

All devices in the network have been configured to generate data at different points of time. The metering application sends meter-reading packets using an exponential distribution with an average interarrival time of 30 minutes. For the demand application packet interarrival time is simulated using a uniform distribution between 25 and 45 minutes. The smart meter supporting the DSM application sends a request packet for information message. Immediate response from the server is configured. The confirmation message from the user (type II message) has a normal distribution with mean value of 30 seconds and variance of 10 seconds. Finally, two types of sensors were simulated. The first set, models the packet interarrival time using a uniform distribution between 1 and 5 minutes. For the second set, three different distributions were used for the packet generation, namely the Sensor Type A uses an exponential distribution with a mean interarrival time of 5 minutes, Sensor Type B exponential distribution with a mean value of 3 minutes, and Sensor type C also uses an exponential distribution with a mean value of 30 seconds. Table 28 lists the described distribution parameters. These distribution patterns were chosen because the characteristics of each application. The metering application is described with an exponential distribution because it describes metering measurements that are not related with other one and have a rate of occurrence close to 30 minutes. The Demand and Sensor applications have minimum and maximum time of data generation, but it characteristics are more close to Uniform distribution rather than normal or tail distributions. Hence, Uniform distribution was chosen.

Application	Distribution	Value
Metering	Exponential	30 min
Demand	Uniform	25min to 45 min
Sensor	Uniform	1min to 5 min
Sensor Type A	Exponential	5 min
Sensor Type B	Exponential	3 min
Sensor Type C	Exponential	30 sec

Table 28. Applications' traffic generation parameters

5.3.2. WIMAX SIMULATION NETWORK MODEL

The simulation model used to analyse the communication network for multiple applications, is divided in three phases. The first phase compares the performance of a network with an increasing number of users between 100 and 500 users, using two different cell sizes of 2 km and 5 km. This first phase of simulation only considers the smart meters with metering and demand applications running on them. For the second set of simulations with different interarrival times of the metering packets is changed from constant value of 1800 seconds to an exponential distribution of 1800 seconds to represent more realistic arrival of metering information. The third set of simulation shows results of the introduction of 200 devices using only sensor applications. All the simulation scenarios were run for 2 hours of simulation. The proposed simulation network is defined with the same network parameters used in the previous chapter as described in Table 20.

5.4. PERFORMANCE ANALYSIS

5.4.1. SMART METERS

A set of simulations was performed to determine the performance of a WiMAX based network for two different applications. In this case, the number of users is incremented from 100 to 500 using a 100-users step. All the simulated nodes were generating meter reading applications and a selected 25% of smart meters implemented the DMS application.

Network admission control

The admission control procedure receives the network entry requests from different terminals and admits or rejects them based on the available resources. This process is carried out at the BS to admit or reject users willing to connect to the BS. This section presents the performance of the admission control procedure used for smart meters. A simple smart meter will be configured according to the application requirements and set its communication parameters accordingly. In the simulation model, the control connections are configured as a Best Effort scheduling type, hence the BW requested by meters will not affect in the capacity of the system. Only non-BE connections affect the capacity. These control connections are *Basic Control*, *System Default*, *Bronze* and *Broadcast*. The function of the *Basic Control* is to exchange control messages for creation or deletion of dynamic service connections. The function of the *System Default* connection is to serve as a default connection for those packets that could not be classified. The function of the *Bronze* connection is to transfer all the BE data packets. And the function of the *Broadcas*t connection is to serve as a mechanism to respond to broadcast messages and is only active for UL connections. Table 29 presents the result of the admission control process for smart meters using DMS and active metering applications. A total of 11 connections are admitted, 6 for the UL and 5 for the DL. If the device has only the Metering application, just 9 connections will be active.

For the UL real time connections, an overhead of 6 bytes is added for the polling procedures, allowing enough space for the polls (a MAC header of 6 bytes). However, the incremented rate is the value of the overhead bits divided by the IPT of the connection, and the result is in bps. Finally, the admitted BW is the integer number of bits per frame of the requested plus polling BW. Equations 39 and 40, present the admitted BW relation for UL and DL connections respectively.

$$ULAdmittedBW = \left\lceil \frac{requestedBW + \frac{MACHeader}{IPT}}{\#Frames/Sec} \right\rceil * \#Frames/Sec \qquad (39)$$

$$DLAdmittedBW = \left\lceil \frac{requestedBW}{\#Frames/Sec} \right\rceil * \#Frames/Sec \qquad (40)$$

where, *admittedBW* refers to the admitted capacity of the connection, *requestedBW* is the requested BW of the particular connection, *IPT* is the inter polling time configured in the service class definition as explained in section 3.2.3, and the *#frames/sec* is the number of

OFDMA frames per second. Equation 41 presents an example for an UL connection for a DMS application.

$$Admitted = \left\lceil \frac{100bps + \frac{48bits}{120s}}{200fr/s} \right\rceil * 200fs/s = \left\lceil \frac{100.4}{200} \right\rceil * 200 = 1 * 200 = 200bps \quad (41)$$

Device name	Direction	Service Class	Application	Scheduling type	Requested BW [bps]	Overhead BW [bps]	Admitted BW [bps]
SM_0	Downlink	Basic Control	None	BE	32	0	0
		Bronze	None		5	0	0
		System Default	None		0	0	0
		Silver	DMS	rtPS	100	0	200
		Silver (nrtPS)	Metering	nrtPS	40	0	200
	Uplink	Basic Control	None	BE	32	0	0
		Broadcast	None		0	0	0
		Bronze	None		5	0	0
		System Default	None		0	0	0
		Silver	DMS	rtPS	100	1	200
		Silver (nrtPS)	Metering	nrtPS	40	1	200

Table 29. Example of an admission result for a smart meter with DMS and Metering application

The results in Figure 63 show that a 5km cell has fewer active connections than the 2Km cell due to the propagation condition. This Figure also shows the relationship between the number of connections and number of smart meters. Each meter has eleven connections, six in the UL and five in the DL. Figure 64, describes percentage of active users in both cell size scenarios. Active users or active smart meters refer to those meters that are able to create stable connections with the BS. The 2Km cell size is able to support and admit all the connections from every smart meter, showing that a single cell antenna with 2Km radius, could admit 100% of the users, unlike the 5Km radius cell where admission rate drops down to 97%.

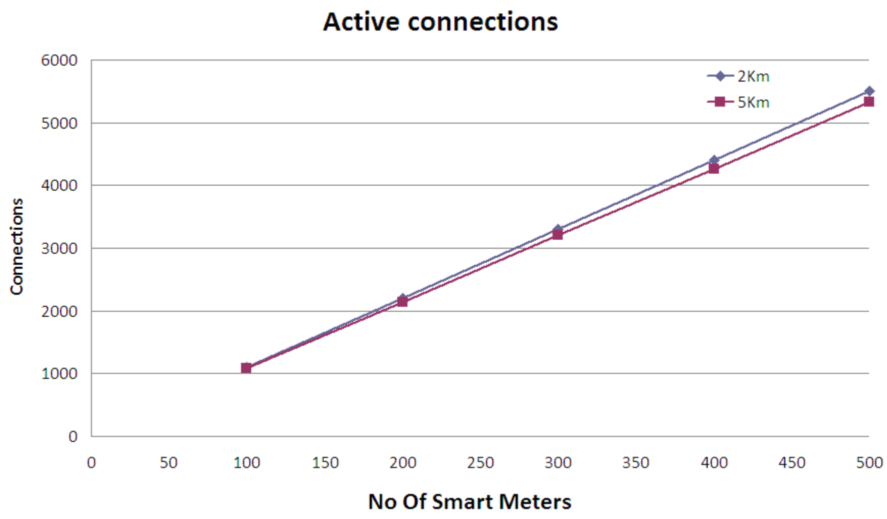

Figure 63. Total number of connections admitted by the WiMAX BS using the circular random distribution.

This reduction is due the low SNR of devices at the cell edge that could not achieve the minimum SNR to be admitted in the network. That means that the maximum transmitted power in the ranging process is not sufficient to overcome the path loss when the shadowing fading is applied. Analysis of the results also shows that because of the simulation model, some connections from the same user could be admitted and some other not. In specific, UL connections are admitted but DL connections are not due the differences in the SNR between UL and DL.

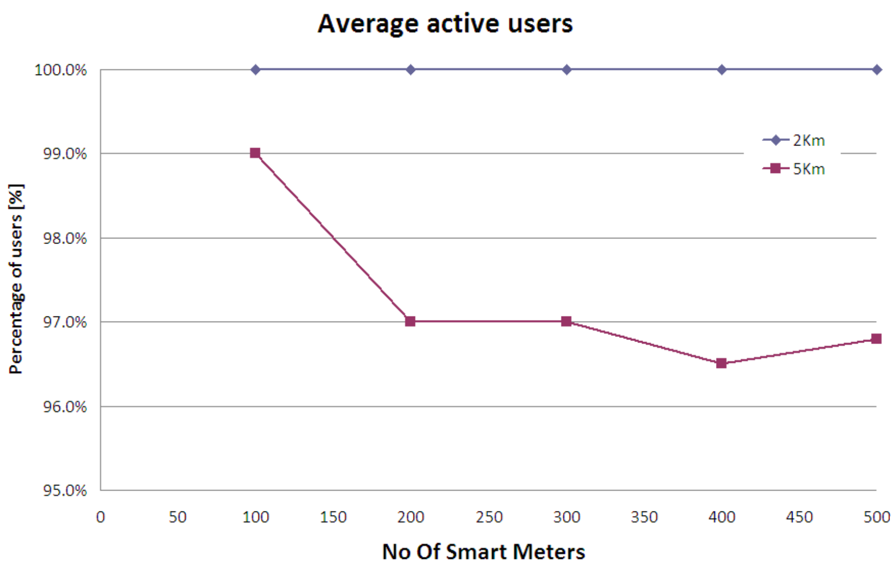

Figure 64. Average number of admitted connections.

Link Delay

The link or packet delay is an important QoS component. Different connections have different delay requirements based on application requirements as described in Table 27 in section 5.2 .

The average delay measured at the BS is a sum of individual delay values of received packets by the BS. These packets could be sent from the metering application or from the DMS application. Moreover the packets from the DMS application could send request packets or packets containing an information message, thus requiring different connections. Figure 65 shows the average delay gathered by two smart meter applications. These applications have IPT of 500sec and 120sec for metering and demand management respectively, and the individual results from those applications are shown in Table 30. The Table shows that the metering application delay values are uniformly distributed with the average delay close to the middle range of the IPT. In contrast the DMS, which its delay value is closer to the maximum delay. This is due the two messages transmitted in the DMS application, which the first one behaves with a uniform distribution, and the second message has a delay value almost as big as the IPT delay due to the fast response of the server. This behaviour is similar to the FTP metering application described in section 4.4.1.

Parameter	Metering	DMS
Maximum average delay [sec]	499.087	119.181
Minimum average delay [sec]	0.220	0.118
Average [sec]	268.42	95.301
Standard deviation	119.781	26.747

Table 30. UL Delay components for Metering and DMS applications

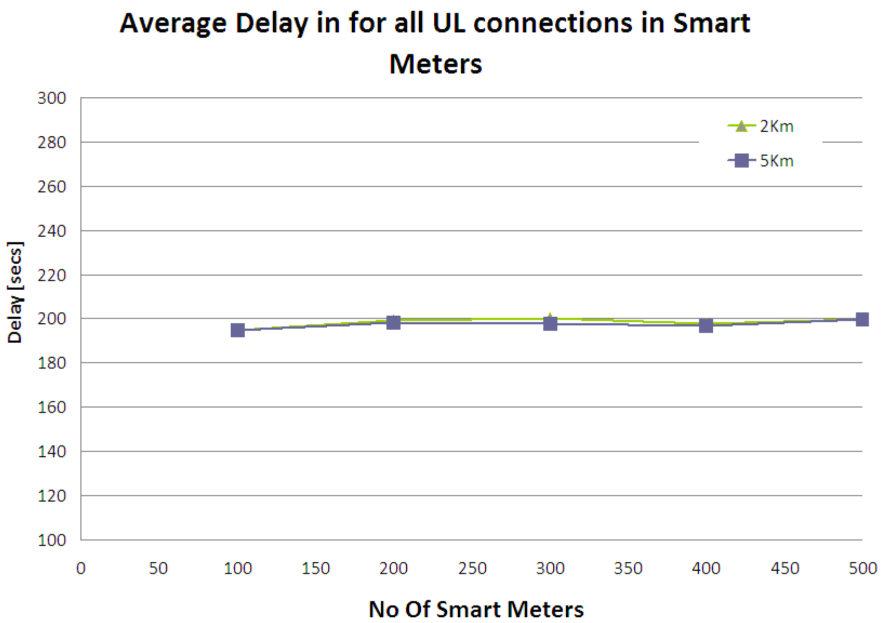

Figure 65. Average delay for all users for the UL measured in the BS.

The probability density function plot of the delay is shown in Figure 66. The delay plot was obtained from different cell sizes with different number of meters. The plot shows the delay spread in different sized cells. The delay spread to some extent depends on the user distributions inside the cell. Figure shows that for a smaller number of users, significant proportion of the meters is experiencing delay. Figure shows that a small number of users in this network could experience significantly long delays. Also, the Figure shows a peak delay value is near the 120 seconds which reflects the delay between the two consecutive transmissions in the DMS application specifically, the time between the server response and the confirmation message.

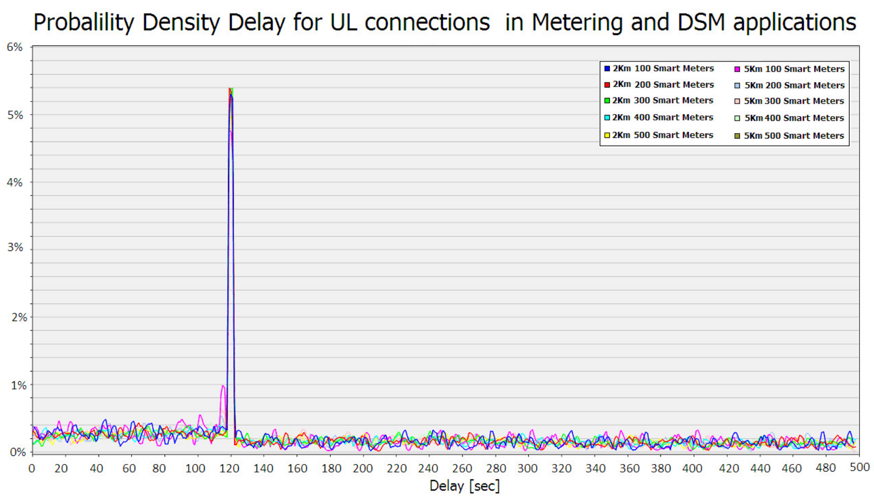

Figure 66. Example of PDF global UL delay in different scenarios for metering and demand modes.

In the case of the DL connections, the delay value is very close to the frame size time. Simulation results show that the average delay value slightly increases with the number of smart meters. As the numbers of devices increase, the mapping allocation is made closer to the left side of the WiMAX DL subframe thus increasing the delay. The DL delay is much lower than the UL delay, because on the DL delay, no ranging or call admission processes are involved. This behaviour is shown in Figure 67.

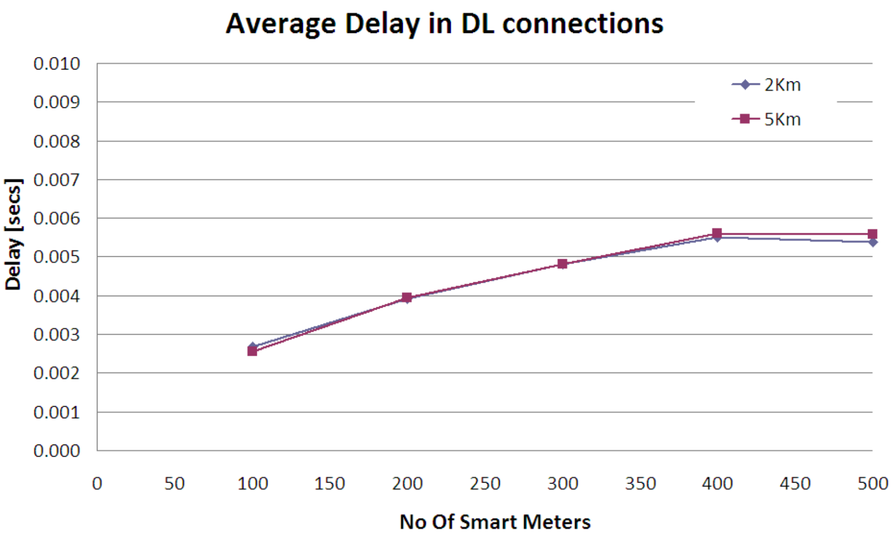

Figure 67. Average delay for all users for the DL measured in the SM.

Connection delay

In order to determine the performance of different applications, the performance of different packet schedulers are analysed. For the Metering application the nrtPS scheduling is used and for the DMS application the rtPS scheduling is used. The measurement of these values was made by taking a sample of 10% of the total active connections and averaging those values.

The metering application delay slightly increases with the number of users. Compared with the delay of the DMS application, one can find that the DMS delay rise is much slower. This is due the fact the rtPS scheduler used for the DMS application needs to assure a minimum delay and has higher priority over the nrtPS scheduler used for the metering application. Thus, the metering application delay value increases a lot faster than the DMS one. These delay components could be seen in Figure 68 and Figure 69 respectively.

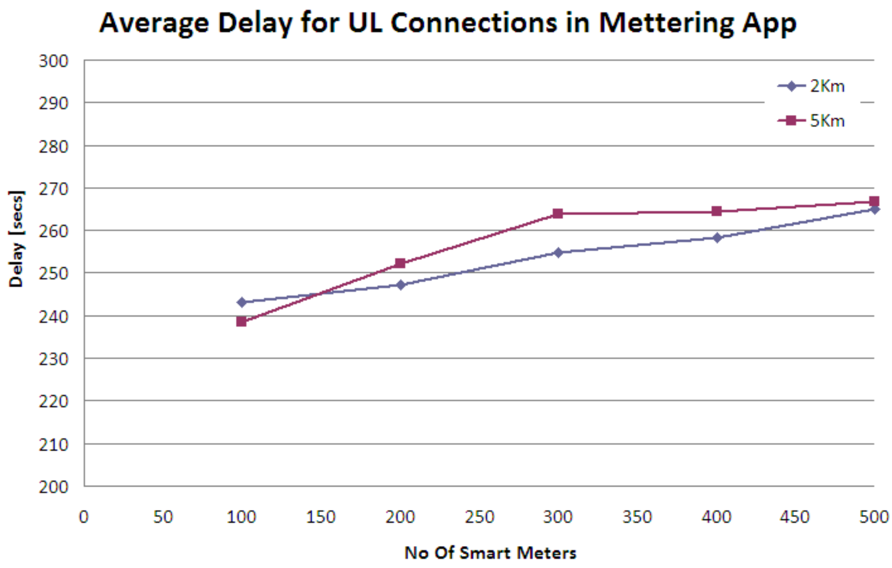

Figure 68. Average UL delay for users using nrtPS connection (Metering application)

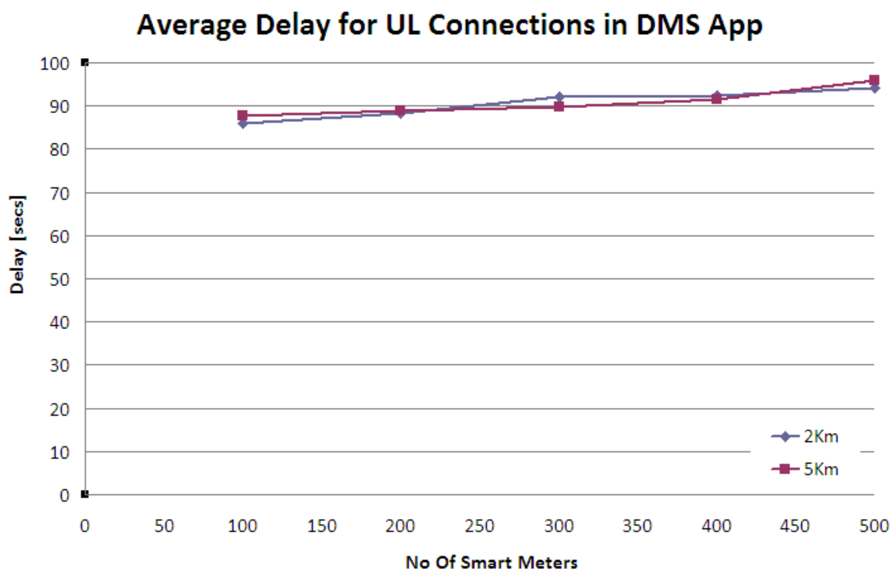

Figure 69. Average UL delay for users using rtPS connection (DMS application)

Figure 70 shows the DL delay for the DMS application. There is no DL delay for metering application because this application uses one-way traffic only. The downlink delay is constant; close to 6 msec. This value corresponds to the frame size plus the preamble and mapping information (DL-MAP) on the WiMAX DL subframe,. In this case almost all the packets need to wait for the next frame to be transmitted.

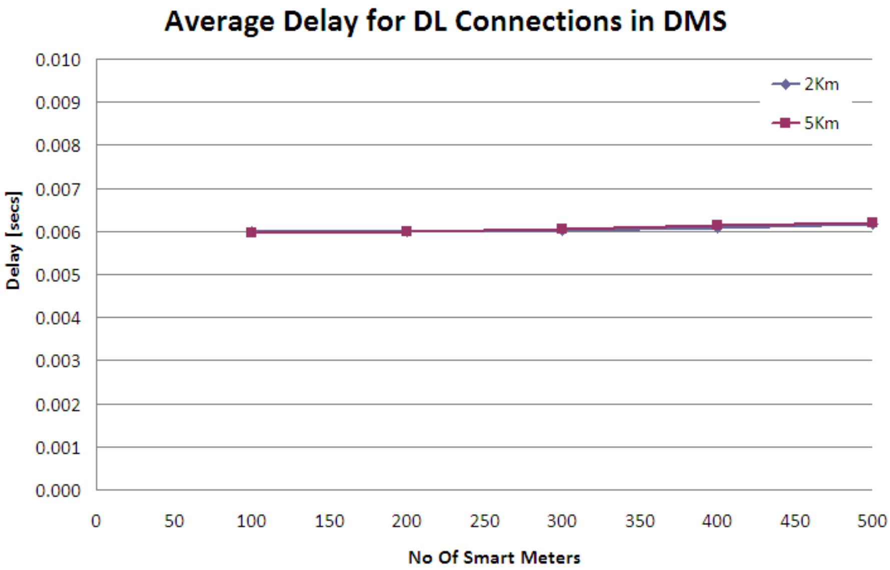

Figure 70. Average DL delay for users using rtPS connection (demand mode).

Smart Grid traffic analysis

In this section the traffic throughput and the traffic load for the smart meters are examined. The offer load is defined by the applications in the system. In this case, the two applications generate a different number of packets in total. Based on a 120 minute simulation, the number of packets generated is calculated by the sum of the packets in the metering application and in the DMS application. For the metering application, the exponential distribution presents a packet interarrival time of 30 minutes leading to four packets per simulation. For the DMS application, the uniform distribution reveals a packet interarrival time of 35 minutes, leading to 6.85 packets per simulation. The total offer load per user on average is 10.87 packets. Equation 42 presents the calculation of the average packet per simulation and Figure 71 shows the results of the sent packets by the smart meters to the BS. The variations presented in this Figure are related with the distribution values of each application. The values are presented in packets per simulation time, due to the small amount of traffic per user. The average offer load of packets per second for this simulation is $1.51*10^{-3}$ packets per second per smart meter.

$$\frac{120\min}{30\min/\,pack} + 2*\frac{120\min}{35\min/\,pack} = 4\,pack + 2*3.428\,pack = 10.86\,pack\,/\,sim \tag{42}$$

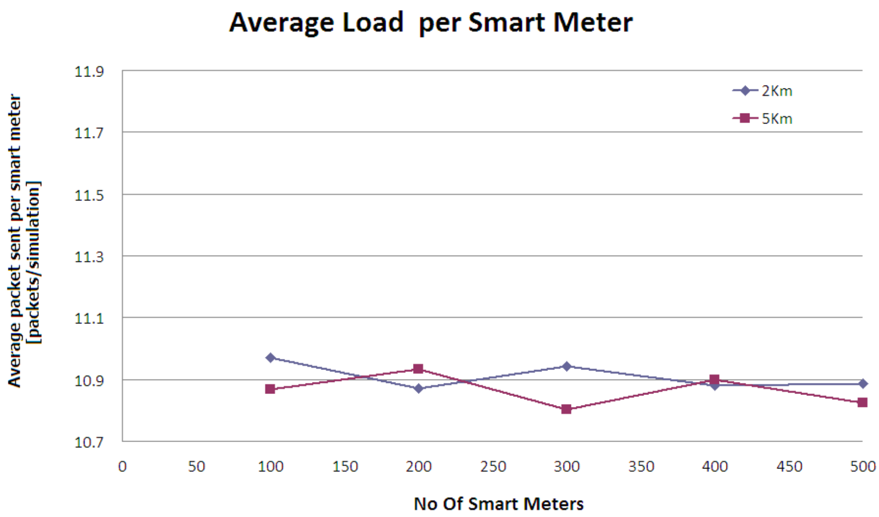

Figure 71. Average total Load in UL connections for admitted users.

The relation between the offered load and the received throughput is presented in the Figure 72. In this Figure, the results show that for the 5 Km cell size simulation, throughput is lower than the 2Km cell throughput. This is due to packet loss resulted from the low SNR. Due to low SNR those meters are not admitted in the network hence those meters do not transmit any packets.

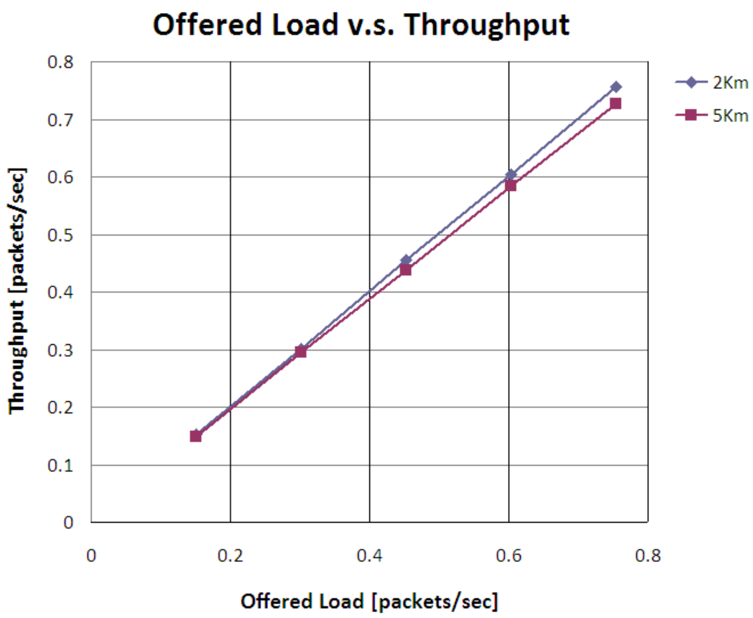

Figure 72. Relation between the total offered load and the total received throughput.

The total number of received packets at the base station is shown in Figure 73, it compares the number of packets in both scenarios of 2Km cell and 5Km cell. As depicted above, in a

5Km cell not all the packets are received at the base station. Hence, a packet loss analysis is made in the next subsection.

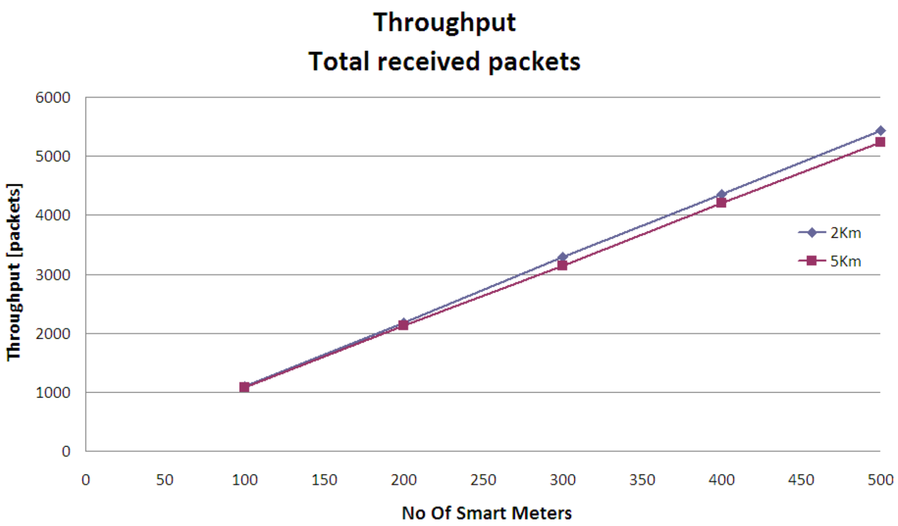

Figure 73. Total UL Throughput measured at the BS.

Network Packet Loss

In this section the packet loss values are calculated using a sample of 50 meters by measuring their load values, throughput and the transmission queue length at the end of the simulation, to count all the packets that were not transmitted at the end of simulation. The difference of these values represent the packet loss due to poor channel quality. The average packet loss value was calculated using the Equation 43. This procedure needed to be implemented due the fact that the packets lost statistics in OPNET simulator, include measurements of ranging process and other undesirable packets in the physical layer not related with the application connection and its traffic.

$$PacketLost\,[packs] = TotalLoad\,[packs] - TotalThroughput\,[packs] - Queue\,[packs] \tag{43}$$

where, *Total Load* is the total number of packets put in the queue by the application layer in a specific connection, *Total Throughput* is the total number of packets received at the BS in a particular connection and *Queue* is the number of packets left in the queue not transmitted. Using the above analysis, total number of transmitted packets is calculated by Equation 44.

$$TransmittedPacket\,[packets] = TotalLoad\,[packets] - Queue\,[packets] \tag{44}$$

where, *Transmitted Packet* is the total number of transmitted packets, *Total Load* is the total number of packets put on the transmission queue and *Queue* is the number of packets left in the queue not transmitted.

Finally, the percentage of packets lost is calculated based in Equation 45.

$$PacketLost[\%] = \frac{PacketLost[packets]}{TransmittedPacket[packets]} \quad (45)$$

The results are presented for the entire system and for all service applications. First, for the metering application, which used the nrtPS connections, there are packet losses due to not employing any retransmission techniques like the ARQ. Figure 74 shows the packet losses for the metering application. The Figure shows that the losses start for scenarios with more than 200 smart meters and these losses are under 2% of the total transmitted packets. In addition, for the case of DMS application, the packet losses are null as shown in Figure 75 due the usage of ARQ retransmission technique.

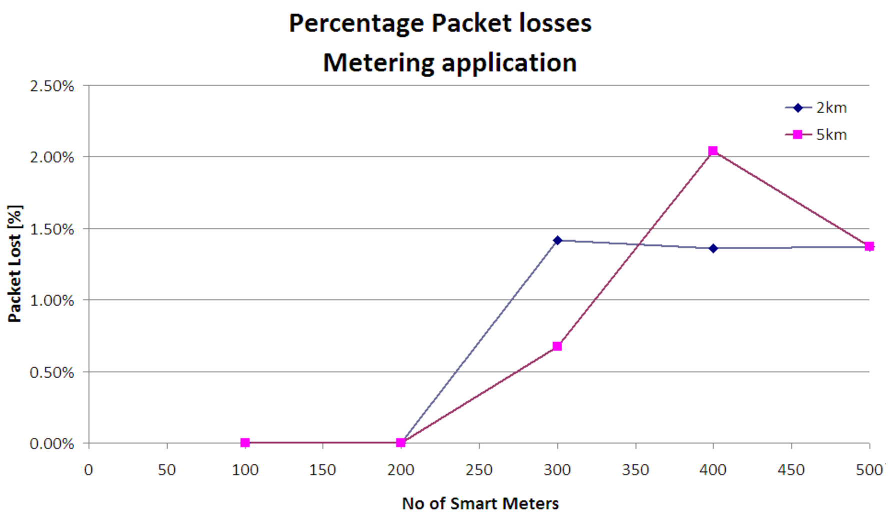

Figure 74. Percentage of packet loss in the metering application.

Packet loss occurs in the WiMAX network due to shadows fading where nodes could lose their connection to the BS due to low link SNR. In this case, any packet arriving at the node buffer will be dropped.

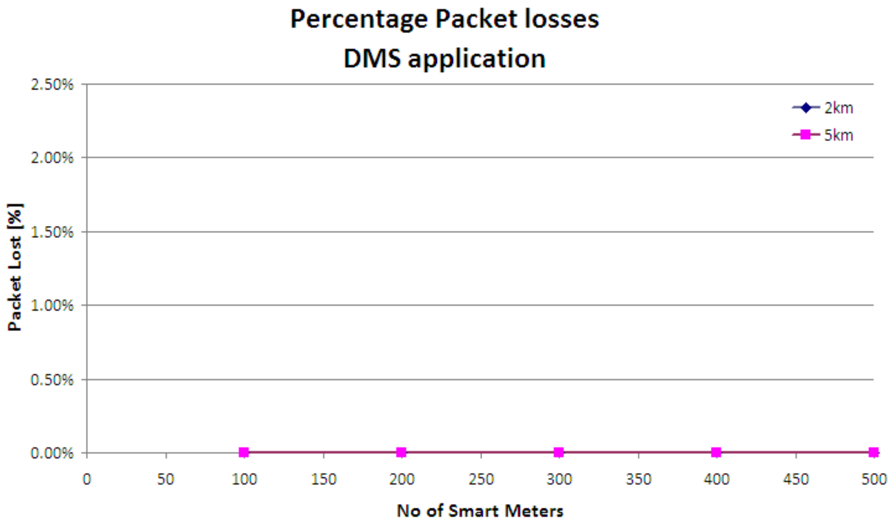

Figure 75. Percentage of packet loss in the DMS application.

5.4.2. *EMERGENCY SENSOR TRAFFIC*

The emergency sensor application simulation was used to analyse the performance of unscheduled messages with very tight delay requirements. The inclusion of emergency sensor application, introduces a new behaviour to the network with diverse scheduling types and different delay requirements. The following sections explain and present the results of the simulations that include the data from emergency sensors. In this case the simulation model used 500 smart meters and 200 sensors in a 2Km radius cell.

Admission control

In a network the admitted capacity is determined by the admission control process used in the ranging entry process. Devices willing to enter a network use the ranging process to send their connection requirements in the ranging field of the UL subframe using a contention access method. The time to admit all the connections in the network is known as the initialization time.

In this simulation 500 smart meters and 200 sensor nodes are used. As described in the admission section 5.4.1 of chapter 5, the admitted capacity is not the same as the requested capacity. The example presented in Table 31 shows the basic characteristics of smart meters (*SM_0*) and sensor nodes (*Sensor_0*). For the UL connection in the sensor device, the value of the overhead is 480bps, which is the result of the 48 bits from the MAC header divided by the 100 msec of the IPT. Equations 46 and 47 present the admitted capacity for UL and DL connections. In Equation 47, the first two multipliers represent the DMS and Metering application connections capacity and the third multiplier represents the sensor application capacity. Moreover, the free capacity of the network could be described as the total capacity less the admitted capacity.

The whole admission process in this scenario, takes up to five seconds in order to complete the admission of 700 devices. Figure 76 shows a graph with the free capacity for the UL and DL connections. It represents the space available after the admitted capacity subtracted from the total capacity. In this scenario, the admitted values correspond with the admitted capacity from Equation 47. In the 2Km radius cell, the received SNR permits that all users are connected to the network, as a result the theoretical values of the admission from Equation 47 are the same as the ones for the simulation result represented in Figure 76.

Device name	Direction	Application	Scheduling type	Requested BW [bps]	Overhead BW [bps]	Admitted BW [bps]
SM_0	DL	DMS	rtPS	100	0	200
		Metering	nrtPS	40	0	200
	UL	DMS	rtPS	100	1	200
		Metering	nrtPS	40	1	200
Sensor_0	DL	Sensor	rtPS	200	0	400
	UL	Sensor	rtPS	200	480	800

Table 31. Example of admitted connections for smart meters and sensor devices.

$$AdmittedCapacity = \sum_{1}^{ApplicationConnection} AdmittedBW * NumberDevices \tag{46}$$

$$DLAdmittedCapacity = 200bps * 500devices + 200bps * 500devices + 400bps * 200devices = 280.000bps$$

$$UL\_Admitted\_Capacity = 200bps * 500devices + 200bps * 500devices + 800bps * 200devices = 360.000bps \tag{47}$$

where the *Admitted Capacity* is the UL and DL admitted capacity at the base station, *Application Connections* is the number of applications that used different connections, *AdmittedBW* is the admitted BW per connection and *Number Devices* is the number of devices using the particular application connection.

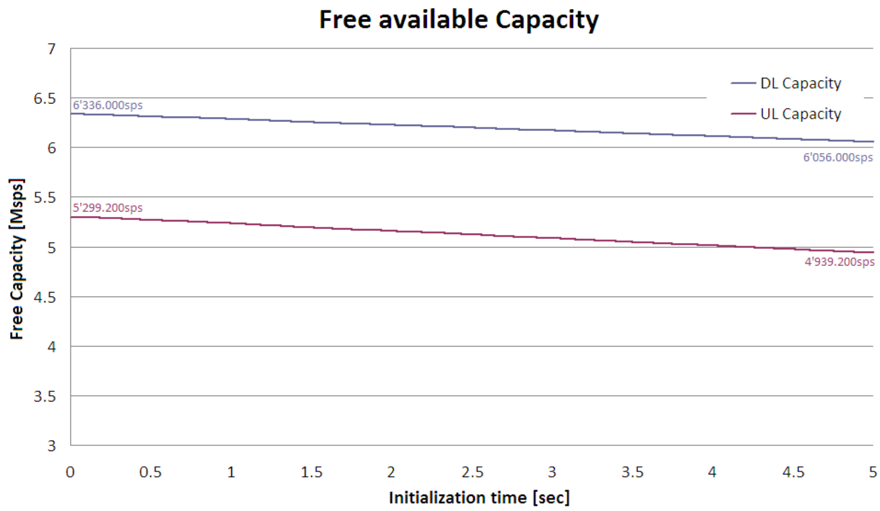

Figure 76. Initialization time to admit 500 smart meters and 200 sensors for a 2Km cell scenario.

Impact of multiple traffic sources

In this section, the impact of the introduction of 200 additional sensor nodes is analysed. The introduction of 200 sensors with higher priority modifies the traffic characteristics in the network. The present subsection analyses the network performance with additional traffic.

In Table 32, there is a comparison for the throughput in terms of packets per second for UL connections. The result shows increase of both offered load and throughput. Additional sensor nodes use a shorter interarrival time to push up the total traffic. As shown in Table 28, the average values for the interarrival time could drop from nearly 30 minutes down before the inclusion of sensor nodes to an average of 3 minutes due the short interarrival time of the emergency sensor application. The theoretical throughput for the sensors using the uniform distribution which has an average interarrival time of 180s and 2 packets per transmission is 2.22 packets per second. Notice that the increase of the throughput due to the introduction of the sensors compared to the no sensor scenario in Table 32. The Table presents the results of the throughput measured at the BS for all the connections. The throughput increases from 0.33 packets per second for the without sensors scenario, to 2.55packets/sec in the sensor scenario.

Parameter	Throughput [packets/sec] Without Sensors	Throughput [packets/sec] With Sensors
Maximum average Throughput	6	16
Minimum average Throughput	0	0
Average	0.33	2.55
Standard deviation	0.63	2.06

Table 32. Comparison of Throughput for UL connections at the BS.

Figure 77 presents the relation between the throughput and the traffic received at the BS. In the Figure, the low rate values have more probability than the higher ones. This is because the probability of having two devices sending data in the same frame is lower than just one device sending data. Moreover, it indicates that the system is not used at full transmission capacity.

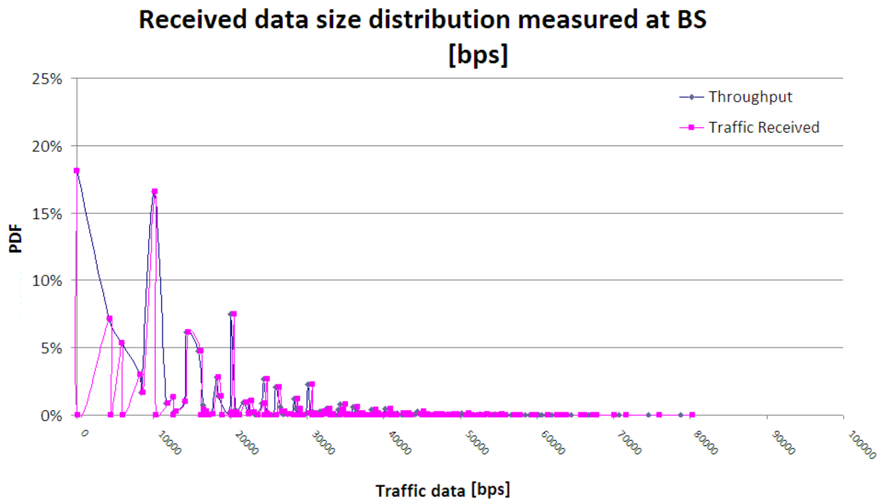

Figure 77. Throughput vs. Traffic Received PDF in bps measured in the BS for 500 users and 200 sensors

For the total load in the BS for DL connections has a similar behaviour as the UL throughput due to the fact that the sensors application generates symmetric load. The value of the load without sensor application is very low due the fact that in this case, only DMS application sends packets in the DL connection.

Parameter	Load [packets/sec] Without Sensors	Load [packets/sec] With Sensors
Maximum average Load	6	16
Minimum average Load	0	0
Average	0.13	2.27
Standard deviation	0.64	2.11

Table 33. Load components for DL connections in BS.

In the DL connections the PDF shows clearly the packetized behaviour due the similar DL packet sizes of the applications. Figure 78 shows the traffic sent and the load for the DL connections. The definition of load in the simulation model is the traffic that arrives to the MAC layer, instead, the traffic sent is the traffic that exits the physical layer and includes all the overheads from physical an MAC layer.

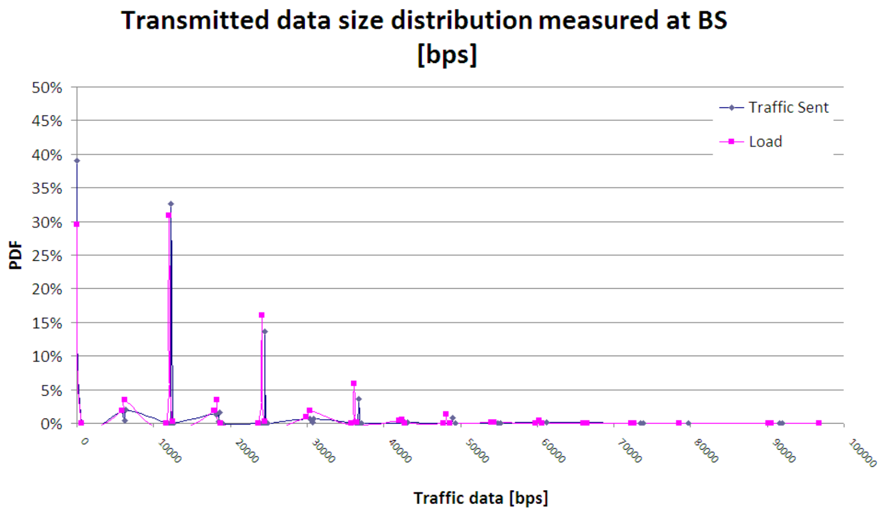

Figure 78. Load vs. Traffic Sent PDF in bps measured in the BS for 500 users and 200 sensors.

In Table 34, the results for the UL throughput and the DL load in bps are presented. The Table shows the relation of all the traffic transmitted by the devices (load) and all the traffic received at the BS (throughput). The load value is higher that the throughput

Parameter	Throughput [bps]	Load [bps]
Maximum average Throughput	78 784	96 784
Minimum average Throughput	0	0
Average	13 465	13 673
Standard deviation	10 906	12 692

Table 34. Traffic results for Sensor application in the BS.

Packet delay for mixed traffic

In this section we analyse the packet delay for different traffic scenarios. The sensors are running an application with rtPS service class configured. This service class assures the bandwidth and possess a higher priority over the nrtPS connections used for metering applications. The higher level of priority is achieved by the usage of different service classes that are being served by the MDRR scheduler which is designed to provide better performance and delay assurance to rtPS connections as is described in 3.2.4. Table 35 presents the results of the delay values for the UL connections in the described scenario with multiple applications. For the smart meter, the maximum delay is below the IPT which are 500s, 120s and 100ms for metering, demand and sensor applications respectively. Notice that the QoS requirements of sensor are fulfilled with maximum values under 110msecs and an average response time of 43msecs.

Figure 79 compares the results of two simulation scenario one including the sensor traffic and one without it. In this Figure, the average delay for metering application, that uses nrtPS service class, increases from 268.0sec to 289.6sec when two classes of traffic is used. For the DMS application the rtPS service class is used which maintains the same level for both scenarios. This is achieved by using the priority mechanism of the MDRR scheduler. In the case of the delay for sensor application, results were obtained for one scenario only.

Parameter	UL Metering Delay [sec]	UL DMS Delay [sec]	UL Sensor Delay [sec]
Maximum average delay [sec]	487.85	119.96	0.109
Minimum average delay [sec]	1.67	3.03	0.009
Average [sec]	289.56	95.7	0.043
Standard deviation	137.41	36.19	0.020

Table 35. UL delay components for diverse applications.

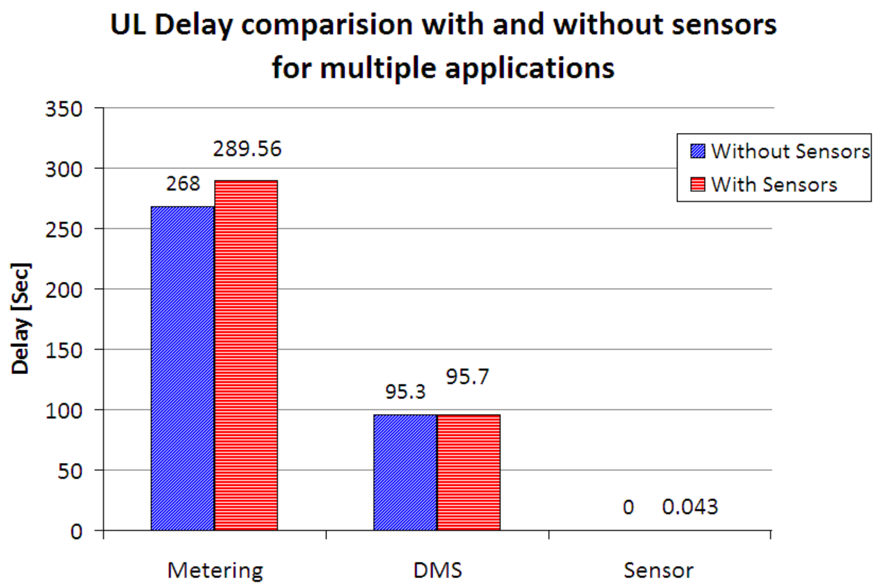

Figure 79. Delay comparison for UL connections

For the DL connections, the values are very close to the frame size time which is 5 msec. Table 36 presents the results for these applications and their connections. For the Sensor application the DL delay is lower. These values could be achieved for DL connections because as described in chapter 3, the DL subframe contains the DL-MAP and the DL data burst in the same subframe which is 2.32msec in this work, hence this is the minimum delay time for DL connections.

The DL delay compared for both scenarios as shown in Figure 80. For combined traffic the delay values for the metering application increase nearly by 7.3%, while the DMS only increases by 0.4%. On the contrary to the UL connections, the combined averaged delay value increases as well as the other connections, by nearly 1.3%. These small values are achieved and are independent of the IPT because in the DL connection no polling is used. Hence the delay is just compounded by the scheduling delay and the transmission delay.

Parameter	DL Metering Delay [msec]	DL DMS Delay [msec]	DL Sensor Delay [msec]
Maximum average delay [sec]	6.58	6.78	7.47
Minimum average delay [sec]	6.18	6.38	4.91
Average [sec]	6.28	6.50	5.26
Standard deviation	0.13	0.15	0.18

Table 36. DL delay components for diverse applications

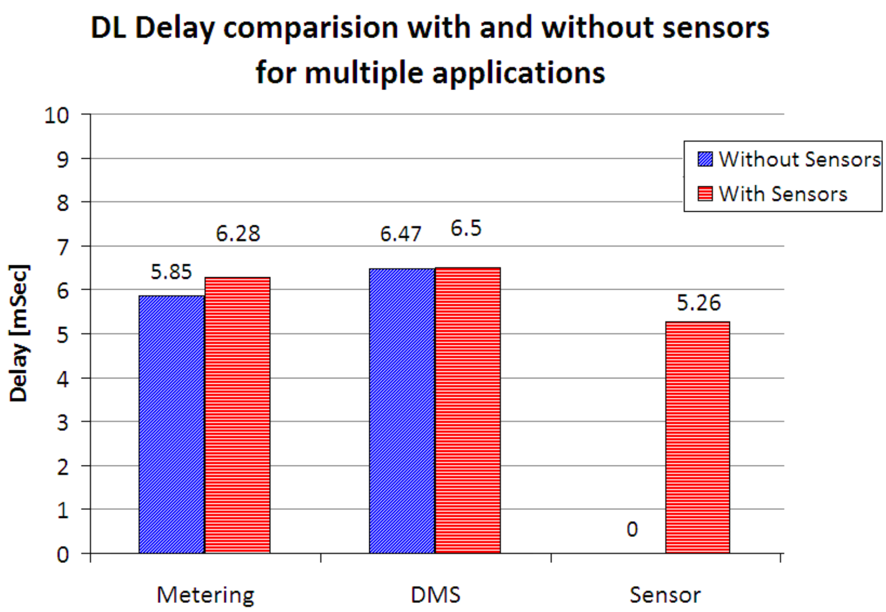

Figure 80. Delay comparison for DL connections

5.5. *CHAPTER SUMMARY*

This chapter introduced the performance of smart grid communication network for multiple applications. First, it explored the three specific applications to be used namely metering, demand meter system (DMS) and emergency sensor. These are configured using the nrtPS service class for the metering and the rtPS service class for the other two applications. Also, the smart meter devices have been configured for the conventional the metering and the DMS applications; while the emergency sensor devices have only been used for sensor applications. Secondly, the chapter describes the simulation model using OPNET modeller including the application traffic model for the three smart grid applications the WiMAX configuration scenario for the diverse devices.

The chapter continues describing the performance results for the metering and DMS applications, describing the admission control process and it results, the delay results for each connection and continues with the traffic analysis which includes the throughput and loads for the different applications. It finalises the section with the results of packets losses measurements. The next section described the introduction of the sensors in the simulation. With 200 additional sensor devices in the network its performance was analysed for multiple applications. The traffic load and delay results were presented and they showed that the system could maintain the QoS parameters for multiple smart grid applications.

CHAPTER 6.

CONCLUSIONS AND FUTURE WORK

6.1. *THESIS SUMMARY*

This chapter summarises the research work presented in this thesis and also propose some future work in the field of research.

In chapter 2 of the thesis, the thesis described a smart grid as an initiative in the electricity distribution system able to provide fast response to load changes through the implementation of a communication network that could support diverse QoS traffic and applications. The thesis reviewed NIST and IEEE P2030 proposals related to the development of a smart grid communication network. This work described seven domains in the smart grid networks and provided an explanation of those domains and their communication needs. The document focused on the wireless communication networks in order to provide adequate communication channels in-between the transmission and distribution domains, in particular the WiMAX networks. Next the thesis presented explains the application requirements for the smart grid and we used three application models to prove our network design.

After defining the basis smart grid communication requirements and a network model, chapter 3 of the thesis focused on the WiMAX network description starting with the physical layer characteristics. Inside the physical layer, the network entry procedures and their relationship with the transmitted, received power and the power control mechanisms are explored. The thesis provided some initial simulation results using the power control mechanisms of the WiMAX network. The initial simulation finding shows that the most appropriate power control mechanism is the Open-loop power control. Following the investigation of the power control algorithm the thesis concentrated on the OFDMA frame structure and its design used in WiMAX and through some analysis, we determined that the maximum cell size for the proposed configuration is 15.9Km. After the frame structure discussion the thesis examined the WiMAX MAC services, such as service class, scheduling type and their components such as maximum sustainable traffic rate and minimum reserved traffic rate. Then chapter 3 described the service flows and the bandwidth request techniques. Continued with the definition of the unicast polling technique and provided deeper information about the interpolling time and the relation with the delay which is further explored in simulations. Next, the thesis introduced the efficient scheduling algorithms for small burst packets based in the modified deficit round robin one. Simulation results presented showed that the new scheduler is able to outperform other schedulers defined for smart grid applications when small burst traffic is used. Chapter 3 finalised the description of WiMAX network with the resource allocation procedures and we concluded that the partial usable of subchannels is the adequate technique to reduce the allocation wastage.

In the second part of the document, a WiMAX network architecture is proposed to support the smart meter application. Chapter 4 started by defining the smart meter location distribution model and the corresponding OPNET simulation model using the WiMAX network configuration and its parameters, simple application model and traffic characteristics. First, the network performance is analysed using the free space and Erceg propagation models as described in the chapter. The simulation results showed that cell size could be as small as 2.2Km for an urban model and 3.5Km for a suburban model, but the usage of power control mechanisms increases the cell size to 4.5Km. Moreover, for different smart meter distributions it shows that the random distribution offers better SNR. Later, the thesis depicted the relation between the IPT and the end-to-end delay for FTP and UDP based traffic. Results showed that UDP datagram delay values are smaller than the FTP application traffic which uses the TCP protocol. In addition we found that for smaller IPT values the amount of unused polls is higher. From the simulation model the number admitted users are measured where the results showed that the random distribution has better admission success probability than circular and uniform distributions. In addition, the simulation results also showed that the ITP affects average queue size which is proportionally related whereas the throughput is inversely related to the IPT..

In chapter 5 models for multiple applications having different traffic requirements were introduced. The chapter described the applications, and the WiMAX network simulation model to support multiple applications. Also it defined the admitted parameters for all of the devices and the implications in the admitted capacity at the base station. Results showed that a 2Km cell could admit 100% of the connections in a random circular device distribution. Later the chapter 5 studied that the connection delay per application is different and is related to the IPT configured for each connection. Afterwards, the emergency sensor application is introduced and its performance of two diverse types of devices with different application configuration parameters is analysed. It was also proved that the new scheduler is capable of maintaining the delay constant for rtPS connections, maintaining the high priority over the nrtPS connections. Moreover the results showed that the inclusion of ARQ technique avoids all packet losses in nrtPS connections.

6.2. FUTURE WORK

The design of Smart Grid communication systems is an emerging research area. This work is an introduction to the WiMAX communication network to provide communication channels for the smart grid applications.

In first place, one of the important aspects that were not cover in this document due to time limitation is the capacity maximisation technique of the network. With such small traffic per device, the theoretical number of connections that could be supported by one single BS would be in the order of thousands. The MAC capabilities and unicast polling mechanisms impose a barrier for the growth of massive number of connections. Hence new MAC connections and bandwidth request handling methods should be explored to overcome the MAC limitations and capacity loss by unicast polling.

Second, rural scenarios are characterized for a low device density. In this case, the area cover by a single BS will provide service to a small number of devices. Hence, the study of coverage extension is a new challenge for these communication networks. As a proposal, the usage of Relay WiMAX, as a solution to the smart grid communications could be implemented. Relay WiMAX is a recent capability for WiMAX network that provides the usage of access points WiMAX enabled which provide BS capabilities but very economical compared with the cost of a BS. In addition, cooperative networking using mesh networks could be used to expand coverage range by maintaining the QoS requirements.

Finally, taking advantage of the customer access network, studies in VPN connected to the service and operator network should be explored to increase the reliability and the capacity of the smart grid communication architecture at lower costs.

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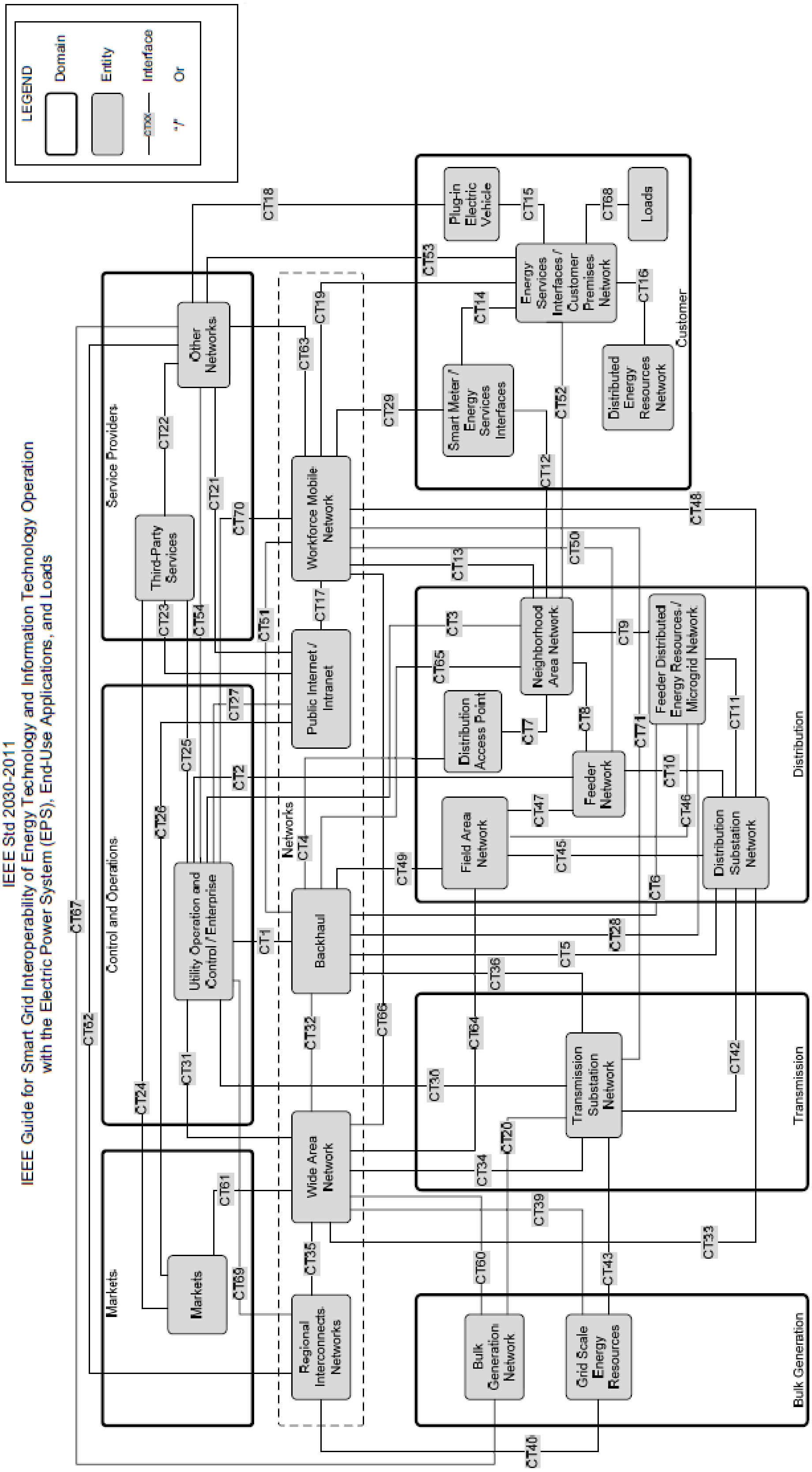
ANNEX A

The Annex A presents the communication section of the IEEE P2030 standard. In this annex, the seven-domain model is presented with the entities and actors that provide communication support to the smart grid networks. These 23 entities are briefly described and some comments of the task force are included for future designers. Moreover, there is a description of the 71 communication interfaces among all the entities and a brief comment about the link consideration. The following graphs and Tables presented in this annex are part of the "*IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*" standard [4], in specific from the communication interoperability section.



Annex A Figure 1. Communication technology interoperability framework from the IEEE P2030 standard.

IEEE Std 2030-2011
IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads

Table 7-1—CT-IAP entities and descriptions

Entity	Description	Comments
Backhaul	The backhaul network connects the utility control/operations, including the AMI enterprise, with the wide area network (WAN), distribution substation networks, DERs, field area network (FAN), NAN distribution access points, etc.	The backhaul network can be owned by the utility and/or managed by a public telecommunications/cable service provider. It can be wireline (dial-up, T1, twisted pair, cable, fiber optic, etc.) or wireless (3G, WiMAX™, point-to-point, pagers, radios, etc.). A typical NAN/FAN usually has more than one backhaul/access point connected to the WAN. In some cases, the backhaul is not used when centralized utility operation manages the networks directly from their back office.
Bulk Generation Network	A network used within a bulk generation facility that connects to various networks.	These networks facilitate large-scale power generation connected at the grid generation-transmission side.
Distributed Energy Resources Network	Customer generation and storage systems are connected to CPN (HAN, BAN, IAN) through energy services interfaces (ESIs) and/or electric submeters, using either wireline and/or wireless networks.	Customer energy resources can be used to balance the utility's electricity load. Energy can be supplied by customers back to the grid. It is expected that customers will have a balanced portfolio of energy generated locally (in their premises) and supplied by the utility, with an energy supply ratio that can be dynamically changed during outages or peak energy periods.
Distribution Access Point	Distribution access point (DAP) is the device that collects and aggregates data coming from/to end devices/users through the NANs. It also interfaces with the backhaul.	DAPs can be considered part of the NAN. These devices have routing and traffic handling capabilities to prioritize multiple data flows. More than one DAP might be used to collect data (e.g., smart meter reading). They interface with the backhaul transport network.
Distribution Substation Network	Distribution substation network interconnects devices within a distribution substation (e.g., comprised of LANs that contain SCADA, IEDs, remote terminal units [RTUs], PMUs, and other field devices that needs to be controlled and monitored via the backhaul network). IEC 61850 [B5] and IEEE Std 1815™ (DNP3) [B13] are the protocols of choice for this network.	The distribution substation is controlled and supervised remotely via the utility's backhaul and interconnects to DERs/microgrids, NAN/FAN networks, and connects to the feeder/distribution electricity grid.
Energy Services Interfaces/ Customer Premises Network	ESIs are a special class of device. It is network-centric and can also be thought of as logical gateways. CPN represents HAN, BAN, or IAN.	It permits applications such as remote load control, monitoring and control of DER, in-home display of customer usage, reading of non-energy meters, and integration with building management systems. It also provides auditing/logging functions that record transactions to and from HAN devices.

Table 7-1—CT-IAP entities and descriptions *(continued)*

Entity	Description	Comments
Feeder Distributed Energy Resources/ Microgrid Network	Feeder DER network is comprised of all renewable and non-renewable sources (e.g., wind, solar, diesel), not part of the centralized energy generation. These energy resources could be interconnected through a LAN. Access communications gateways can then connect these DERs and storage LAN networks to the main grid, creating grid-connected energy sources. Utility scale storage energy systems connected at the distribution substation are also considered.	Feeder DERs/microgrid networks are used for low-medium (kilowatt) distributed energy generation and storage energy resources that are connected to substations and/or feeder networks. In most cases, the generation sources are located in campuses, industrial parks, etc. (e.g., microgrids).
Feeder Network	Feeder or distribution network is the communications network overlaid on the electrical grid. It comprises wireline or wireless communications technologies.	In some cases, the feeder communications network consists of wireless or cabled connections to exchange information with field devices (reclosers, switches, cap banks, etc.). It also controls volt/var optimization, power quality, and other advanced DA applications.
Field Area Network	FANs connect the distribution substations, the distributed/ feeder (field devices), and DERs/microgrids, including the utility scale electric storage, to the utility control and operation center.	The FAN connects critical utility assets and transport operations control data.
Grid Scale Energy Resources	These are large-scale energy resources (wind, solar, storage, etc.) that are connected to the transmission/generation side of the grid and can handle several hundreds of megawatts.	Utility-scale renewables are remotely located from the energy consumption centers and require new transmission lines and communications links to be built (if not available) to control these remote assets.
Loads	Loads can communicate through local networks using a variety of technologies. These networks provide functionality to exchange information for load management.	Loads can be appliances, pump controls, HVAC, PEVs, etc. Loads can be located in industrial facilities, commercial facilities, or homes.
Markets	Markets will provide energy information services with variable energy/electricity pricing information to allow dynamic exchange of energy services to/from consumers and utilities, establishing a buyer's or seller's energy market.	Markets will communicate to third-party providers and utilities through secure public Internet connections.
Neighborhood Area Network	NANs connect smart meters, distributed/feeder (field devices), DERs/microgrids, including the utility scale electric storage, to the utility control and operation center.	The NAN supports several applications and can either use wireless or cabled (power line, fiber, twisted pair, etc.) networks.
Other Networks	Optical or electronic wireline or wireless networks will play a role in AMI/NAN networks, DA, substation automation, backhaul, workforce automation, and also on PEV mobile/roaming schemes. Wireless networks can use a variety of radio technologies such as paging, point-to-point and point-to-multipoint networks, multiple-address radio networks, or satellite links.	In some circumstance, inter-grid communications must be provided through the wireless networks so drivers can access information (such as location of the nearest charging station, pricing schemes, etc.) on the road through their mobile phones or on-board EMSs.

Table 7-1—CT-IAP entities and descriptions *(continued)*

Entity	Description	Comments
Plug-in Electric Vehicle	PEVs or plug-in hybrid electric vehicles are considered both "load" and "source/storage" to provide power back to the grid to balance energy supply.	PEVs are considered a load when the vehicle is stationary and energy is drawn from the grid to charge their batteries. Proper dimensioning of the utilities distribution networks with PEV adoption forecast is important to avoid unexpected peaks of energy consumption when charging PEVs. The mobile/roaming case is also considered when PEVs need to access charging, billing, and positioning information.
Public Internet/ Intranet	Public Internet may be the primary communication path between utility enterprise data centers, market, and third-party energy providers.	Energy management services may be offered to customers by third-parties, utilities, or Internet service providers (ISPs) via the Internet. A certain level of protocol security must be provided to all levels of energy management services through the Internet. ISPs provide Internet access to the CPN.
Regional Interconnects Networks	Regional interconnects connect the utilities communications networks to other utilities networks. This could be done through their own proprietary networks or through public carrier backbones.	These are core network interconnections using synchronous optical network/synchronous digital hierarchy and/or dense wavelength-division multiplexing and internet protocol fiber rings. In some new constructed utility-owned networks, fiber optical power ground wire cables is the technology medium of choice.
Smart Meter/ Energy Services Interfaces	The smart meter/ESIs entity performs a variety of intelligent metering tasks. The smart meter is typically part of the AMI. The ESI function (optionally located within the smart meter) acts as the communication gateway between the NAN and CPN, which includes the HBES, loads, PEVs, and customer DER network.	The NAN, CPN, HBES, and DER networks may each be associated with different physical transmission mediums, and consequently, in order to maximize interoperability, standards involving communication with the smart meter should not be restrictive to a particular transmission medium (e.g., only RF or only power line). Standards allow a variety of physical transmission mediums (e.g., twisted pair, power line, and RF) and, in general, any standardized protocol and interface.
Third-Party Services	Third-party value-added energy services can offer managed energy services (home and building), demand response, and other emerging services to end consumers and utilities.	Third-party energy management services require data access from devices connected to the CPN. Communications paths may be via a utility network infrastructure or the public Internet. Third-party services may include monitoring of specific customer devices, support for control, scheduling, or shaving of loads to accommodate customer energy usage policies.
Transmission Substation Network	Transmission substation network interconnects devices within a transmission substation (e.g., the substation may contain Ethernet networks that connect SCADA, IEDs, RTUs, PMUs, and other field devices that need to be controlled and monitored via the backhaul network).	The transmission substation is controlled and supervised remotely via the utility's WAN/backhaul network.

Table 7-1—CT-IAP entities and descriptions *(continued)*

Entity	Description	Comments
Utility Operation and Control/ Enterprise	Utility control and/or SCADA operation (substation automation, distribution substation, etc.) and AMI enterprise center control, supervise, manage, and monitor all utilities' assets, processes, and customers.	The utility control/operation network, also called back-office, and AMI enterprise control, monitor, supervise, and manage processes, data flows from meters, SCADA, substations, and all critical and non-critical information flow. The control/operations center can be a single integrated entity that manages transmission and distribution and customers or one control entity (DMS/EMS and others) for each transmission and distribution grid segment, depending on the type of utility or energy service provided model.
Wide Area Network	A communication network entity that connects other networks including bulk generation, substation, backhaul, and last mile networks to/from utility control/operations/enterprise center.	A WAN covers a large geographic area communications requirements and may utilize wireless or cabled (e.g., fiber optic) communications technologies.
Workforce Mobile Network	Workforce mobile network (WAN) is used by the utility's workforce to provide dispatch, maintenance, and normal day-to-day operations.	It can use either AMI-NAN/FAN utility-owned networks or public 3G/WiMAX services provided by wireless service providers (WSPs). The substation hot spots can be used in conjunction with this network to download/access broadband data to/from the utility control center.
NOTE—WiMAX is a trademark of the WiMAX Forum. This information is given for the convenience of users of this standard and does not constitute an endorsement by the IEEE of these products. Equivalent products may be used if they can be shown to lead to the same results.		

Table 7-2—CT-IAP interfaces

Interface	Entity 1	Entity 2	Comments
CT1	Utility Operation and Control/ Enterprise	Backhaul	Either owned by the utility or managed by a telecommunications service provider through a secure connection.
CT2	Utility Operation and Control/ Enterprise	Feeder Network	This is a centrally based network where the communications to/from the utility center does not require backhaul. It is usually owned by the utilities.
CT3	Utility Operation and Control/ Enterprise	Neighborhood Area Network	This is a communications network that connects directly to the utility center. It is usually owned by the utility.
CT4	Backhaul	Distribution Access Point	The access point is the demarcation point between the NAN/FAN-AMI and the backhaul. It can also be called collector, aggregation point, cell relay, or gateway. It usually contains dual-radio communications interfaces—one facing the backhaul (e.g., 3G or WiMAX) and one facing the last mile network (e.g., RF mesh radio). It can be a mesh RF collector, a point-to-multipoint RF radio (e.g., 3G or WiMAX), or a wireline access node (e.g., BPL/PLC).
CT5	Backhaul	Distribution Substation Network	This is the connectivity between the distribution substation networks and the utility control/operation/SCADA network via the backhaul WAN network. Typical connections are usually a secure wireline (e.g., T1 line, dial-up) or wireless point-to-point microwave radio links. In some cases, the substation networks are connected together.
CT6	Backhaul	Feeder Distributed Energy Resources/ Microgrid Network	It provides the DER communication integration to the grid (connecting utility scale solar/wind and other non-renewable DERs)/microgrids to/from the backhaul/WAN network to/from the utility control operations and/or enterprise center. It also interconnects utility scale energy storage networks and systems.
CT7	Distribution Access Point	Neighborhood Area Network	The access point can also be considered as an element of the NAN, or just an interface between the NAN and the backhaul.
CT8	Feeder Network	Neighborhood Area Network	It interconnects the NAN to the distribution network, also called the feeder network, which contains intelligent field devices that go on poles, such as cap banks, reclosers, switches, smart transformers, field sensors, etc. Some elements of the distribution network are also found within the distribution substations.
CT9	Feeder Distributed Energy Resources/ Microgrid Network	Neighborhood Area Network	This is an alternative to CT6 where the connectivity to the utility scale DERs, located within the utility's distribution network, is done through the NAN/AMI network.
CT10	Distribution Substation Network	Feeder Network	It provides the connectivity between the distribution substation networks and the distribution network field devices. It can use radio or wireline (BPL/PLC) hubs (e.g., towers) within the distribution substation to connect to distribution network field devices.

Table 7-2—CT-IAP interfaces *(continued)*

Interface	Entity 1	Entity 2	Comments
CT11	Distribution Substation Network	Feeder Distributed Energy Resources/ Microgrid Network	It interconnects the utility scale DERs/microgrids to/from the utility control/operations/enterprise center through the distribution substations.
CT12	Smart Meter/Energy Services Interfaces	Neighborhood Area Network	Connects the smart meters through wireline or wireless NAN. Smart meters could be residential (including building/business) or industrial-grade.
CT13	Workforce Mobile Network	Neighborhood Area Network	The NAN can be used as a conduit between a workforce mobile network and the utility control center. The NAN can provide redundancy in cases where a primary workforce mobile network is out of range or unavailable. Access to the NAN by workforce mobile worker devices will be used to diagnose and repair problems in the NAN and with NAN devices.
CT14	Smart Meter/ Energy Services Interfaces	Energy Services Interfaces/ Customer Premises Network	In general, the ESI is the gateway between the smart meter and the end-use devices and loads. By definition, the physical communication links between the ESI and the loads are part of the CPN (see CT68, CT15, CT16). In many cases, the ESI is physically located within the smart meter (i.e., the meter and ESI are one in the same). However, this may not always be the case. CT14 describes the properties of the link in this latter case.
CT15	Energy Services Interfaces/ Customer Premises Network	Plug-in Electric Vehicle	This provides connectivity between the ESI (which may be a stand-alone device or could be integrated into the smart meter itself) and the electric vehicle service equipment (EVSE) and/or electric vehicle (EV) in order to support functions such as charging, billing, load shedding and storage, and positioning information. It is assumed that the EVSE (also known as the charging station) is a part of the CPN, and likely connected to the EMS or similar system on the customer premises. Here (CT15), we only consider the case where the EV is physically located at a premise with an EVSE and is capable of communication with the ESI. Note that the ESI/CPN may communicate with the vehicle not only when it is located on the customer premises (e.g., parked or plugged into an on-site charging station) but also when the vehicle is mobile (e.g., to support services like mobile charging, billing, diagnostics, and positioning information). There are other links/paths in the reference architecture that deal with the case of communicating with the vehicle while it is mobile (e.g., CT53–CT18).
CT16	Energy Services Interfaces/ Customer Premises Network	Distributed Energy Resources Network	This provides connectivity between the ESI (which may be a stand-alone device or could be integrated into the smart meter itself) and the DER network via the CPN to the DER in order to support functions such as charging, billing, load shedding, generation, and storage. Here (CT16), we only consider the case where the DER is capable of communication with the ESI.
CT17	Workforce Mobile Network	Public Internet/ Intranet	The public Internet may provide access for workforce mobile networks to third-party information such as maps, news, or weather.

Table 7-2—CT-IAP interfaces *(continued)*

Interface	Entity 1	Entity 2	Comments
CT18	Other Networks	Plug-in Electric Vehicle	This connectivity is used as a direct communications path to the EV and can be used when the vehicle is stationary, mobile, and/or roaming. This can replace and/or supplant CT15 as another means to reach the head-end software. This connectivity can provide complete communications to the EV to support functions such as charging, billing, uploading rate/tariffs, load shedding and storage, and positioning using on-board energy information systems. For those EVs employing on-board smart chargers, complete EV charging control and vehicle information can be accessed. This connectivity is typically described as telematics and is widely utilized by several vehicle equipment manufacturers OEMs. The connection is established typically by wireless connectivity to the telematics provider head-end system wherein specific applications can provide connectivity to utilities and/or supplier head-end system. The WSP could use 3G/GSM, 4G/LTE™/WiMAX, or satellite transponder technology inside the vehicle as the means to communicate.
CT19	Workforce Mobile Network	Energy Services Interfaces/ Customer Premises Network	Workforce mobile networks can access the ESI via the HAN, IAN, or BAN to retrieve ESI logging data to be able to perform maintenance and repair work.
CT20	Bulk Generation	Transmission Substation Network	—
CT21	Public Internet/ Intranet	Other Networks	It connects the ISPs to the other networks (e.g., WSPs).
CT22	Other Networks	Third-Party Services	It connects other networks (e.g., WSPs) to the third-party network (value-added service provider).
CT23	Public Internet/ Intranet	Third-Party Services	It connects the third-party network (value-added service provider) to the public Internet.
CT24	Markets	Third-Party Services	It connects the third-party network (value-added service provider) to the markets for energy/electricity price signaling information.
CT25	Utility Operation and Control/ Enterprise	Third-Party Services	It connects the third-party network (value-added service provider) to the utility control/operation/enterprise center. It is usually part of an open ADE data exchange arrangement where the third-party network accesses customer metering/billing and energy consumption information through the utility's data repositories. Other schemes involve third-party demand response and other services.
CT26	Markets	Public Internet/ Intranet	It connects the market with utilities and other third-party providers through the public Internet.
CT27	Utility Operation and Control/ Enterprise	Public Internet/ Intranet	It connects the utility control/operation/enterprise center to the third-party service provider, ISP, WSP, and other providers through the public Internet.
CT28	Backhaul	Feeder Distributed Energy Resources/ Microgrid Network	It connects the backhaul to/from field devices (reclosers, cap banks, switches, etc.).

Table 7-2—CT-IAP interfaces *(continued)*

Interface	Entity 1	Entity 2	Comments
CT29	Workforce Mobile Network	Smart Meter/Energy Services Interfaces	Workforce mobile networks can access smart meters and the ESI to retrieve ESI logging data to be able to perform maintenance and repair work.
CT30	Transmission Substation Network	Utility Operation and Control/ Enterprise	This provides direct connectivity between devices on the transmission substation network and the utility control/operations/enterprise LAN. This interface consists of legacy services, (PSTN, serial, satellite) (i.e., not WAN-based).
CT31	Wide Area Network	Utility Operation and Control/ Enterprise	This provides data flow between the utility's control/operations center and the WAN. This interface maintains isolation between the WAN services (e.g., regional interconnections, WAN last mile (backhaul/ WAN), and the transmission substation networks).
CT32	Wide Area Network	Backhaul	This is the connection between the WAN and the WAN last mile (backhaul/WAN). The WAN last mile serves as the extension of the WAN to connect primarily the distribution networks.
CT33	Wide Area Network	Distribution Substation Network	This securely interconnects devices within a utility's distribution substation network and the WAN of the utility. This connection is common to utilities with combined transmission and distribution substations.
CT34	Transmission Substation Network	Wide Area Network	This provides data flow between the transmission substation network of the utility and the WAN. This interface normally carries all IT and OT traffic including EMS and RAS traffic from the substation to the control center.
CT35	Regional Interconnects Networks	Wide Area Network	This provides data flow between other utilities and a utility's WAN to facilitate regional interconnections. The interface is primarily used for monitoring RTUs of another utility to enable RAS applications, as well as PMU data for inter-utility wide-area situational awareness.
CT36	Transmission Substation Network	Backhaul	This provides data flow between the transmission substation network of the utility and the WAN last mile. This interface maybe used as an alternative for direct WAN (CT34) connectivity or where there is inadequate capacity on legacy services (CT30).
CT39	Grid Scale Energy Resources	Wide Area Network	This connects grid scale energy resources in the generation domain of a utility including hydro, geothermal, wind, and photovoltaic plants with the WAN of the utility. The connectivity can be provided via wireline (fiber, dial-up, xDSL, T1) or wireless (WiMAX, UMTS™, GPRS, 3G, etc.).
CT40	Regional Interconnects Networks	Grid Scale Energy Resources	This provides data flow between the grid scale energy resources in the generation domain of a utility and other utilities' communication networks. The connectivity can be provided via wireline (fiber, dial-up, xDSL, T1) or wireless (WiMAX, UMTS, GPRS, 3G, etc.).
CT41	Workforce Mobile Network	Feeder Distributed Energy Resources/ MicroGrid Network	This provides data flow between DERs and the workforce mobile network. It may be wireless to support mobility of the workforce.

Table 7-2—CT-IAP interfaces *(continued)*

Interface	Entity 1	Entity 2	Comments
CT42	Transmission Substation Network	Distribution Substation Network	This interconnects directly devices within a utility's transmission substation network to the devices within the utility's distribution substation including SCADA, IEDs, RTUs, PMUs, and other field devices. Data flow between these two entities is latency critical.
CT43	Grid Scale Energy Resources	Transmission Substation Network	This connects grid scale energy resources in the generation domain of a utility including hydro, geothermal, wind, and photovoltaic plants with devices in the transmission substation network of the utility.
CT45	Field Area Network	Distribution Substation Network	This provides data flow between a FAN of a utility and the distribution substation network of the utility. Thus, information can be carried between SCADA, PMUs, RTUs, and IEDs in the distribution substation network and the utility's control/operations center over the FAN.
CT46	Field Area Network	Feeder Distributed Energy Resources/ Microgrid Network	This provides data flow between a FAN of a utility and the DERs/microgrid network. Thus, information can be carried between SCADA, RTUs, and IEDs in the distribution substation network and the utility's control/operations center over the FAN.
CT47	Field Area Network	Feeder Network	—
CT48	Workforce Mobile Network	Distribution Substation Network	Wireless hotspots or wired connections into the distribution substation network will be used to provide additional information to the workforce mobile network devices for diagnosis and repair work.
CT49	Backhaul	Field Area Network	—
CT50	Workforce Mobile Network	Feeder Network	An interface between feeder networks to workforce mobile network devices will allow for faster and more accurate diagnosis, isolation, and repair of feeder network problems.
CT51	Workforce Mobile Network	Backhaul	In addition to AMI communications, a backhaul/WAN can provide communications links to mobile workers.
CT52	Energy Services Interfaces/ Customer Premises Network	Neighborhood Area Network	The ESI is the interface between NAN and HAN. Through ESI, NAN and HAN can communicate to each other even though they might use different communication technology.
CT53	Other Networks	Energy Services Interfaces/ Customer Premises Network	This provides connectivity between the ESI (which may be a stand-alone device or could be integrated into the smart meter itself) and WANs (e.g., GSM, EDGE, UMTS, GPRS, LTE, WiMAX, WCDMA, CDMA, microwave, satellite, etc.) in order to enable wide-area connectivity into the CPN (typically the ESI/EMS is the entry point) from a variety of other end-points (e.g., the utility distribution control/operations center, mobile PEV, and many others). This link could be associated with the following applications: AMI/NAN, DA, workforce automation, outage management, PEV (mobile charging, billing, localization, etc.), DER management/control, and various other applications.
CT54	Utility Operation and Control/ Enterprise	Other Networks	—

Table 7-2—CT-IAP interfaces *(continued)*

Interface	Entity 1	Entity 2	Comments
CT60	Bulk Generation	Wide Area Network	—
CT61	Markets	Wide Area Network	—
CT62	Regional Interconnects Networks	Other Networks	—
CT63	Workforce Mobile Network	Other Networks	Other networks not called out specifically can also be used for workforce mobile networks. These other networks can be either the primary network or a redundant backup network for mobile networks.
CT64	Wide Area Network	Field Area Network	—
CT65	Backhaul	Neighborhood Area Network	The meter information goes through NAN and is collected by DAP and then publishes to backhaul through WAN. The information from backhaul goes through WAN to DAP and then distributes to meters through NAN.
CT66	Workforce Mobile Network	Wide Area Network	A WAN is one of the alternative networks that can carry data to/from workforce mobile network access points and base stations. The WAN itself can be used as a network for dispatch communications.
CT67	Bulk Generation	Other Networks	—
CT68	Energy Services Interfaces/ Customer Premises Network	Loads	This provides connectivity between the ESI (which could be physically located on the smart meter itself) and the various loads (possibly thousands) within the customer premises in order to support functions such as energy management, lighting control, solar protection, HVAC control, security/access control, control of audio/video services. The physical links associated with CT68 are generally considered a part of the HAN/BAN/IAN. Also, note that some of the key customer premises systems and controls such as HBES, BACS (building automation and control system), and EMS could physically reside in the ESI, or in a separate device connected directly to the ESI via CT68.
CT69	Regional Interconnects Networks	Utility Operation and Control/ Enterprise	—
CT70	Workforce Mobile Network	Utility Operation and Control/ Enterprise	Dispatch, maintenance, and restoration work will be managed over the workforce mobile network between the utility control center and the mobile workers. A variety of communications solutions ranging from public carrier networks to dedicated private voice and data networks are used.
CT71	Workforce Mobile Network	Transmission Substation Network	Wireless hotspots or wired connections into the transmission substation network will be used to provide additional information to the workforce mobile network devices for diagnosis and repair work.

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