

FIBER-WIRELESS SENSOR BROADBAND ACCESS NETWORK INTEGRATION (FI-WSN) FOR THE SMART GRID

by

Nima Zaker

Thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
For the MAsc. degree in
Electrical and Computer Engineering

School of Electrical Engineering and Computer Science
Faculty of Engineering
University of Ottawa

© Nima Zaker, Ottawa, Canada, 2013

Abstract

During the last century, the significant increase in electricity demand, and its consequences, has appeared as a serious concern for the utility companies, but no essential change has been applied to the conventional power grid infrastructure till now. Recently, researchers have identified efficient control and power distribution mechanisms as the immediate challenges for conventional power grids. Hence, the next step for conventional power grid toward Smart Grid is to provide energy efficiency management along with higher reliability via smart services, in which the application of Information and Communication Technology (ICT) is inevitable. ICT introduces powerful tools to comply with the smart grid requirements. Among various ICT properties, the telecommunication network plays a key role for providing a secure infrastructure. The two-way digital communication system provides an interaction between energy suppliers and consumers for managing, controlling and optimizing energy distribution. We can also define the smart grid as a two-way flow of energy and control information, where the electricity consumers can generate energy using green energy resources. The main objective of this thesis is to select an effective communication infrastructure to support the smart grid services by considering wireless and optical communication technologies. Fiber-wireless (FiWi) networks are considered as a potential solution to provide a fast and reliable network backbone with the optical access network integration and the flexibility and mobility of the wireless network. Therefore, we adopt the integration of the wireless sensor network (WSN) to Ethernet Passive Optical Network (EPON) as a broadband access network to transmit smart meter data along with the Fiber To The Home/Building/Curb (FTTX) traffic through the shared fiber. Finally, we present and analyze the simulation results for the aforementioned infrastructure based on our adopted priority-based FTTX-WSN integration model.

Acknowledgements

I would like to offer special thanks to my thesis supervisor, Professor H. Mouftah, for his excellent professional guidance and especially for his personal support during my research work on this thesis. He challenged me to implement our ideas with my own original network simulation software and set me on a path toward my future research career.

I also thank Dr. Melike Erol Kantarci and Dr. Burak Kantarci, who were so generous with their time and ideas, often working with me on a daily basis. Discussions with them helped me to shape, direct and complete this thesis.

I would like to acknowledge the financial support of the NSERC strategic grant initiated by Dr. Martin Maier of INRS Telecommunications of Montreal.

I am thankful for the contribution of Rouzbahan Rashidi Tabrizi, whose technical advice helped me to first implement my network simulation.

Finally, I would like to thank my good friend Majed Rostamian, who encouraged me all along the way.

Dedication

I dedicate this thesis to my late father, Hadi Zaker, in fulfillment of his desire for me to further my graduate education, and to my mother, Marzieh Haji Mirza, for her steadfast support throughout my life.

I thank them both from my heart for their encouragement for me to come to Canada to pursue my graduate studies.

Table of Contents

Abstract	ii
Acknowledgements	iii
<i>Dedication</i>	iv
List of Figures	vii
List of Tables	ix
List of Algorithms	x
List of Acronyms	xi
Chapter 1 Introduction	1
1.1 Background	1
1.2 Motivation	4
1.3 Contributions	5
1.4 Thesis Outline	6
Chapter 2 Power Grid and Fiber-Wireless Technology	7
2.1 Introduction	7
2.2 The Smart Grid Roadmap and Vision	8
2.2.1 Micro-grids	10
2.2.2 G2V and V2G Paradigms	10
2.2.3 Smart Metering	10
2.3 Smart Grid Enabling Communication Technology	12
2.3.1 Wireless Technology	13
2.3.2 Fiber to the Home/Building/Curb	14
2.4 State-of-the-art in Fiber-Wireless Networks	16
2.4.1 Radio-over-Fiber Networking	18
2.4.2 Radio-and-Fiber Networking	20
2.4.3 Related Works on FiWi	23

2.5	Summary	28
Chapter 3	FiWi Network Development for the Smart Grid	29
3.1	Introduction	29
3.2	System Architecture and Requirements	30
3.2.1	WSN Message Prioritization	31
3.2.2	WSN Opportunities and Challenges.....	39
3.3	Adopted Fi-WSN Integrated Architecture	41
3.3.1	Fi-WSN Gateway Design	45
3.4	Summary	50
Chapter 4	Simulation and Performance Results	51
4.1	Introduction	51
4.2	Simulation Settings and Assumptions.....	51
4.3	Performance Results.....	56
4.4	Summary	68
Chapter 5	Conclusion and Future Work	69
5.1	Concluding Remarks	69
5.2	Future Research Work.....	71
	Bibliography	73
	Appendix A.....	79
	Result Graphs.....	79
	Appendix B	82
	Confidence Interval.....	82

List of Figures

Figure 2.1 WDM PON Architecture.....	15
Figure 3.1 Inside the Smart Home	32
Figure 3.2 Inside the Smart Farm	36
Figure 3.3 Inside the Smart Substation.....	38
Figure 3.4 Fi-WSN Broadband Access Network System Model	42
Figure 3.5 MPCP Protocol Discovery Messages.....	45
Figure 3.6 Minimalist illustration of a Fi-WSN Gateway	46
Figure 4.1 WSN Topology with 49 sensors and one SN.....	52
Figure 4.2 Technique for Next Hope Node Selection in WSN.....	53
Figure 4.3 Average End to End delay vs. Target Load.....	57
Figure 4.4 End to End Delay vs. Target Load	57
Figure 4.5 End to End Delay vs. Target Load	58
Figure 4.6 End to End Delay vs. Target Load	59
Figure 4.7 End to End Delay vs. Target Load	60
Figure 4.8 End to End Delay vs. Target Load	60
Figure 4.9 End to End Delay vs. Target Load	61
Figure 4.10 End to End Delay vs. Target Load	61
Figure 4.11End to End Delay vs. Target Load	62
Figure 4.12 End To End Delay vs. Target Load.....	63
Figure 4.13 Maximum Delay vs. Target Load.....	64
Figure 4.14 Maximum Delay vs. Target Load.....	64
Figure 4.15 Maximum Delay vs. Target Load.....	65

Figure 4.16 Packet Loss Ration vs. Target Load	66
Figure A.1 End to End Delay vs. Target Load	79
Figure A.2 End to End Delay vs. Target Load	79
Figure A.3 End to End Delay vs. Target Load	80
Figure A.4 Maximum Delay vs. Target Load.....	80
Figure A.5 Maximum Delay vs. Target Load.....	81
Figure A.6 Maximum Delay vs. Target Load.....	81
Figure B.1 Normal sampling distribution by 95% Confidence Interval	84

List of Tables

Table 2.1 FiWi Enabling Technology Comparison	21
Table B.1 The t-distribution.....	83

List of Algorithms

Algorithm 3.1 Burst Generation at a Fi-WSN Gateway	47
--	----

List of Acronyms

AP	Access Point
AMI	Advanced Measuring Infrastructure
AON	Active Optical Network
BER	Bite Error Rate
BS	Base Station
CBR	Constant Bit Rate
CI	Confidence Interval
CN	Concentrate Node
CO	Central Office
CoS	Class of Service
DCF	Dispersion Compensating Fiber
DG	Distributed Generator
DER	Distributed Energy Resource
DES	Discrete Event Simulation
DESL	Discrete Event Simulation Library
EPON	Ethernet Passive Optical Network
EV	Electric Vehicle
E2E	End to End
FiWi	Fiber wireless network
Fi-WSN	Fiber-Wireless Sensor Network

FTTX	Fiber to the X (Home/Building/Curb)
GBANT	Green Broadband Access Network Technology
GHG	Green House Gas
GPON	Gigabit Passive Optical Network
GR	Geographical Routing
GSM	Global System for Mobile
G2V	Grid to Vehicle
HAN	Home Area Network
ICT	Information and Communication Technology
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
MAX-DLY	Maximum Delay
MCN	Mobile Client Network
MPCP	Multi-Point Control Protocol
MZM	Mash-Zehnder Modulator
OADM	Optical Add-Drop Multiplex
ONU	Optical Network Unit
PDU	Protocol Data Unit
PHEV	Plug in Hybrid Electric Vehicle
PLR	Packet Loss Ratio
PON	Passive Optical Network
P2MP	Point to Multi-Point

QoS	Quality of Service
RAU	Remote Antenna Unit
RF	Radio Frequency
RN	Remote Node
RoF	Radio-over-Fiber
R&F	Radio-and-Fiber
SCM	Sub-Carrier Multiplexing
SEP	Smart Energy Profile
SMF	Single Mode Fiber
SN	Sink Node
STH	Size Threshold
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
ToU	Time of Use
UMTS	Universal Mobile Telecommunication System
V2G	Vehicle to Grid
WAP	Wireless Access Point
WDM	Wavelength Division Multiplexing
WMN	Wireless Mesh Network
WSN	Wireless Sensor Network

Chapter 1

Introduction

1.1 Background

The increasing demand in energy consumption as well as Greenhouse Gas (GHG) emissions reveal that enhancements are needed in the energy consumption efficiency in existing power grid. These enhancements would deal with the reduction of peak-time demands and exploit distributed power generation devices [12]. Based on present research and annual reports [4] [8] [12] [49], we see much more negative impacts of increasing power consumption and carbon emissions in the upcoming decades. For these reasons, both the industry and research community have been actively involved to find effective solutions towards the smart grid and energy management mechanisms, which would provide the quality and power demands needed in the field.

In fact, the lack of monitoring and pervasive communication tools has caused poor quality and major blackouts in old-aged power grids [4]. This is due to the imbalance between increasing demands and the decrease of conventional energy resources (e.g. fossil fuels, nuclear fission, etc.). Therefore, a smart infrastructure system with capabilities of intelligent admission control,

using recent advancements of information and communication technologies, can play a key role in the new power grid infrastructure [1].

The current trend of smart grid system is to use intelligent devices with communication interfaces that provide an interface between the utility companies and the consumers for power consumption information. This information can be used to shift power demands in order to minimize the peak load. In order to implement such a smart grid application, the smart home products are equipped with a smart meter to provide the Time of Use (ToU) tariffs based on electricity consumption for different appliances and different electricity rates based on the time of use. Due to the fact that homes consume over 50% of generated electricity [2], residential energy management techniques have become a hot research topic in academia. On the other hand, residential consumers can also be places of distribution of renewable power resources, e.g., solar panels, wind turbines or even by stored energy in Plug-in Electronic Vehicles (PEVs). During peak-time hours they themselves can provide power, thus smart homes rely on years of advancement of communication between consumers and the utilities [2].

Accordingly, the smart grid is not limited only to delivering electricity, it can also be used to carry bidirectional information, in order to provide communication between the utility companies and consumers. Providing a reliable and efficient communication network infrastructure will have an undeniable role in the implementation of smart grid features which were mentioned above.

One of the main tasks toward establishing a smart grid is recognizing a suitable communication network for supporting the requirements and features of the new power grid. Meanwhile, the goals of access networks are mobility, flexibility, robustness and high capacity in addition to

being a cost effective solution in one seamless infrastructure. The required communication network for smart grids is not an exception to these features. Optical networks feature provides high bandwidth, long range transmission, and robustness, in addition to supporting low maintenance cost, low delay and error-rate. The mobility, flexibility and ubiquity properties can be provided by a wireless network technology. Therefore, the combination of these two communication network technologies can achieve the goals and features of the broadband access network. Consequently, the future of access networks will be the co-existence and convergence of optical and wireless technologies in the form of the Fiber-Wireless (FiWi) broadband access network. For the rest of this thesis, we mainly focus on the implementation of this technology for broadband access networks under smart grid applications. The implementation is based on the integration of fiber to the wireless network with a cost effective solution, along with Quality of Service (QoS) capability in mind.

According to Xiao-min *et al.* [12], the existence of Advanced Metering Infrastructure (AMI) can provide a powerful system to support metering systems. A trend in smart grids is the adoption and deployment of AMI. AMI systems will need a robust two-way communication system to create a platform for sending metering information, including ToU, remote disconnection, and demand response from consumers to suppliers in the power grid. In fact, smart homes themselves can be the suppliers by generating energy from renewable sources, such as solar cells and wind turbines. They can sell their surplus energy to the utility companies, especially during peak-time hours in the framework of smart grid technology. Therefore, as a main part of this thesis, we introduce Wireless Sensor Network (WSN) technology for demand side shaping at smart homes as well as for monitoring wind/solar farms and substations [1] [2] [4].

1.2 Motivation

The increasing electricity demands and dramatically growing population, from 6.1 billion in 2000 to an estimated 7.5 billion by 2020, will cause an increase in energy consumption by 75% in 2020, compared to the year 2000 [2]. In addition, according to the annual report by the U.S Energy Information Administration, the residential consumers are forecasted to have a 24% increase in energy consumption within the following decades [4]. Therefore, the consequences of these increasing energy demands is a tremendous increase in CO₂ levels and GHG, as well as diminishing fossil fuels and lack of resilience of the power grid. For example, the pervasive blackouts in 2001 and 2003 in Canada and California led to between 7 to 10 billion U.S. dollars of economic damage. This can be contributed to the lack of monitoring tools and effective communication infrastructures [2] [4] [5].

In addition, there are some opportunities and also challenges for the smart grid which draw our attention. For instance, PEVs require a lot of energy to fully charge their batteries, while naturally there is no storage mechanism for the power grid and it is continuously in use [2]. Therefore, the smart grid is an opportunity to render surplus PEV's energy to the utility companies during peak times. To support this capability a two-way communication network is needed. On the other hand, by shifting electricity consumption from peak-time usage and towards optimizing the power consumption for all of the homes can introduce another peak-time bound after the existing peak-time hours [2]. Hence, providing a seamless communication network based on the inter-home connectivity, i.e. between consumers' homes, is another important aspect in the smart grid, whereby the main focus of this thesis is the improvement of advanced demand controlling mechanisms by using telecommunication networks.

Apart from all of the aforementioned challenges, researchers are also becoming seriously concerned with the environmental aspect, besides the growth in demands. It led us to find a cost effective and a simple solution, with QoS considerations at the application level in mind, besides providing an infrastructure to exploit the opportunities around smart grids by applying information and communication networks. In principle, the smart grid is an advancement of the conventional power grid, which improves the electricity demand response by establishing a broadcast power network in the form of distributed power generators as well as a few central power generators to a large number of energy consumers.

1.3 Contributions

This thesis achieves two main contributions by means of Information and Communication Technology (ICT) for enhancing power engineering. Two-way communications between the customers and the utility, advanced monitoring tools and intelligent control mechanisms are the key components to realize the new services of the smart grid.

We consider the “last mile” of the Internet access technology for supporting the requirements and features of the new generation of power grid. The future broadband access network will take the advantages of both optical and wireless technologies as complementary communication networks. Optical lines provide the high speed and robustness, while the wireless network offers the mobility, flexibility as well as reduction of the installation cost, due to eliminating the need of running fiber to each customer. Recently, several studies have been done regarding the integration of fiber and wireless technologies [16] [17] [20] [25] [40] [60]. For this thesis, we adopt the Fiber-Wireless Sensor Network (Fi-WSN) to support both WSN data and Fiber To The

Home/Building/Curb (FTTX) traffic. The optical network used in the thesis is the Ethernet Passive Optical Network (EPON) and the same medium is shared between fixed and mobile users.

We have developed a Fi-WSN gateway design, as an interface between the WSN sink and the Optical Network Unit (ONU), that allows data prioritization, maintains the QoS of FTTX users and delivers WSN data in a reliable manner under the Radio-and-Fiber (R&F) technology. Furthermore, we have developed a computer simulation program for the integrated optical-wireless network using the Discrete Event Simulation (DES) method written in C++ with the MSVS 2010 compiler [6] [7].

1.4 Thesis Outline

The thesis is organized as follows. Chapter 2 provides background information on the power grid, the vision of a smart grid, and also a review of telecommunication networks with an emphasis on FiWi networks. In Chapter 3 we present our adopted system model by considering the contribution of ICT to the power grid. In that chapter we also adopt the Fi-WSN broadband access network technology and introduce the Fi-WSN gateway as an interface between optical and wireless networks for the new generation of the power grid. Chapter 4 presents the simulation results and assumptions, within the provided constraints, in simulation settings, and also analyzes the performance of the adopted system model based on the proposed FiWi interface gateway. Our work concludes in Chapter 5 where we describe some future research opportunities.

Chapter 2

Power Grid and Fiber-Wireless Technology

2.1 Introduction

The dramatic increase in energy demands and the effects of global warming caused scientists to devote their research on exploiting and developing renewable energy resources. In turn, the governments are engaging in tighter control and management of energy consumption for industrial, commercial and residential clients. Recent studies [4] [9] [24] [49] have shown that the traditional electricity delivery grid-based system, with its basic functionality and one-way communication, is not adequate for today's electricity demands. In contrast, adding a set of smart features to the traditional power grid system with a two-way communication system can address many of the fundamental weaknesses of the previous power system.

Traditionally, the power grid delivers electricity from a centralized power generator to the consumer premises. The process of electricity generation is based on exploiting such natural conventional energy resources as gas and fossil fuels. As stated in [3] [9], the transmission and distribution sections of the power grid consist of critical equipment which include transmission and distribution power lines and substations. The power lines connect utilities (power plants) to substations using transmission lines when utilities are very far away from substations. Based on the provided statistics in [8], on average up to 8% of the transmitted power is lost during

transmission and distribution due to large transmission distances from substations to the customer premises.

One of the main challenges in the old power grid system is the lack of an infrastructure for providing safe delivery of power, as well as mechanisms for controlling power consumption under the metering systems. But using telecommunication technology can have a prominent role in solving the existing challenges of traditional electricity delivery systems [1] [4].

This chapter is structured as follows. Section 2.2 describes the technical vision of the smart grid and the requirements for implementing such a system. In Section 2.3 we consider the telecommunication technologies for the new generation of the power grid communication subsystem. Section 2.4 introduces the FiWi network and we discuss its advantages and challenges. We also look at related technologies for this type of telecommunication network. Then, this section continues by providing and comparing previously conducted work on integrating fiber to wireless technology. Finally, a summary of the chapter is provided in Section 2.5.

2.2 The Smart Grid Roadmap and Vision

Due to the increasing usage of energy, resources such as natural gas, fossil fuels, and coal are consequently diminishing. Besides that, we have witnessed pervasive blackouts, the majority of them being in industrial countries in the world due to the imbalance in demands and electricity production. We also witness that the electrical power grid has continued to operate in the same way for more than 40 years [8]. Therefore, considering the outdated power grid system, new, intelligent grids are needed.

Due to the aforementioned challenges, modernizing today's power grid system is inevitable and various countries have invested in progressing smart grid technology. Among these countries, the United States and European countries have pursued the smart grid objectives. For example, the authors of [9] indicated that the U.S. Energy Independence and Security Act of 2007 directed the National Institute of Standards and Technology (NIST) to start the integration and development of an infrastructure for interoperability of intelligent devices (i.e. autonomous electronic devices connected to the Internet) to the smart grid system. As pointed out in [8] [9], investment in the development of smart grid systems has been seen in East Asia, e.g., China and India, and is gaining momentum in other countries as well. The conducted research has described vast different roadmaps and categories for smart grid perspectives, which focus on different smart grid aspects, e.g. from the environmental aspect (GHG and carbon emission) and from a technical vision aspect (aging and deficiency infrastructure, lack of digital communication system). Particularly, energy monitoring tools at the customer premises as well as event and ambient monitoring tools at the substations, power lines and vaults play a significant role in managing and protecting the smart grid. In fact, the smart grid is the next generation of power grid which enhances the efficiency, security and reliability of electricity generation, delivery and consumption by contribution of ICT.

As stated in [9], Micro-grids, Grid to Vehicle (G2V) and Vehicle to Grid (V2G), and smart metering paradigms have been investigated for the realization of intelligent power grids in terms of "two-way flow of electricity and information". In V2G system, Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicles (PHEV) deliver their surplus electricity to the power grid while in G2V, EV and PHEV receive electricity from power grid.

2.2.1 Micro-grids

In [63], the author explores the Micro-grid approach as a set of localized power generators, storage and loads that can generate the low voltage electricity through multiple distributed renewable energy sources, such as solar panels and wind turbines. This localization capability provides multiple distributed generators and the ability to isolate the Micro-grid from a large network disturbance, in addition to providing a highly reliable electricity supply, with self-healing ability, improvement of penetration of renewable power sources and efficiency as reported in [9].

2.2.2 G2V and V2G Paradigms

Fully EV and PHEV are gaining popularity nowadays. In G2V systems, EVs store power from an external power source [1]. The main challenges for the utilization of G2V/V2G have been considered in [1] [2]. In fact, the authors stated that the two main challenges are that they impose significant load on the existing Distributed Generators (DG) and the availability of EVs, as EVs can only deliver power to the grid when they are parked and also connected to the grid. One solution is to optimize the charging profile to reduce the EV's negative effective.

2.2.3 Smart Metering

An important capability of the intelligent grid is to provide a service from utility companies to customers to provide them ToU pricing. This enables the customers to control their electricity usage and encourage them to use off-peak times, when pricing is less. This type of control

system will be valuable for utility companies, by avoiding over loads to the power grids as well as minimizing the possibility of major blackouts in peak-time hours [2] [12].

A more precise definition of the smart meter has been reported by authors in [1] [4] [9] as an electrical meter that records a client's consumption in intervals of an hour or less and sends information at least daily back to the utility company for monitoring and billing purposes.

Using two-way digital communication facilitates the automation of data acquisition and real-time supervisory control of appliances at the smart homes, industrial and commercial premises. As stated in [12] [27], the first requirement for implementation of such a platform is automatic electricity metering and AMI as a key technology to bridge intelligent appliances and a utility management office.

To enable better demand side management, the extension of conventional power grid to the consumer premises is offered in the smart grid by authors in [14], based on using embedded smart meters at each appliance. Therefore, the utility management office can implement on-line monitoring of the power grid periodically. On the other hand, the aforementioned feature for the smart grid can also be of an assistance role to enhance stability and efficiency of power systems via delivering client's surplus distributed energy generation back to the grid (bidirectional measuring) at peak times usage [10] [15]. Furthermore, authors in [12] are reported that this new feature of the power grid can encourage power consumers to use the lowest ToU tariff in peak-off time tariff in terms of flexible price policies.

The authors of [27] point out that AMI, with its powerful ability to monitor power grid lines and electricity consumption, consists of software, hardware and communication components as this infrastructure can be practically implemented by wireless communication technologies, e.g.

ZigBee, WiMAX, Wi-Fi, 3GPP- Long Term Evolution (LTE), etc., or can even be implemented by wired communication technology as stated in [10].

According to the considered industry view in [5] [50], the new intelligent power grid presents important opportunities in terms of customer QoS, based on isolating the failed power line or broken substation equipment via detection of related sensors for monitoring.

In IEEE P2030 [62], a system level approach is provided to the guidance for interoperability between communication, power system and information technology components. Smart grid interoperability refers to the organization mechanisms with effective communication ability and the ability to transfer meaningful data that may be used for a variety of information systems.

As a result, the research on the AMI confirms that a flexible technology for easy development in addition to robustness and reliable telecommunication infrastructure is needed for the implementation of an AMI technology. Therefore, we focus on this aspect of the smart grid according to its necessity for realization of today's required intelligent power grid.

2.3 Smart Grid Enabling Communication Technology

This section presents an overview of various telecommunication network technologies for satisfying the communication requirements of the smart grid application. As discussed in Section 2.2 and due to the addressed challenges, the requirement of fundamental innovations to the power grid of today is apparent. According to previous research [3] [11] [44], the access networks can enhance the planet's energy infrastructure and overcome power challenges for the new demands of the next hundred years. The development of the AMI monitoring model adopts

a reliable and flexible communication platform which manages an autonomous power grid that can monitor and react in real-time and in critical situations [49].

Nowadays, communication access networks are mainly divided into two technologies: wireless and wired technology. From a technical standpoint, each technology has its own strengths and weaknesses. For the wired technology we consider optical access due to its capabilities for offering huge bandwidth, long range data transmission, low delay, robustness, and low maintenance cost, which is just the price of maintaining a passive splitter. Finally, fiber network adopts the “first\last mile” access medium technology rather than copper cables [16]. The disadvantages of it are that fiber technology cannot support some capabilities such as extending everywhere (e.g. rugged environment), and also suffers from high implementation cost [17]. In addition, fiber medium has a high propagation delay due to its extended reachability [18].

2.3.1 Wireless Technology

Wireless access networks have some advantageous compared to wired networks, such as low implementation cost in addition to the ability to go almost everywhere [18], mobility and ubiquity features. However, this flexible front-end technology is challenged by a limiting data rate, which is up to 1 Gb/s for down link, high degree of Radio Frequency (RF) interferences, and low transmission range [3] [19] [20].

There is no doubt that emerging of the ICT is inevitable for the new power grid. Although, as reported in [2] [18], conducted research confirms that we could not find yet a particular agreement on the selection of a specific networking technology which should be adopted and implemented on the vast different domains of the smart grid application.

The Wireless Mesh Network (WMN) IEEE 802.s standard has been considered in [21]. WMN technology implements multi-hop routing and enhances the MAC protocol. Consequently, reliability and automatic network connectivity based on redundant paths are some other strong points of WMNs.

As stated in [23], the ZigBee standard and ZigBee Smart Energy Profile (SEP) are the most commonly used communication standards for both metering as well as energy management in Home Area Networks (HAN) (used in the customer premises network domain) for smart grid applications by NIST (National Institute of Standards and Technology). Based on conducted research in [13] [14] [24], ZigBee has recently been considered as a potential candidate for device that need to provide real-time pricing, text messaging, load control and demand response facilities.

Nowadays, as reported in [26], Ericsson is working on the smart grid for Australia's leading smart grid project. An agreement between Ericsson and Ausgrid was reached to provide electricity distribution networks based on future wireless broadband 4G LTE technologies. As stated in [3], the 4G LTE technology provides a wireless technology option for previously wired networks which is 10 times faster than 3G. An LTE smart grid also transforms energy electricity networks into a smarter, greener and more efficient network.

2.3.2 Fiber to the Home/Building/Curb

As stated in [28], the strong points of the fiber medium confirm that this technology is a good candidate to become close to the end users in terms of FTTX, due to providing high speed and unprecedented bandwidth for today's growth demands. Passive Optical Networks (PON) [6], as a

type of FTTX network are known as a cost-effective access network solution by longevity, low attenuation features and supporting a wide range of high quality new services and applications. It provides two single wavelength channels, where one single channel is used for downstream and another wavelength channel is applied from subscriber to the Central Office (CO) based on Time Division Multiplexing (TDM) bandwidth assignment technique. EPON (IEEE 802.3ah) has a symmetric line rate of 1.25 Gb/s and Gigabit PON (GPON) has 1.244Gb/s and 2.448Gb/s as an upstream line rate and downstream line rate respectively. Moreover, initiation of the IEEE 802.3av standard by International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) provides 10 Gb/s EPON [18] [35]. Other conducted research works on the optical networks are stated in [25]. Kazovsky *et al.* [25] presented Wavelength Division Multiplexing (WDM) PON by adding the wavelength dimensions to the conventional TDM PONs, as shown in Figure 2.1, to provide separate services, privacy and improving the network scalability by accommodating more end users.

In [29], the authors focus on Long-Reach PON (LR-PON) to increase the split ratio of PON up to 1000-way and PON service ranges up to 100KM as an attempt to provide cost-saving and simplicity of network operation.

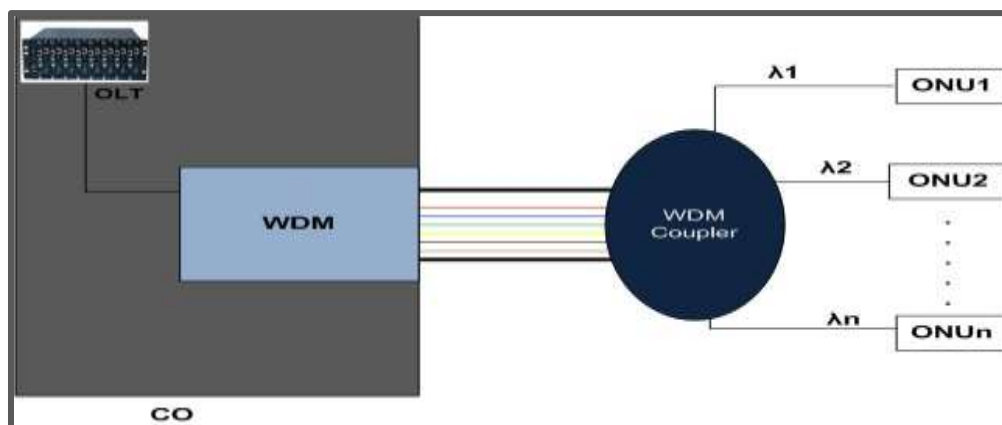


Figure 2.1 WDM PON Architecture [25]

However, LR-PON suffers from increasing propagation delays on the feeder fiber that consequently causes performance decreases in the network. The authors in [30] have addressed several related solutions to cope with the mentioned challenges. PON access networks designed with the Dynamic Bandwidth Allocation (DBA) algorithm [18] [28], can have a key role to satisfy QoS for the access networks.

2.4 State-of-the-art in Fiber-Wireless Networks

For this section, first we explain the possible challenges of the communication system in a smart grid. Then we review the conducted proposals for combining fiber and wireless technology in the literature which guide us to addressing the adopted telecommunication infrastructure for this thesis.

In view of the general challenges in the near future of smart grid communication infrastructure, the authors in [9] have classified the present issues as follows.

- 1. Conjunction with communication technologies:** Introducing the new generation of the power grid requires applying many technologies. For instance, some technologies should be applied for supporting the flexibility feature to extend the smart grid infrastructure everywhere. On the other hand, smart grid needs to apply effective communication protocols to allow supporting a very fast data rate infrastructure for exchanging smart metering information. Therefore, providing connectivity between various communication protocols and technologies is a challenge in the smart grid.

2. Communication topology Instability: The telecommunication infrastructure in the smart grid deals with a variety applications. Some applications, such as PHEVs or wind turbines, are not predictable. They may be disconnected or connected from/to the smart grid communication network and change the communication topology anytime. Hence, the new power grid system requires a suitable communication infrastructure and protocols which can support the dynamic network topology feature.

Therefore, to address these challenges and capitalize on the complementary strong points of both fiber and wireless technologies, the hybrid FiWi network technology will be a promising broadband access network.

The FiWi aims to integrate fiber to wireless networks for “last mile” telecommunication networks, where the flexibility feature can be achieved by expanding fiber from CO to the premises as far as possible, while wireless network can continue the access network to some locations where the installation of fiber networks is not possible. As reported in [34], the main reason for a lack of this flexibility for the optic-fiber network is due to the large number of buildings/homes/premises and amount of difficulty and capital costs. Hence, the use of wireless creates a cost-effective solution for the smart grid communication infrastructure. Indeed, the FiWi networks efficiently exploit the huge available bandwidth in the optical access network, while the mobility and flexibility are deployed by the wireless network [8] [16] [18].

From the networking viewpoint, two main enabling schemes are investigated for convergence of optical and wireless technologies under FiWi networks which are discussed below.

2.4.1 Radio-over-Fiber Networking

In the Radio-over-Fiber (RoF) technology, an optical carrier signal is generated by a laser diode of a central light source at the CO to modulate the wireless RF and FTTX baseband signals via a Mash-Zehnder Modulator (MZM-1 and MZM-2, respectively) separately. Then, wireless RF and FTTX modulated signals are multiplexed by MZM-3 (or through a phase modulator) to filter optical signals (E/O). Consequently, the filtered optical signals are propagated via an analog fiber link to a Remote Antenna Unit (RAU) which is a distributed antenna system connected to the Base Station (BS) [35]. Finally, the filtered signal is transmitted to each client (Wireless and FTTX by de-multiplexing technique) for downstream traffic by applying photodiode O/E conversion [36] [37]. Therefore, the analog radio signals carry out digital data. This simple FiWi infrastructure can provide an economical ICT solution by using few components [38], where signal processing and complex operations are carried out only at the CO. Indeed, the RoF technology can be considered as a low cost implementation (CAPEX¹) as well as reduced maintenance costs (OPEX²) network. In this FiWi network architecture, the RAUs are connected to each other and also connected to the CO on the other side using fiber link that implements an optimized resource allocation algorithm, besides improving handover functionality of Cellular networks [16]. In contrast to the WSN, the FiWi broadband access network based on RoF scheme improves attenuation, data rates, transmission range and makes enhancements to the performance of traditional wireless networks based on the improvement of radio coverage [39]. As one successful RoF project, the Georgia Institute of Technology implemented the RoF test-

¹ Capital expenditure for a company is the cost of implementing physical and fixed assets such as equipment, or upgrading existing assets in order to add value of company business [65].

² Operational expenditure refers to the day-to-day cost of the maintenance and development of the product and system [66].

bed to send standard and high definition (SD and HD) real time video stream through 2.5 km Single Mode Fiber (SMF) with 60 GHz frequency. The results have shown good performance, indicated by the Bit Error Rate (BER) for a given distance, in sending multimedia traffic [16].

However, the concept of RoF technology has been considered since 1984 by Military Electronics Division of the TRW Electro Optic Research in California [40] and during the last three decades has experienced some challenges. The main issue with this enabling technology arises from the Medium Access Protocol (MAC) layer, in which the optical link range is limited to a maximum range (up to 50 km), especially for Point to Multi-Point (P2MP) transmission modes. Because of the additional propagation delay that is injected into the wireless networks from optical distribution networks, there is an increase in wireless MAC timeouts, thus degrading the performance of the FiWi networks. Hence, using a shared transmission medium introduces layer 1 challenges, such as propagation delay, for enabling upper layer for P2MP transportations [41].

With respect to current technology, the integration of fiber networks to wireless can be done using WiMAX and optical networks, as recommended by authors in [41]. WiMAX's centralized polling and scheduling MAC protocol is less affected by the additional fiber propagation delay based on the RoF approach.

On the other hand, RoF puts the FiWi network structure at risk to the CO as a possible bottleneck for access network based on the aforementioned RoF simple infrastructure. Therefore, accruing some failure cases inside the CO creates serious dis-connectivity problems for the whole network [40].

2.4.2 Radio-and-Fiber Networking

The limitation of RoF scheme that is mentioned in the previous section can be eliminated by using R&F enabling technology for FiWi [35]. This technology applies a different MAC protocol at the optical and wireless network separately to control the integrated network as a single infrastructure. In fact, this seamless FiWi infrastructure can be achieved via a protocol translation interface by taking place at the optical-wireless borderline and focusing on the networking aspects of integration of optical to wireless networks [41]. In contrast with the RoF networks, WLAN-based FiWi network can be implemented using R&F technology due to the WLAN distributed MAC protocol (e.g., Distributed Coordination function (DCF)) which limits the optical transmission range. The resilience feature can be considered as an advantage of R&F networks by providing the connectivity in the wireless domain when the optical access network loses the connectivity [16] [19].

Although the R&F technology is not a new concept, many relevant opportunities and open challenges still exist as active research topics before making a commercial solution for FiWi networks. One of the main challenges is related to the fabrication of different MAC protocol-based devices. For instance, the experimental result in [19] confirms that the assigned MAC protocols in EPON and WMN independently under the R&F approach creates degradation on the QoS of multimedia traffic by increasing the number of hops in WMN. On the other hand, this mentioned feature makes a huge amount of the optical available resources underutilized. Hence, adoption of a hybrid integrated MAC protocol will be necessary to make efficient use of available resources. In addition, applying efficient routing algorithms based on OSI layer 3 protocols can reduce the number of hops in WMNs [40].

As an overall view, we provide a summary for comparison between RoF and R&F technology in Table 2.1.

Enabling Technology	Infrastructure Complexity	CAPEX & OPEX	Flexibility	Resilience	Robustness	MAC protocol
RoF	Low	Low	Average (depends on the adopted wireless technology)	Low	High Risk	Optical distributed transmission (Access control by CO)
R&F	Average (high in some cases)	Average	High	High	Low Risk	Hybrid Optical-Wireless)

Table 2.1 FiWi Enabling Technology Comparison

Furthermore, there are many potential FiWi network architectures based on the aforementioned enabling technologies. Hence, we apply ICT facilities to develop the communication networks that will be able to satisfy the control and monitoring tasks in terms of two-way flow of information between power generators (utilities) and consumer premises.

Regarding our research and due to the last reports in [42], there is no consensus about the selection of a specific telecommunication network architecture, technology and protocol for the implementation of the smart grid communication infrastructure yet.

Finally, we have adopted FiWi broadband access network architecture and adopted the R&F approach on top of it to integrate EPON as the back-end network and WSN technology for the front-end access network at the premises segments for this thesis. In fact, we have selected the R&F as a candidate protocol for applied FiWi network because of its high level of flexibility by using wireless technology to extend the FiWi network rather than RoF technology, and also

providing better performance in terms of network robustness and resilience capabilities which are essential features for the smart grid communication network, as we discussed earlier in Section 2.2.

The coexistence of optical access networks with wireless technologies shape a seamless broadband access network for the near future of telecommunication networks [17]. However, this type of hybrid network technology provides important challenges in the emerging FiWi technologies by the expansion of physical, data link and routing layers as a comprehensive integrated network [5] [16]. In fact, providing a seamless infrastructure led to apparent challenges in MAC protocol translation between fiber and wireless mediums and bandwidth allocation through designing routing protocols which should be aware of bandwidth allocation on the PON. The rest of the challenges are addressed by QoS criteria, such as congestion control and survivability issues. Therefore, experimental research is needed to consider a QoS-aware routing protocol in wireless network topologies. Various QoS bandwidth allocations for different applications can be seen as a solution for the future of the hybrid access network challenges [16] [18] [23].

Furthermore, for the survivability aspect, the FiWi networks should provide a suitable interface as a wireless network gateway to interconnect with the optical backhaul through multiple points and enable multipath routing in addition to applying an appropriate protection switching function with an optical backhaul [43].

2.4.3 Related Works on FiWi

The potential opportunities that are offered by FiWi networks provide a motivation for service providers and academia to conduct several studies in the past decades. In Section 2.4, we have considered the FiWi networks to integrate fiber technology as a back-end technology to the wireless technology as the front-end access network. Therefore, we briefly elaborate on the different conducted integration approaches which have been carried out on FiWi architectures recently. Finally, studying these approaches led us to our FiWi network design under the smart grid application by selecting an appropriate protocol for each optical and wireless technology.

Generally, for the backhaul of broadband access networks we can employ PON networks, e.g. EPON, LR-PON or WDM PON for the sake of supporting P2MP topology as the promising wire-line access network. Due to the mentioned capabilities of EPON networks in Section 2.3.2, we focus on the classification of FiWi networks based on the selected wireless technologies for the front-end access network. Therefore, we briefly review the integration prototypes that combined EPON to Wi-Fi, WiMAX and Third Generation Partnership Project (3GPP) Long Term Evolution-Advanced (LTE-A) which are closer to our adoption of the FiWi network architecture in this section [3] [11] [17] [44].

First, we consider the integration of EPON as a back-end network technology with WiMAX acting as a front-end communication infrastructure. As the authors stated in [17], the best advantage of this type of hybrid is the good capacity match at the ONU-BS gateway among other EPON-WiMAX integration benefits. This well matched behavior occurs based on OLT with a splitting ratio of 16 to each ONU that has 62Mb/s data rate for upstream and, on the other hand, referring to Section 2.4.1, WiMAX provides 75Mb/s as a data rate. However, some challenges related to resource allocation and scheduling issues for the EPON-WiMAX integration are

addressed in [17]. The authors in [17] have investigated minimizing the number of ONU-BSs, besides satisfying the QoS factors, such as an end-to-end delay network performance factor in order to provide an efficient system. In fact, this approach can provide cost-effective solutions in addition to the low network installation costs and the average level of QoS which directly depend on the bandwidth allocation mechanism at the ONU-BS gateway [19].

We summarize available topologies for EPON and WiMAX integration as follows [18]:

- 1. Independent Architecture:** This architecture is classified under R&F networks where WiMAX Base stations as Mobile Client Nodes (MCNs) are integrated to ONUs. For this hybrid network, EPON and WiMAX are connected through the Ethernet interface and operate separately.
- 2. Microwave-Over-Fiber Architecture:** This topology is another type of hybrid RoF network where the modulated WiMAX signal is multiplexed with the baseband EPON signal on a common wavelength at the ONU-BS. Then the central WiMAX BS and OLT process the WiMAX BS and EPON signals respectively.
- 3. Hybrid Architecture:** In this network topology the ONU and WiMAX BS are integrated in both hardware and software. The ONU-BS provides the dynamic bandwidth allocation by carrying an Ethernet frame.
- 4. Unified connection-oriented Architecture:** This topology is implemented under the R&F approach. On the other hand, the Unified architecture develops the Hybrid architecture by carrying WiMAX MAC Protocol Data Units (PDUs) compared to the Hybrid architecture. The unified topology provides an opportunity to grant bandwidth finely.

Secondly, we briefly summarize the combination of EPON to the WLAN which were pursued recently. Chowdhury in [41] developed a test-bed for this type of hybrid technology by considering a full duplication protection mechanism for EPON backhaul network and optimal routing. However, the results made clear that the performance of the distributed MAC protocols, such as DCF in IEEE 802.11 a/b/g WLANs [19], degrades with increasing the number of wireless hops. The aforementioned performance degradation is essentially seen for multimedia applications such as video streams, for the sake of considering EPON and WMN as independent networks.

On the other hand, the combination of WDM/TDM PON and WMN is provided by authors in [20], to use the huge optical network bandwidth and QoS to improve performance to end users. They recognized that this type of FiWi integration can improve throughput of the access network by decreasing the impact of the interference from wireless sub-networks [23] [41].

On the other hand, the authors in [18] have provided a classification for integration of EPON and Wi-Fi technologies as a hybrid access network:

- 1. Unidirectional fiber ring:** In this Wi-Fi based network, MCNs are connected to their associated Wireless Access Points (WAPs) where a unidirectional fiber ring interconnects the CO and WAPs. The CO deals with data transmission management between MCNs and their WAPs in addition to channel assignment using one or more wavelengths as a gateway to others networks. This type of network supports the path diversity feature by sending data to neighborhood WAPs from the CO. Furthermore, the multi-hop relaying feature extends the range of connectivity as well as increases the reliability of the wireless links.

- 2. Two-level Bidirectional path-Protection Ring for DWDM/Subcarrier multiplexing (SCM):** This network architecture increases the reliability of the network compared to the unidirectional fiber ring network infrastructure by using a bidirectional path-protected ring topology. Remote Nodes (RNs³) are connected to the CO via dual fiber rings, where each RN connects WAPs to the CO through Concentration Nodes (CNs⁴). Furthermore, this network provides high capacity using the DWDM technology.
- 3. Hybrid (combination of optical star and ring networks):** This type of hybrid FiWi network architecture consists of fiber ring and star topology. The WAPs are connected via a fiber ring network while an optical switch interconnects each fiber ring network to the CO and two adjacent fiber rings. In fact, this FiWi architecture introduces a robust integrated network in terms of one or more link failure events. On the other hand, using the optical switching provides enough capacity, and also supports load balancing by wavelength conversion capability.
- 4. Unidirectional ring/PON:** This FiWi network architecture is based on merging of the optical WDM backhaul ring with multiple single-channel or multichannel PONs. For connection between OLT of each PON to WDM ring, the Optical Add-Drop Multiplex (OADM) is used while connectivity between PONs and WMNs are provided by the wireless gateway. The main advantages of this architecture are scalability, high flexibility besides providing cost effectiveness, bandwidth efficiency and supporting wide transmission coverage.

³ Consists of a protection unit and a bidirectional wavelength add-drop Multiplexer based on a multilayer dielectric interference filter.

⁴ Consists of a protection unit, where each WAP offers services to MCNs.

Furthermore, LTE, as a recent wireless technology that supports a large number of clients and offers a high data rate [45], and its integration with LR-PON (Section 2.3.2) provides a simple infrastructure while LR-PON mitigates the operational and deployment costs. These can be considered the strong points to extend reachability of this type of FiWi network [3]. However, increasing the propagation delay by LR-PON and the higher targeted peak data rate of up to 1Gb/s (500 Mb/s) in download (upload) using existing Universal Mobile Telecommunications System (UMTS) are addressed as main challenges that are considered by authors in [3]. In addition, the authors in [3] have proposed an energy-efficient framework for a green access network that can significantly decrease the average packet delay besides providing the energy saving for the access network.

2.5 Summary

In this chapter, we have reviewed the progress of the power grids toward the smart grid technology by considering technical requirement tools such as the smart metering and AMI systems as the technology to increase energy efficiency and monitor the system. We highlighted one of the main applications of smart metering as the real-time measurement for the amount of generated power by wind turbines or solar panels. In addition, we investigated that there is not a suitable energy storage mechanism for the energy generated by renewable resources, compared to some limited storage methods that exist for traditional power generation grids. In the aspect of technology, we depicted that the smart grid should be investigated on the optimization, reliability, flexibility, cost efficiency (economic solution), security, speed, and robustness of communication infrastructure features. We have mainly focused on the communication sub-layer of the smart grid system in order to offer a suitable telecommunication network by considering different aspects of wired and wireless technology.

Chapter 3

FiWi Network Development for the Smart Grid

3.1 Introduction

Nowadays, communication network infrastructures are expected to be simple to reduce the cost of implementation for service providers. Meanwhile, the combination of the fiber and wireless technologies, as a broadband access network technology to support an efficient and economical communication network, has attracted lots of attention from industry and academia [3]. We have considered FiWi networks and investigated RoF and R&F schemes as enabling technologies to integrate optical and wireless networking. Consequently, we have applied the R&F approach due to its potential capability to create a seamless network infrastructure.

In this chapter, we propose a telecommunication infrastructure solution which has the properties of being flexible, economically efficient, robust, reliable, and with QoS in mind to support the required communication infrastructure for the smart grid. First, in Section 3.2, this chapter describes the WSN infrastructure and its requirements in detail as the front-end communication network that collects the different smart metering data from sensors in the premises. Then, Section 3.3 presents our view of the FiWi network architecture by providing a system model in terms of the Fi-WSN broadband access network under the R&F scheme. Thereby, we introduce a

gateway to the integration of EPON to WSN. Finally, Section 3.4 provides a summary of this chapter.

3.2 System Architecture and Requirements

Various sensors can be embedded in indoor and outdoor appliances. The applications of sensor networks determine the requirements for hardware and network protocols. Generally, sensors are low power, low cost and consist of small nodes that have the capability of providing a multi-hop and short range wireless communication. Their main applications are sensing the temperature, humidity, and noise from the environments. They achieve this through the distribution and interconnectivity between nodes in sensor distributed environments for system diagnostics and observation. They are used in such areas as smart homes, buildings and monitoring critical equipment in industrial environments [24].

Selecting the appropriate WSN protocols, some of which were discussed in Section 2.4.1, depend on the specific application. WSN for smart grid is a promising technology which provides metering, monitoring and energy management systems [46].

The functionality of the WSN in the smart grid application will be the collection of data from sensors that are distributed at the premises with specific routing algorithms. We adopt Geographical Routing (GR) protocol to collect metering from the smart appliances, substation embedded sensor equipment, and solar cell farms and wind turbine farms, based on the location of the embedded sensors. For this purpose, the GR algorithm needs a connectivity matrix, which can be calculated using the maximum transmission coverage range among sensors for a front-end

smart grid communication access network. According to the GR protocol in WSN, the next hop for each transmitter sensor node is selected using the shortest distance between all of the transmitter node neighbors and the Sink Node (SN) based on the connectivity matrix of the wireless network. The GR algorithm is explained in detail in Chapter 4.

3.2.1 WSN Message Prioritization

WSN can provide the capabilities for an automated power grid which can monitor ambient change and failures in the power grid.

From a system standpoint, we employ WSN for monitoring smart homes'/buildings', substations' and farms' (wind turbines' and solar panels' energy production) resources to the utilities and in the opposite direction as well. Regarding the addressed challenge in [1], in an integrated Fi-WSN, the heterogeneity of the front-end network applications introduces the biggest challenge in the design of a generic Fi-WSN gateway. Thus, we have decided to propose a scheme for classifying the generated messages that come from the real-time applications by assigning high and low priority to the packets. This approach provides a feasible solution to the management of inter-home energy consumption, which has been discussed in Section 2.3.1, in addition to the energy management and optimization in HAN under the adopted Fi-WSN network for the smart grid communication infrastructure [2].

3.2.1.1 Smart Homes

For the automation of the power grid, the customer premises are the main part of the smart grid. This point provides the interaction between utilities and premises (residential, industrial and commercial) and here the energy management optimization is done.



Figure 3.1 Inside the Smart Home

Today, smart homes are locations which distribute their renewable energy generation via wind turbines and solar panels, as shown in Figure 3.1 above. Due to the fact that residential homes consume 50% of the generated power by the utilities [42], automated control is a key role for energy management in intelligent power grids.

The implementation of the home automation and management systems is done through smart home appliances, based on embedded sensors that create the HAN. In this HAN, WSN can be implemented through different wireless networks, such as Wi-Fi, ZigBee, and others [2] [24].

WSN in HAN applications can be used for ambient measurements, such as temperature and pressure. Clients can even remotely turn on/off or regulate the home thermostat and appliances (e.g. air conditioner) when they are not at home for a long time.

This functionality provided by WSN can save lots of energy for smart homes leading to energy optimization for utilities, especially in peak-time hours, and cost saving for customers. Based on our system model, once a smart appliance would like to start working, first the embedded sensor sends a message through the WSN using multi-hop routing to the SN, then based on the assigned priority of the sent message from the related appliance, the SN decides what type of process should be done for the received packet. If the sent message has a low priority that means the appliance has low power consumption and imposes a low load on the power grid. For this type of packet, the SN buffers the received low priority packet. Otherwise, the SN receives a message from an appliance that means the appliance imposes significant load on the power line. Hence, once the SN receives a high priority packet, the SN sends immediately the received packet to the utility data center via the WSN-ONU gateway. All packets either low or high priority are sent through an optical link which is shared with FTTX traffic as well. Therefore, the received

packets are processed, for instance, as the ToU tariff for the consumer. Finally, after cost calculations for the appliance, a feedback message is sent by the utilities to the consumer informing him about the cost of using the appliance in real-time. The low priority packets, as we mentioned, do not create significant load for the power grids, thus they are buffered until they reach their assigned threshold for bursting and sending all of the messages from different low power appliances to the OLT which is located at the utility data center to calculate the related bill for the electronic devices.

In fact, priority assignment for appliances can be done based on European Union Energy Label of each appliance that specifies the rates of energy consumption for each electronic product [61].

Therefore, as discussed in Section 2.2.1, the smart grid technology expects that consumers generate and supply electricity through solar panels that can be installed on the top of the roof or via wind turbines for homes that are located in the suburbs. Generation of energy via Distributed Energy Resources (DERs) is limited, and is dependent on the geographical location and the rate of energy consumption by consumers. These premises, acting as distributed energy generators, can sell their surplus generated energy which has been generated by their DERs to the power grid. Therefore, the smart grid technology requires an infrastructure for interaction between distributed generators and utilities. To support this functionality, the wind turbines and solar panels at consumer premises are equipped with sensors to connect them via a WSN to the smart grid communication network. We assign the generated message from the DERs as a high priority packet, as an energy supplier. DERs can provide the required energy for a power grid, especially in critical situations such as peak hours or during blackouts in some regions.

Furthermore, the PHEVs are considered as a dual role application, they impose heavy load on the power grid in terms of power consumption and can also provide power themselves [1] [2]. Since we consider the inter-home management scenario using Fi-WSN broadband access network, efficient energy management among consumers (e.g., neighbors) for this type of allocation is very essential in avoiding significant load on the power line, especially in high demand hours. For this purpose, it will be necessary to assign high priority for received packet from PHEVs whether they are acting as power consumer role or as a DER to deliver stored generated energy by renewable resources.

3.2.1.2 Smart Farms

Green energy resources, such as wind turbines and solar cell farms, are gaining popularity in the world. The renewable property of wind turbine and solar cell farms attracts the attention of researchers from industry and academia. However, the main concern in using them as DERs is the difficulty in predicting the wind or solar energy generation. For accurate estimation of the rate of energy generation, many factors are involved, such as geographical position, air pressure, humidity, wind direction and so on [48]. Therefore, sensors are embedded in all of the distributed wind generators and solar panels in the farms or offshore farms to collect and acquire data to predict energy generation for the smart grid with WSN as a real-time and reliable technology [48].

In Figure 3.2 we depict the flexibility of WSN topology that provides a good solution for DER generators, such as wind turbines and solar panels that have a fluctuation in energy generation. This fluctuation is based on the dependency of these resources on the weather situation, season,

and location in which they are installed. As an example, due to the nature of renewable power generators, one or more solar panel or wind turbine cannot generate energy for undetermined periods, thus these sensor nodes are temporarily not part of the WSN. Hence, the WSN is flexible by applying the self-healing technique in uncertain situations [5] [49].

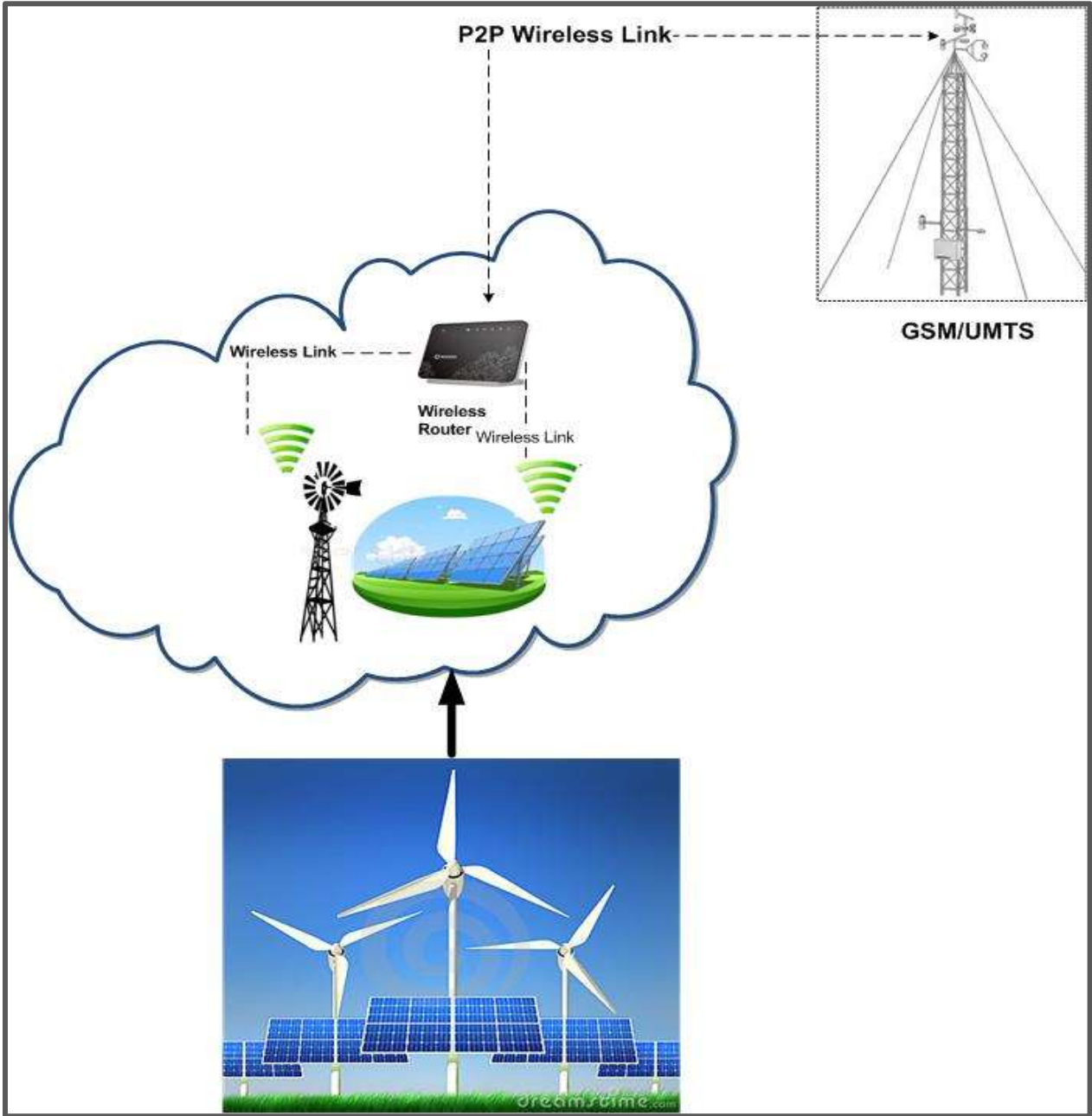


Figure 3.2 Inside the Smart Farm

We consider messages sent from sensors embedded in DERs as high priority packets because of their key role in energy generation for utilities today, as well as their essential and critical functions for supplying the required energy for Micro grids when a blackout occurs.

Therefore, WSN is a feasible solution for providing connectivity to distributed energy generators and also enabling utilities to communicate with DERs efficiently for monitoring and controlling purposes. The WSN infrastructure at the smart farms can be covered under IEEE 802.11 wireless protocol as well [48].

3.2.1.3 Smart Substation

For the next generation of power grids, substations are considered as the critical locations for power transmission and distribution. To reduce the risk of service disruption, they require real-time monitoring and controlling mechanisms, since they include critical power components and protective equipment, such as ambient temperature power lines and transformers.

Developing monitoring applications for circuit breaker⁵ in the substations is of great importance, since the monitoring task can detect the source of the fault in the power lines.

In addition, transformers consist of mechanical components (e.g., fans, pump) that distribute high voltage electricity to the customers, thus additional sensors for monitoring vibration and acoustic signals are necessary.

⁵Circuit breakers are applied for automatic electrical switch operations in power lines in order to protect overloaded electrical circuits.

Regarding the mentioned features for circuit breakers and transformers, any messages that are sent from these power grid devices will have high priority in our applied system, since they deal with the transmission and distribution of a large amount of electricity and thus have critical roles in the power grid [50].

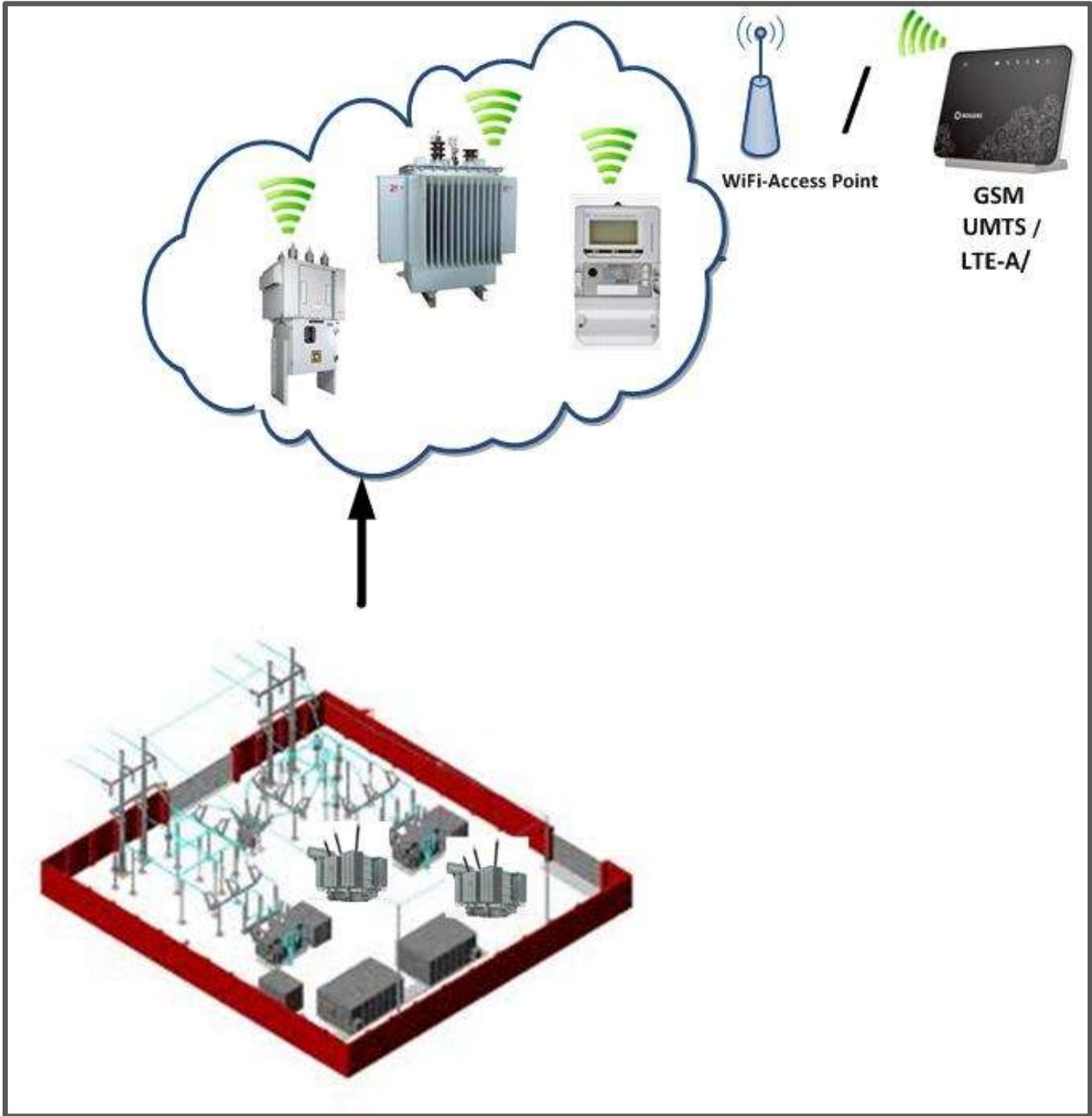


Figure 3.3 Inside the Smart Substation

As shown in Figure 3.3, the ambient temperature monitoring is performed by wireless sensor nodes for the whole substation site temperature or even for the measurement of substation's components surface temperature.

In contrast to the transformers and circuit breakers, temperature measuring sensors are not directly involved in the generation/transmission/distribution or even electricity consumption of the power grid. For this reason, we assign low priority for the received packets from these sensors in the substations.

Substations, in addition to the farms and offshore farms, are mostly distributed in bad locations in terms of either temperature or physical situations, thus, WSN is considered. One of the main characteristics of WSN is the capability of sensor nodes to operate accurately in harsh environments and in extreme ambient conditions.

3.2.2 WSN Opportunities and Challenges

The application of WSN in premises provides scalability for the smart grid communication network, while also providing a significant reduction in implementation cost. However, as discussed, solar cell and wind turbine farms are mostly placed in harsh environments. The extension of wiring and the use of wired access networks, e.g. FTTX, to the mentioned sites is either not possible or expensive. Therefore, for the extension of smart metering applications in these cases, a viable solution can be proposed by applying cellular network communication for the connection between smart meters and backhaul utilities for far nodes. T-Mobile Global System for Mobile communication (GSM), including 2G, 2.5G, 3G, WiMAX and LTE, is employed (studied in the literature) for the expansion of the smart grid communication

infrastructure without the burden of additional cost for installation of dedicated network structures. For example, as we have depicted in Figure 3.2 and Figure 3.3, transmitted data from wind turbines or solar cells can be received at a GSM wireless router that acts as a relay node for sending received data to a UMTS antenna that is in the coverage zone of the GSM wireless router in the wind turbine and solar cell farms. In the worst case scenario, the GSM wireless router can be used to send the smart metering data from embedded sensors to a remote antenna (omnidirectional/directional) that can be installed between the GSM wireless router and a UMTS antenna.

However, WSN suffers from some weaknesses, recognizing which would help us improve the smart grid communication infrastructure. As stated in [46], the two main challenges of WSN in smart grid applications are low data rate and the limited energy of sensors, which limits their lifetime. In dealing with these challenges, the authors in [46] also point out energy efficient MAC and routing protocols, then address harvesting energy mechanisms. They also mention an important weakness regarding harvesting energy for indoor monitoring, e.g., substations, where harvesting energy is sometimes not efficient or possible. The authors discussed a novel approach called Sustainable wireless Rechargeable Sensor network (SuReSense) through mobile wireless charger robots, based on replacing the batteries of the sensor nodes. Moreover, the results confirm their scheme can increase the sustainability for the sensor's lifetime in WSN that will be a great achievement for the smart grid monitoring application.

On the other hand, in [22], the authors believed that applying IEEE 802.11 protocol for sensor networks is a promising standard to increase the data rate up to 54 Mb/s, besides providing minimum infrastructure cost.

3.3 Adopted Fi-WSN Integrated Architecture

IEEE P2030 is a standard in defining the Smart Grid interoperability of the power engineering with end-user applications and loads, with focus on energy technology and ICT. The Smart Grid, as an aggregation of an electricity delivery grid with ICT capabilities, is introduced to be widely applied to monitoring and control of changes from power plants to each customer's appliance [23] [51].

The idea of the Fi-WSN is founded on embedded Fiber Bragg Grating (FBG), based on expensive fiber-optic sensors as measurement tools for measuring temperature, vibration and so on [50] [52]. Introducing the Fi-WSN enables various digital services for monitoring real-time power components and generators as well as appliances in the premises [42].

Upgrading the traditional fiber-optic sensor, by deploying wireless sensor nodes, causes a higher degree of fault tolerance, in addition to making enhancement to the system accuracy and coverage services, which are vital factors for the smart grid communication infrastructure [48].

As mentioned in Chapter 1, our motivation is to propose a reliable, cost effective and bidirectional smart grid communication infrastructure based on the required services, such as energy management and monitoring for the power grid as the main pursued purpose, led us to introduce the Fi-WSN model as a broadband access communication infrastructure for smart grid applications.

For the integration of EPON and WSN networks we provide the high-level network model in Figure 3.4 based on the aforementioned applications in Section 3.2.

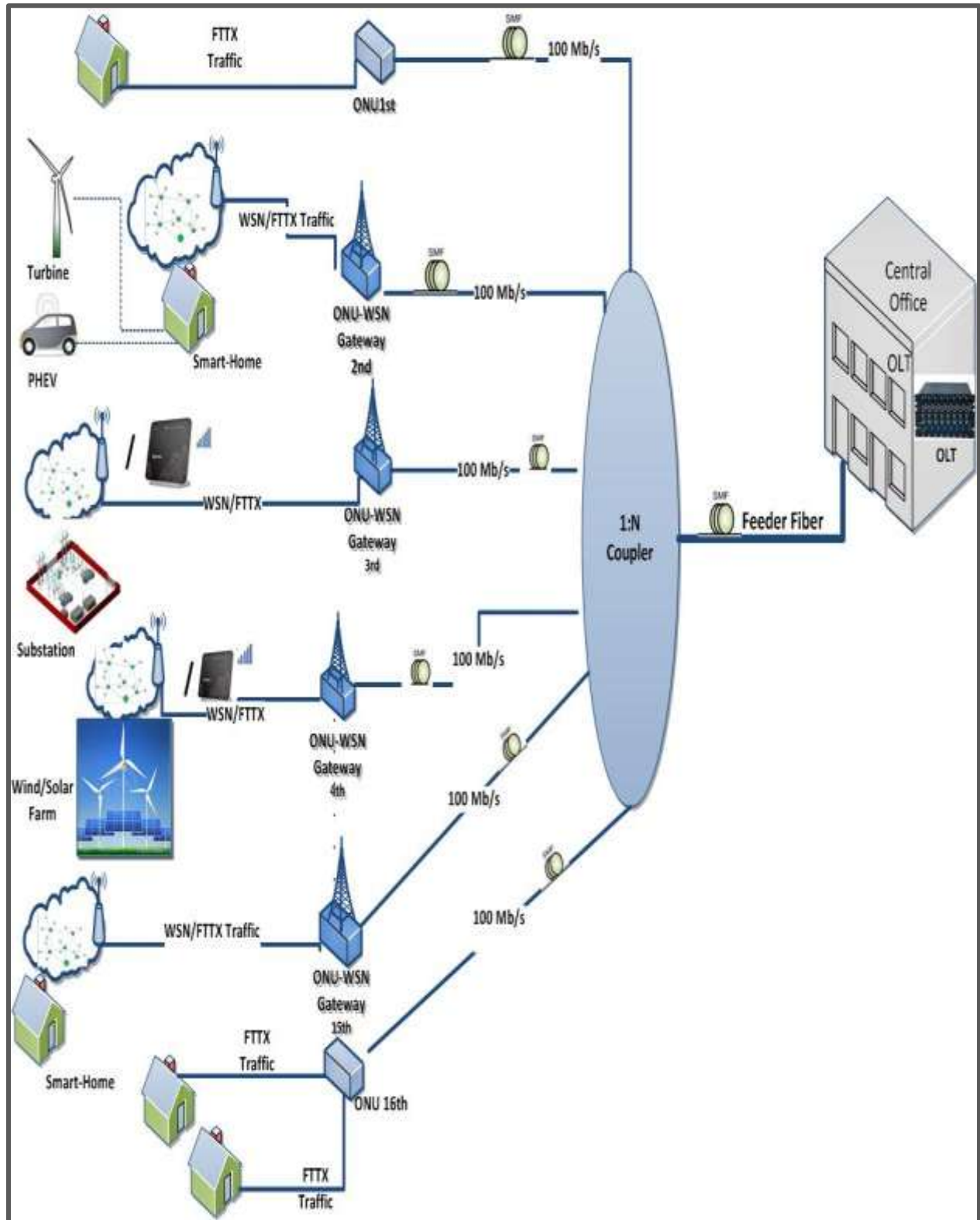


Figure 3.4 Fi-WSN Broadband Access Network System Model

Every energy producer and consumer is connected through this adopted infrastructure which provides real-time interaction to exchange smart grid information services [53].

As seen in Figure 3.4 smart grid data is transmitted to the central office through a broadband access network, which is mainly an EPON. Each distribution fiber connects an ONU to the Central office, and an ONU can be serving either a FTTX user or a group of FiWi users. Here, a FiWi user can denote either a wireless device receiving service via a FiWi network or a smart grid asset which is being monitored and reported to the operator by a WSN. WSNs can assist the smart grid to ensure reliable monitoring and efficient management of power transmission, distribution and utilization at the customer premises.

According to the applied system model, we selected EPON as the optical backhaul access network to support high bandwidth with a robust backhaul infrastructure. We have applied wireless technology as a front-end network to connect the end users, including smart homes, smart substations and wind turbine/solar cell farms, to a broadband access network infrastructure. Therefore, traffic transmitted by the WSN should not disrupt the FTTX traffic, i.e., QoS degradation for FTTH users are not tolerated. On the other hand, WSN data is expected to be delivered to the central office with low delay and low delay variation. As we have discussed in Section 2.4.2, FTTX is not a new technology, as it is older than 30 years and satisfies the increasing service demands with a reasonable cost [54].

Moreover, choosing PON technology rather than Active Optical Network (AON), based on a shared feeder fiber between multiple ONUs (P2MP architecture) to support both WSN and FTTX traffics, is considered as an economical broadband access network solution.

Although the EPON and Wireless MAC protocols are out of the scope of this thesis, we consider the general principles for further understanding of their functionality, especially for the EPON network. Basically, EPON uses the TDM method in downstream broadcasting data from OLT to the ONUs through RN. This method consists of a passive coupler/splitter component that has no power consumption, and selects the related packet for appropriate ONU. EPON applies the Time Division Multiple Access (TDMA) using the multi-point control protocol (MPCP) at the RN as well. The main function of MPCP is the allocation of timeslots, whereby bandwidth allocation can be mapped to the timeslots sequentially. In general, the MPCP protocol is responsible for two types of operation modes, normal and auto discovery. In the normal mode, MPCP assigns transmission time slots to initialized ONUs, while the detection of recently connected ONUs, the MAC address of new ONUs, and calculation of the round-trip delay is done by the auto detection mode. MPCP is defined within the MAC protocol layer to generate five control messages to assign and request bandwidth allocation for termination of Ethernet frames. These messages are GATE, REGISTER_REQUEST, REGISTER and REGISTER_ACK. They are time stamped by local time when they are transmitted by MAC protocol layer, as we illustrate in Figure 3-5. MPCP allows efficient transmission of data between OLTs and ONUs, based on synchronization of ONUs with a timing reference [55].

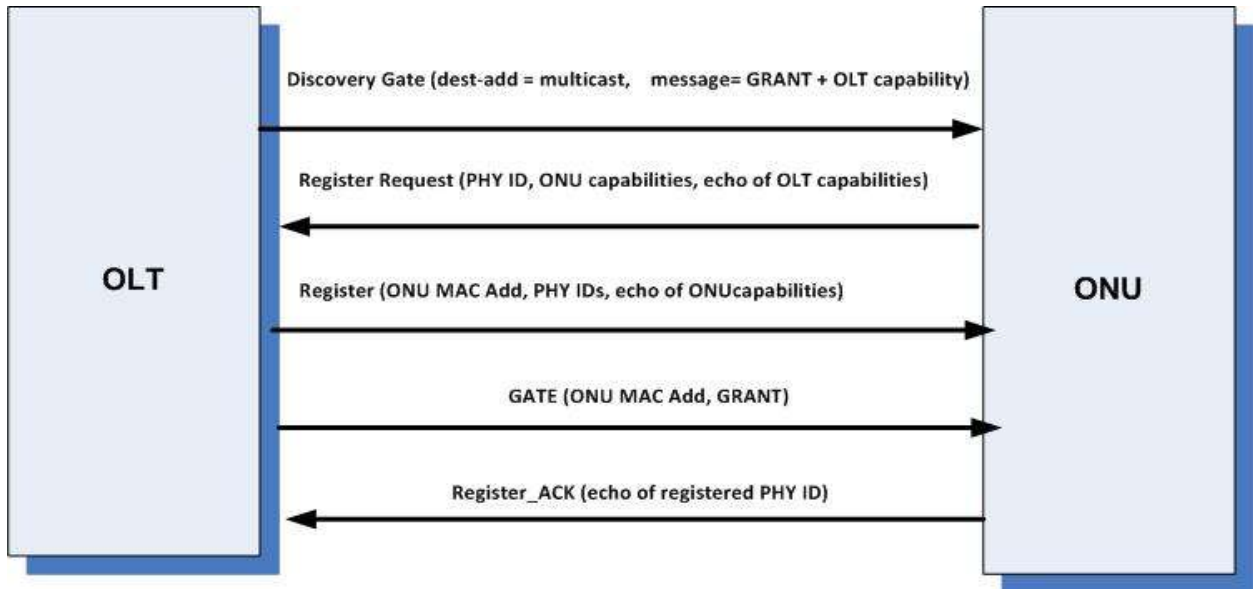


Figure 3.5 MPCP Protocol Discovery Messages

3.3.1 Fi-WSN Gateway Design

We have designed a Fi-WSN gateway for the integrated Fi-WSN network in Figure 3.4. As mentioned in Section 3.2.1, the collected data from embedded sensors is received at the SN (e.g., Wi-Fi Access Point (AP), UMTS antenna, etc.) carrying a priority value (High/Low) in the Smart Grid.

In fact, we have proposed an interface between wireless gateways and ONUs, named the ONU-WSN Gateway. The Fi-WSN Gateway implements the R&F scheme that logically presents a seamless communication infrastructure that integrates EPON and WSN.

Figure 3.6 illustrates an overview of the Fi-WSN gateway. As seen in the figure, packets arriving to the gateway through the Base Station first undergo a classification phase where they are inserted into the priority queues.

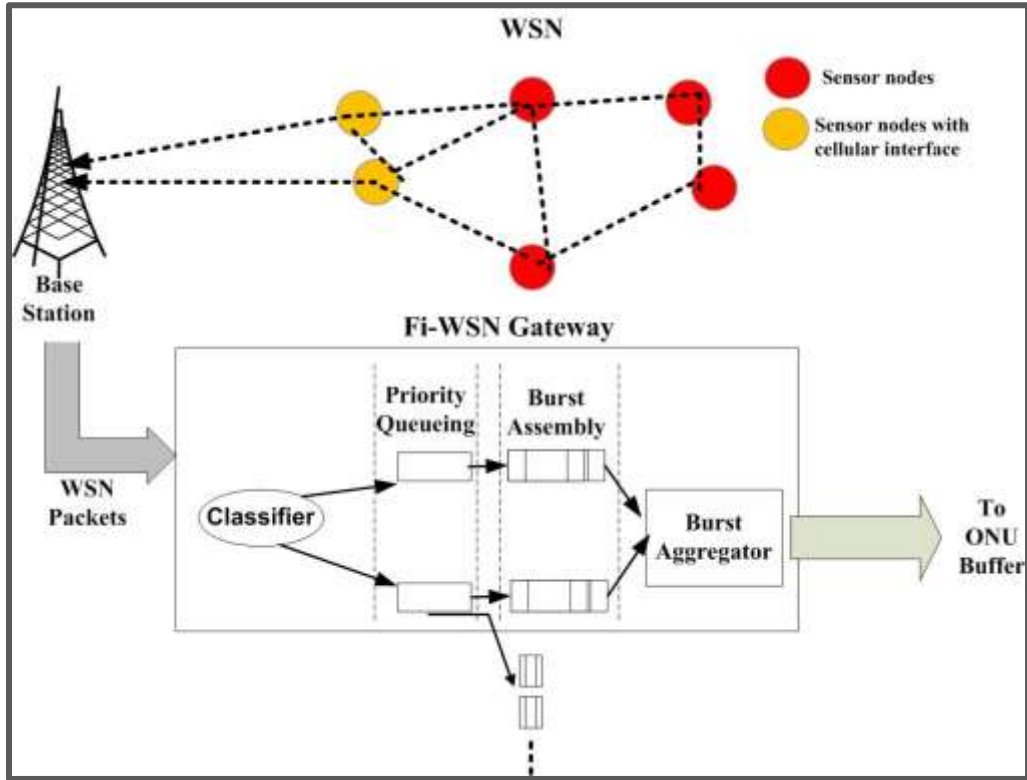


Figure 3.6 illustration of a Fi-WSN Gateway

The burst assembly mechanism forms the bursts, encapsulates them in the Class of Service (CoS) queues which finally undergo a burst aggregation prior to the ONU buffer. The pseudocode in Algorithm 3.1 presents the steps of the burst assembly process in the Fi-WSN gateway.

As seen in the pseudocode, Fi-WSN gateway continuously receives arriving packets through the WSN sink. If the incoming packet carries a high priority message, the gateway aims at forwarding it to the back-end immediately; hence it checks the high priority buffer occupancy. If the high priority buffer has at least one packet, it may be due to either of the following conditions: *i*) High priority buffer is already being dequeued; *ii*) Low priority burst is being assembled. In either case, the incoming packet is inserted into the high priority queue, and it will be dequeued immediately if the high priority dequeuing is in progress.

t_d^l : Departure time of a low-priority packet at its source node
 t_d^h : Departure time of a high-priority packet at its source node
 STH : Size threshold of the low-priority queue
 MP : Monitoring period for the corresponding asset
 B^l : Low priority queue occupancy
 B^h : High priority queue occupancy
 ρ_i : Priority level of packet- i
 $\nu_i(t)$: Validity of packet- i at time- t
 $S_b(t)$: Burst size at time- t
 S_p : Packet size

```

1:  $t$ : Current time
2: while (1) do
3:   Wait for the next arriving WSN packet- $i$ 
4:    $t \leftarrow$  Arrival time of packet
5:   Retrieve  $\rho_i$  and insert the packet into the appropriate
   queue
6:   if (  $\rho_i = \text{HIGH}$  ) then
7:     if ( $B^h=0$  AND  $B^l < STH$ ) then
8:       Send the packet to the ONU buffer
9:     else
10:      High/low priority burst aggregation in progress
11:      Insert packet into the high priority buffer
12:      if (Any low priority packet arrives) then
13:        Insert packet into the low priority queue
14:         $B^l \leftarrow B^l + S_p$ 
15:      end if
16:    end if
17:   else
18:     {//  $\rho = \text{LOW}$ }
19:     if ( $B^l \geq STH$ ) then
20:       Form the low priority burst and send it to the
       ONU buffer
21:        $counter \leftarrow 0$ 
22:       while  $counter < STH$  do
23:         if ( $\nu_i(t) = \text{true}$ ) then
24:            $B^l \leftarrow B^l - STH \cdot S_p$ 
25:         end if
26:         if (Any high priority packet arrives) then
27:           Insert packet into the high priority queue
28:            $B^h \leftarrow B^h + S_p$ 
29:         end if
30:          $counter \leftarrow counter + 1$ 
31:       end while
32:     else
33:       {// Low priority buffer is not full yet}
34:       Insert packet into the low priority queue
35:        $B^l \leftarrow B^l + S_p$ 
36:     end if
37:   end if
38: end while
Algorithm 1: Burst generation at a Fi-WSN Gateway
  
```

Algorithm 3.1 Burst Generation at a Fi-WSN Gateway

Otherwise, the packet will be dequeued at the end of the low-priority burst aggregation period. Since low-priority packets do not carry delay-sensitive data, in order not to disrupt the ongoing FTTX traffic, low-priority packets are buffered until the queue occupancy exceeds the Size Threshold (STH).

Equation 1 formulates the mathematical expression of burst assembly and determination of the burst size. As seen in the equation, as well as in the pseudocode, validity of the low-priority packets is checked prior to assembling them into the burst. Since low-priority packets are buffered for longer time, the data might be outdated.

$$S_b(t) = S(x) = \begin{cases} STh - [\sum_i(1 - v_i(t))] \cdot S_p, & B^l \geq STh \\ B^h \cdot S_p, & B^h \geq 1 \\ 0, & \text{else} \end{cases} \quad (1)$$

In case of an outdated message, the corresponding packet is dropped from the burst assembly queue and the algorithm goes with the next packet in the buffer. Validity of high priority packets is not checked. Thus, a high priority packet is always treated as a packet carrying a valid message. Even though the packet may have spent long time being routed towards the sink in the WSN, the gateway does not perform any validity check on a high priority packet, and leaves its interpretation to the upper layer protocol.

Validity of the packets can be formulated as shown in Equation 2. Thus, if the waiting duration of the packet since its generation exceeds the pre-determined monitoring period, MP , the packet is considered to be invalid (i.e., $v_i(t) = 0$), otherwise, it is marked as valid ($v_i(t) = 1$). Besides, as mentioned above, a high priority packet is always considered to be valid by the gateway.

$$v_i(t) = \left\{ \begin{array}{l} 1 \\ 0 \\ 1 \end{array} \right. \left. \begin{array}{l} t - t_a^l \leq MP \wedge p_i = 'LOW' \\ t - t_a^l > MP \wedge p_i = 'LOW' \\ p_i = 'HIGH' \end{array} \right\}$$

(2)

It is worthwhile to note that the heterogeneity of the front-end network is not only due to the diversity amongst the monitored assets but also due to the protocol suites used by the WSNs. Selection of the protocol suite (e.g., Zigbee, WiFi, etc.) varies with respect to the application. The design presented above can provide a generic gateway implementation for heterogeneous Fi-WSN networks.

3.4 Summary

In this chapter we have investigated WSN as a front-end technology in detail that can be implemented using different wireless protocols such as Wi-Fi, ZigBee etc. The front-end technology can be implemented at the smart homes, smart farms and substations for the purpose of smart metering and controlling operations in smart grid applications. In Section 3.3, we have described in detail our system model based on the Fi-WSN network. In this scenario, the fiber in the EPON backhaul access network infrastructure is considered a main and shared medium for both WSN and FTTX traffic. Finally, we have developed an algorithm for the ONU-WSN gateway interface under the R&F standard.

Chapter 4

Simulation and Performance Results

4.1 Introduction

In this chapter we evaluate the performance of the adopted Fi-WSN architecture under the R&F enabling technology system model presented in Section 3.4. We focus on the simulation environment, which is developed in Microsoft Visual C++.Net 2010. Section 4.2 continues with a description of the simulation settings and assumptions. Section 4.3 presents the simulation results under different parameters, along with their analysis. Finally, Section 4.4 provides a summary for this chapter.

4.2 Simulation Settings and Assumptions

According to the adopted system model, Figure 3.4, we simulate the behavior of sixteen distributed ONU-WSN nodes as the optical backhauls for our adopted FiWi infrastructure. The WSN and FTTX traffic is sent from users through ONU-WSN gateways. It is then sent via a shared fiber with 100Mb/s data rate that is assumed between each ONU-WSN gateway and coupler, out of the possible 1Gb/s data rate of the feeder fiber, with 5km distance, where distance between the OLT and ONU-WSN Gateway is varying between 10km to 20km. First of all, we

develop a simulation model for the WSN, based on the aforementioned GR technique, to collect and route data from embedded sensors to SN.

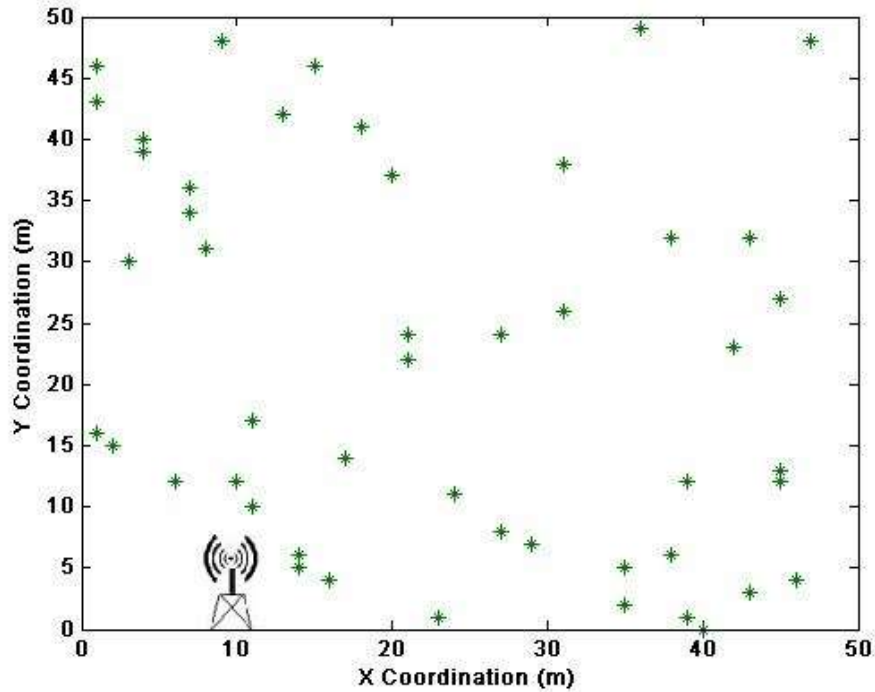


Figure 4.1 WSN Topology with 49 sensors and one SN

The performance of GR is directly related to the distance between the sensor and location of the SN in a distributed region. In addition, the time interval between event generations by each sensor is another property affecting WSN performance, requiring investigation. In this thesis we assume that the routing algorithm is applied in a 50x50m region with 49 sensors and one sink node distributed in it (a total of 50 nodes). We distribute the sensors, as well as the SN, in the mentioned region randomly by assigning a random coordinate for each of them, as shown in Figure 4.1. A distance matrix is needed for holding the distance between all of the distributed nodes and the SN. We can calculate the connectivity matrix using the distance matrix, where the connectivity matrix contains the distance between connected nodes based on the assumed transmission range for sensor nodes.

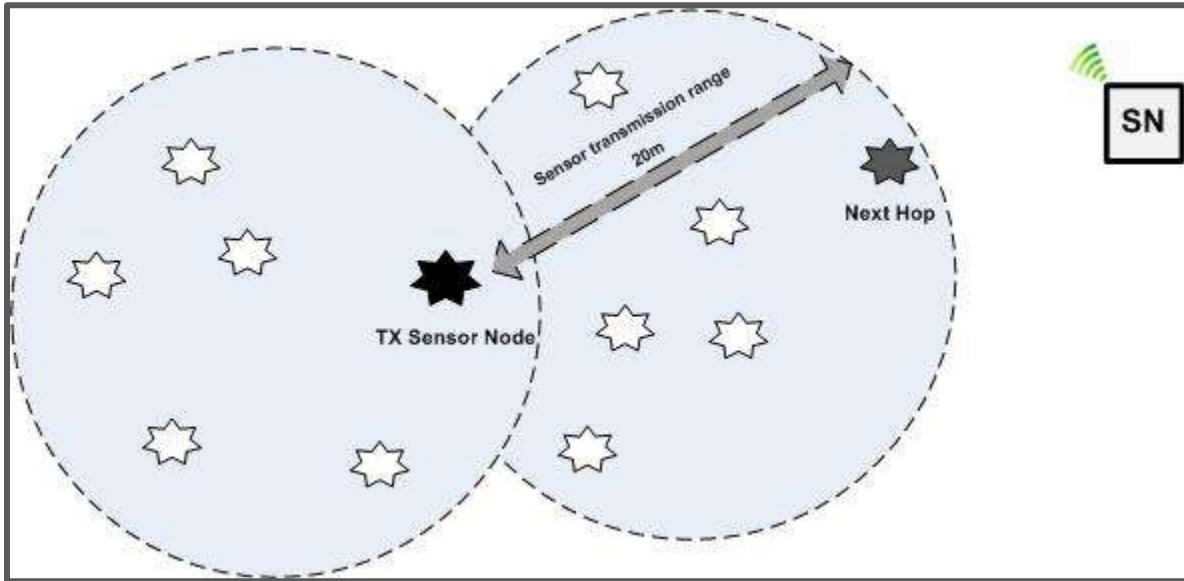


Figure 4.2 Technique for Next Hop Node Selection in WSN

As described in Section 3.4, we do not employ a specific wireless protocol or a specific sensor type for this thesis. We just considered a reasonable coverage range, which is equal to 20m between sensor nodes, for routing and collecting sensor's data in the simulation setting. Moreover, we assumed that WSN packets are generated in fixed 128 bytes-sized packets, based on the Constant Bit Rate (CBR) model with varying bit rates, and we assign another parameter, which is the intermediate node's buffer size with up to 20 packets capacity, as another threshold for each distributed sensor in WSN. Therefore, if an intermediate sensor node receives a packet which is equal to or more than the aforementioned size threshold the last received packet will be dropped at the occupied sensor. Regarding the topology shown in Figure 4.1, the GR technique, Section 3.3.4, is applied for each transmitter sensor node to find the next hop node, as depicted in Figure 4.2.

The simulated system is based on DES method where the main parts of each event are the timestamp (time generation of the packet) as well as its action [56]. As we have discussed in Section 3.3 about differentiating traffic, our implementation of this feature is to subdivide the

generated packets into high and low priority, where 10% of the packets are generated as high priority packets, while 90% are assigned as low priority packets.

EPON simulation has been carried out based on the use of Discrete Event Simulation Library (DESL) under the Microsoft Visual C++.NET 2003 [57]. Due to the EPON simulation settings, traffic generation from FTTX users is characterized by self-similar modeling with $H=0.8$ [58], and is based on different load levels from 0.1 to 0.9 Erlang, where it is assumed that the EPON system can support limited services of up to 10^6 FTTX packets [59]. In addition, the ONU has a finite total buffer size, 1Mbyte for threshold adjustments.

The time interval of event generation for WSN nodes is one of the main factors that have a direct impact on the network performance. Accordingly, we run the simulation under different inter-arrival times including 500, 750, 1000ms which are selected empirically for each sensor node. For example, 500ms as the inter-arrival time means that every 500ms all of the distributed sensors generate an event to send in WSN. Furthermore, we assume that the duration runtime of the WSN simulation is set to 50 seconds (50000ms).

Finally, we have developed an ONU-WSN gateway interface in Microsoft Visual C++.NET 2010, where 0.1Mbytes of the total ONU queue size (1Mbytes) is assumed to be the buffer size for WSN demands. However, if this capacity is not utilized by the WSN traffic, the FTTX makes use of this parameter. Basically, we allocate two priority queues with different sizes for each ONU-WSN gateway with a ratio of 90% to 10% for low and high priority packets respectively. Therefore, the threshold to issue a burst command at the ONU-WSN Gateway is set to be 720 low priority WSN Packets. The low priority buffer threshold is calculated with the fixed WSN packet size (128 bytes for each WSN packet) and the total assigned buffer size for the ONU-

WSN gateway (0.1 Mbytes), while we allocate the buffer size for high priority WSN packets at ONU-WSN gateway of up to 80 packets as the threshold. In addition, we consider the adopted Fi-WSN network infrastructure with different parameters, where we assume that the low priority buffer capacity decreases to 640 packets for burst threshold, to investigate the network performance factors under different scenarios. In Appendix A we have provided more graphs of the applied Fi-WSN network under other simulation scenarios where we assumed 70% of the WSN generated packets have low priority, while the rest (30%) are generated with high priority.

Each result in the figures represents the average of ten runs with 95% Confidence Intervals (CI) and we present the error-bars in the plots accordingly. We describe the general applied method for CI calculations in detail in Appendix B.

4.3 Performance Results

In this section, we present simulation results based on the aforementioned settings in Section 4.1 with the GR protocol collecting data from sensors for various mentioned applications (smart homes, smart farms and substations) and receiving them at the OLT in the CO for processing.

In the simulations, average End-to-End (E2E) delay, maximum delay (MAX-DLY) and Packet Loss Ratio (PLR) are the key performance metrics to evaluate the Fi-WSN gateway design. Note that for a WSN packet, E2E delay is the sum of the routing delay in the WSN (d_{route}^{WSN}) buffering delay at the sink node (d_{queue}^{sink}), queuing delay at the ONU (d_{queue}^{ONU}), and the polling and granting delays (d_{poll}^{OLT} , d_{grant}^{OLT}) introduced by the OLT as formulated in Equation 3.

$$d_i^{E2E} = \left\{ \begin{array}{l} d_{route}^{WSN} + d_{queue}^{sink} + d_{queue}^{ONU} + d_{poll}^{OLT} + d_{grant}^{OLT} \quad \text{WSN} \\ d_{queue}^{ONU} + d_{poll}^{OLT} + d_{grant}^{OLT} \quad \text{FTTX} \end{array} \right\}$$

(3)

We start the investigation of the adopted network infrastructure with different inter-arrival times including 1000, 750 and 500ms for WSN packets, where the sink buffer size threshold is set to be 720 packets for bursting the low priority queued packets.

Figure 4.3 shows that adding WSN packets to the FTTX traffic via the shared fiber does not have an effect on the E2E delay for FTTX packets by increasing the load of the hybrid network. While the E2E delay rises for the high priority packets significantly when increasing the target load of the network, especially when this parameter is equal or more than 0.4 as the total network load. In fact, this behavior is expected due to increasing FTTX load level in the integrated network.

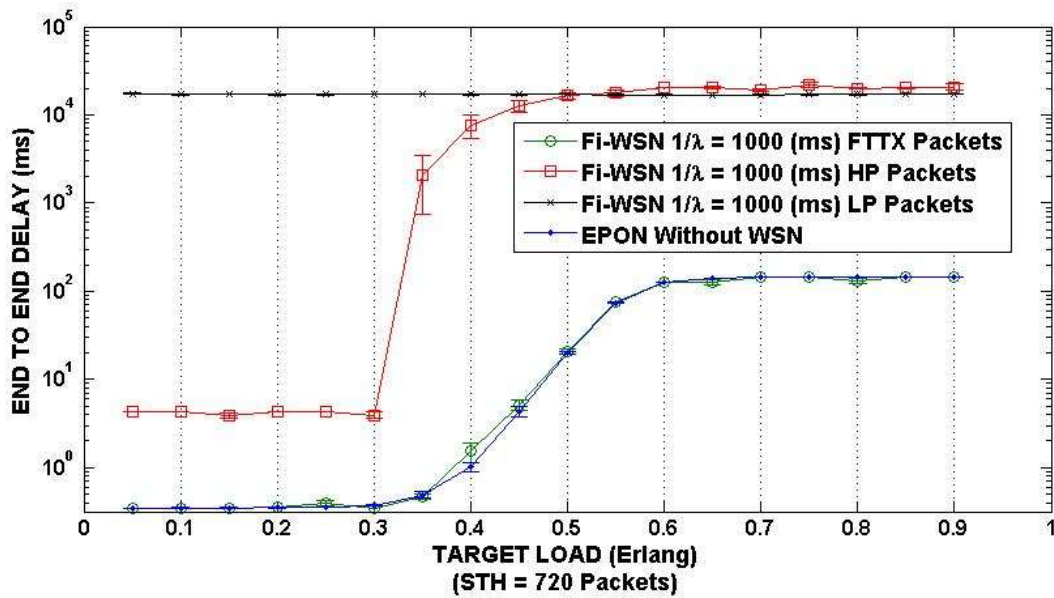


Figure 4.3 Average End to End delay vs. Target Load

However, we can see decreasing delay for the high priority packets when decreasing the inter-arrival time for the WSN packets, as we show in Figure 4.4, while the average delay for high priority packets is close to the low priority packet delay.

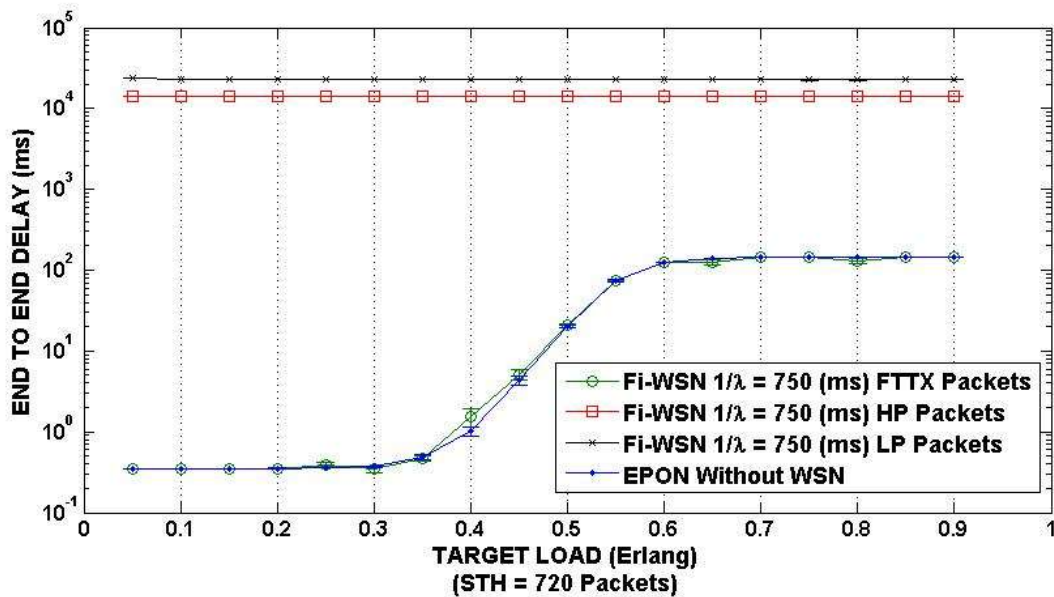


Figure 4.4 End to End Delay vs. Target Load

The reason of this phenomenon is that high priority packets do not undergo a buffer threshold-based burst assembly. Hence, the more the high priority packets at the sink, the better the chance to utilize the reserved buffer capacity at the ONU buffer.

As we expect, Figure 4.5 depicts better results in terms of decreasing average delay for the high priority packets when the packet inter-arrival time is reduced to 500ms, by providing more burst operation at the SN.

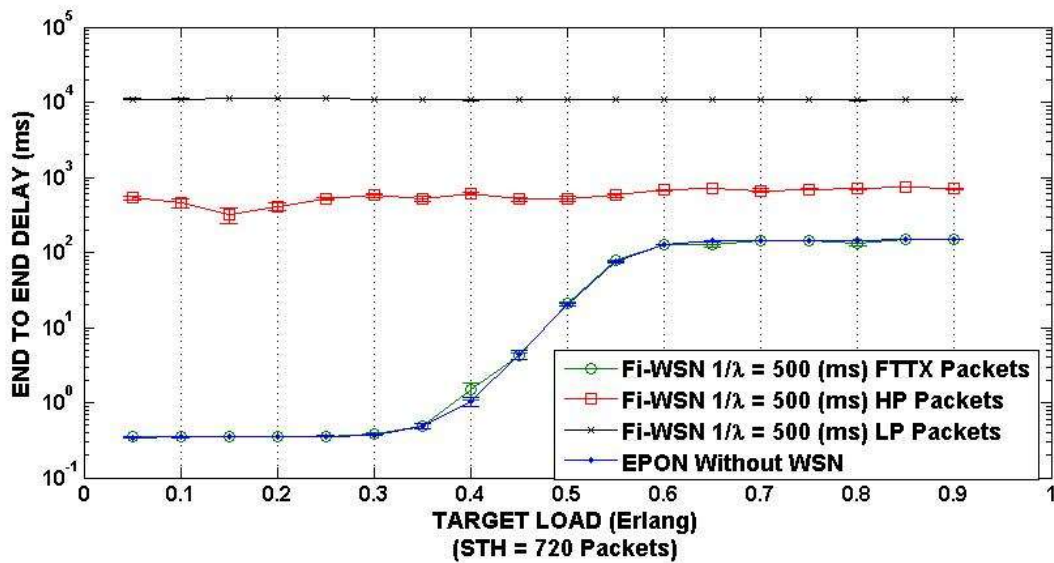


Figure 4.5 End to End Delay vs. Target Load

In Figure 4.6, we can see an improvement on the average E2E delay for high priority packets by reducing the STH parameter at the sink node from 720 to 640, when the inter-arrival time is 1000ms, particularly after increasing the load of network by 50%. Furthermore, the reduction of the SN buffer size to 640 provided a decrease of the mean E2E delay for low priority packets in comparison to Figure 4.3 and Figure 4.4, when the inter-arrival time for the WSN packets has considered 1000ms and 750ms respectively. The reason for this behavior is that greater STH

value leads to larger bursts of low priority packets. Therefore, longer buffering times are experienced by the high priority packets both at sink and at the ONU.

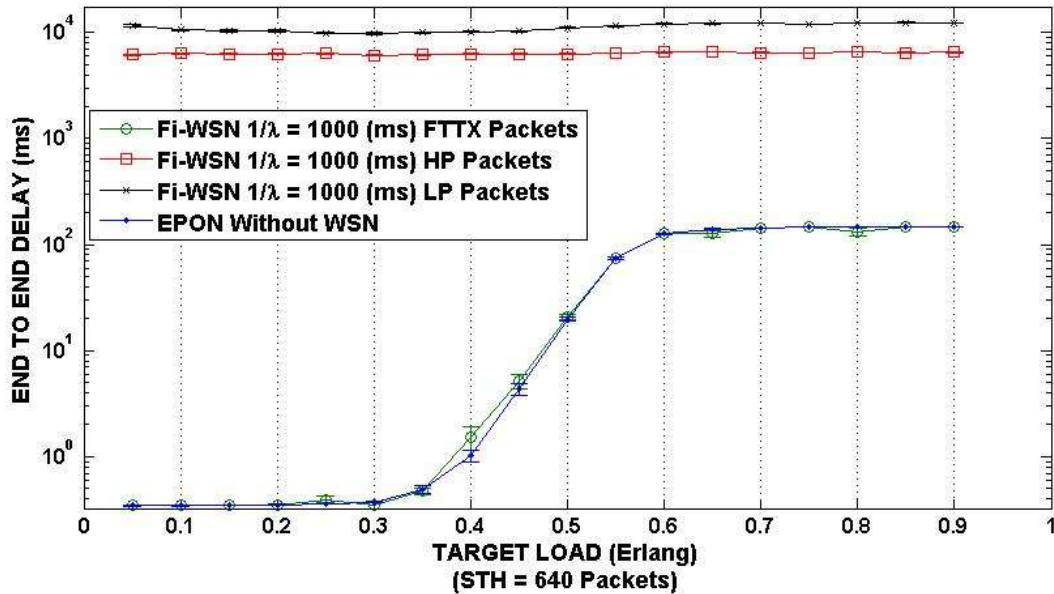


Figure 4.6 End to End Delay vs. Target Load

By decreasing the STH to 640 WSN packets, we can see a more smooth result with an impressive reduction for the mean E2E delay for high priority packets. In Figure 4.7 and Figure 4.8, by using fewer intervals for packets inter-arrival times at 750ms and 500ms, the SN is faced with more burst operation frequency at the ONU for WSN packets. Hence, average E2E delay for high priority packet approaches to that of the FTTX packets.

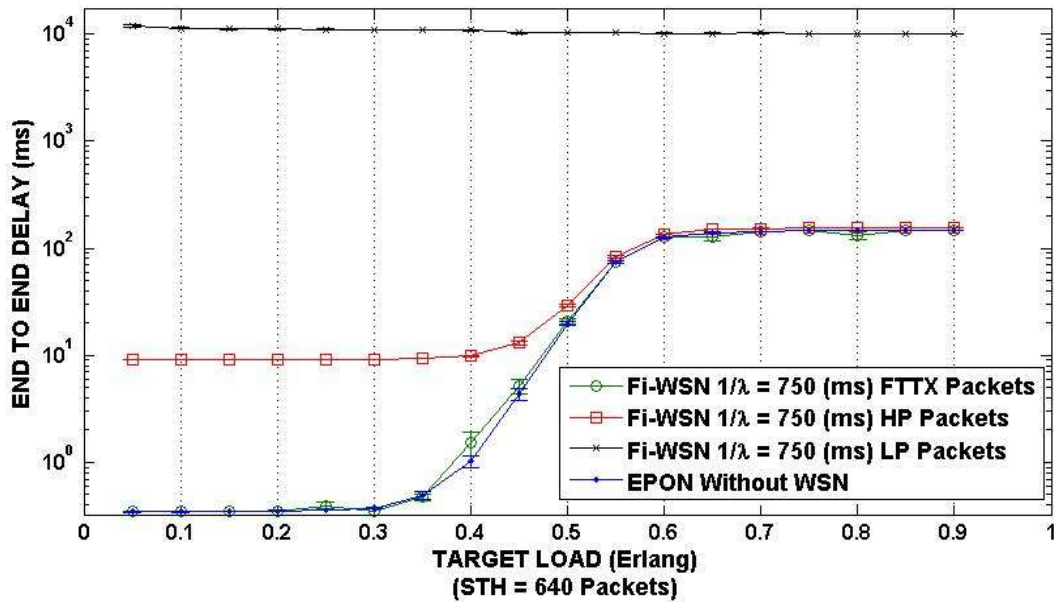


Figure 4.7 End to End Delay vs. Target Load

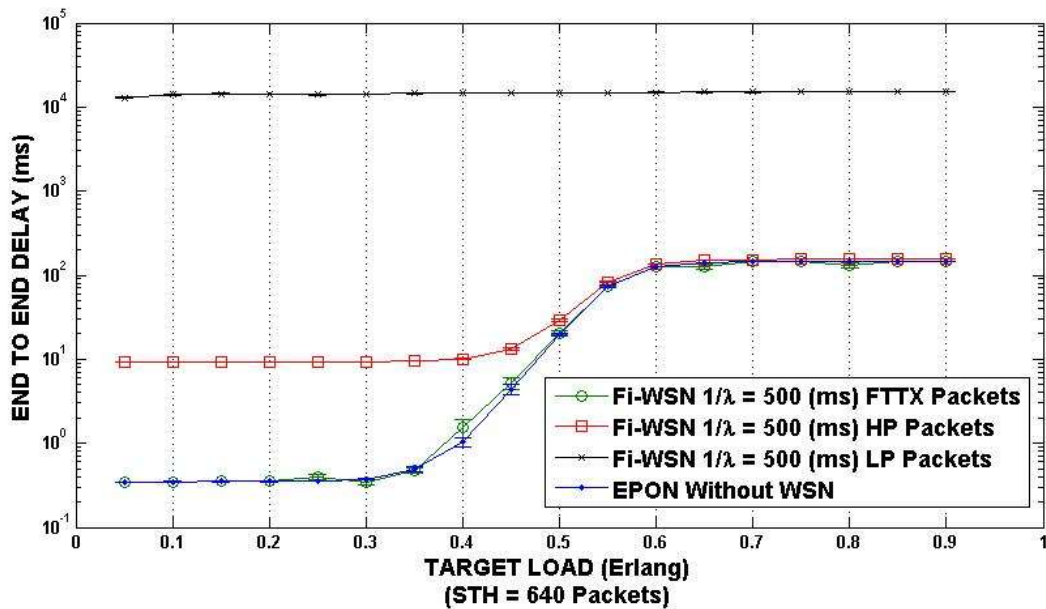


Figure 4.8 End to End Delay vs. Target Load

Figure 4.9 and Figure 4.10 show the measured E2E delay for FTTX packets, which has almost the same behavior in the integrated network compared to when we did not inject the WSN traffic, as well as when fixed under different aforementioned parameters, such as STH and the

inter-arrival times for packets. However, the mean E2E delay for high priority packets with less inter-arrival times (750ms and 1000ms), based on the smallest STH parameter (560 packets) is higher than FTTX packets, while we can still see that the average delay for the high priority packets is less than the measured E2E delay for low priority packets.

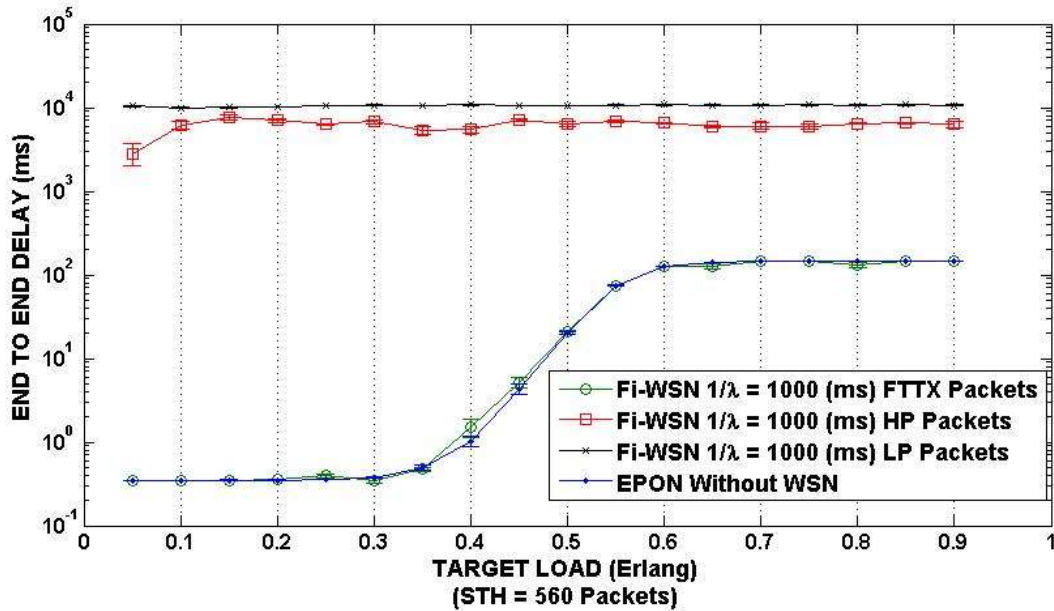


Figure 4.9 End to End Delay vs. Target Load

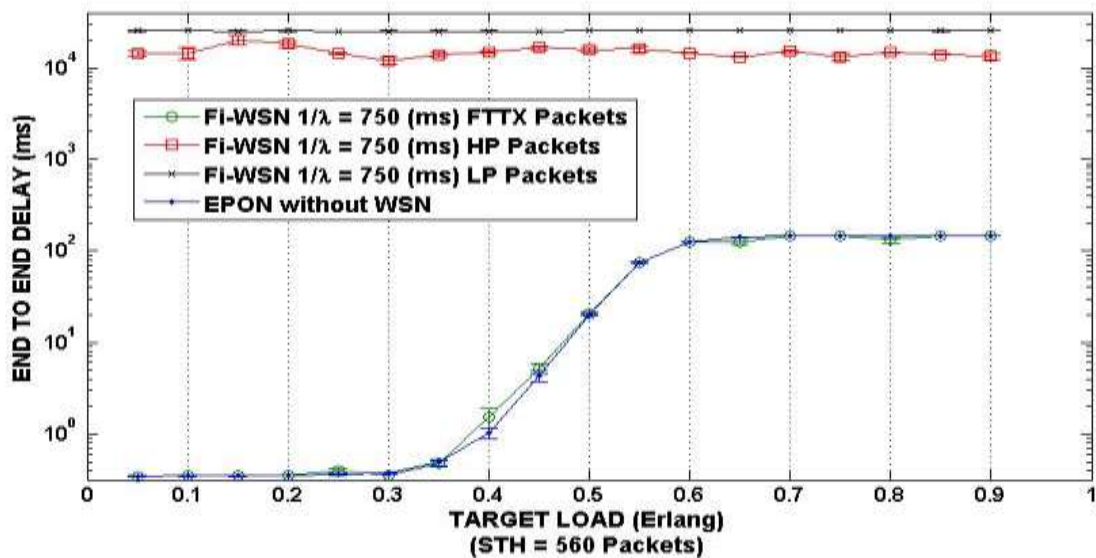


Figure 4.10 End to End Delay vs. Target Load

As expected, Figure 4.11 shows that the delivery of the high priority packets can be handled even quicker by increasing the inter-arrival times for packets at every half second, when we have decreased the buffer size threshold to 560 packets at the SN.

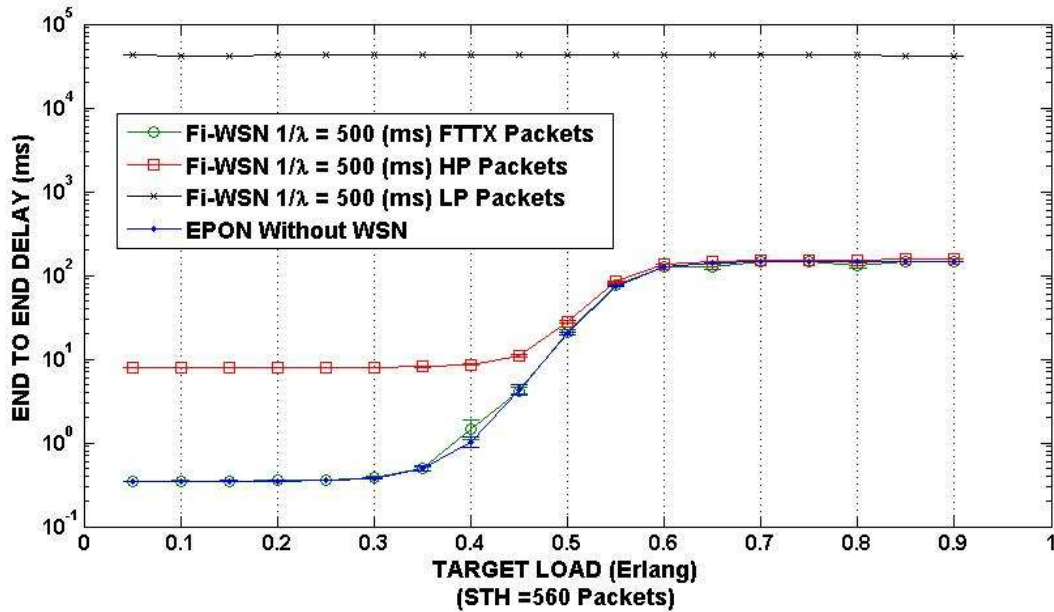


Figure 4.11 End to End Delay vs. Target Load

Therefore, the simulation results show that the mean measured delay for high priority packets can have a better behavior. This performance factor for high priority packets is getting very close to the average delay for FTTX packets in higher network loads by decreasing the STH parameter at the SN and increasing the inter-arrival time value for the packets.

Considering the integrated network the average E2E delay based on different inter-arrival times, we set the STH parameter to 640 packets at the SN. Figure 4.12 shows that the measured mean delay for the high priority packets have the same values at 750ms and 500ms as the inter-arrival time parameter, while we can see significant increase in the mean delay for high priority packets by decreasing the inter-arrival times of packets at each second.

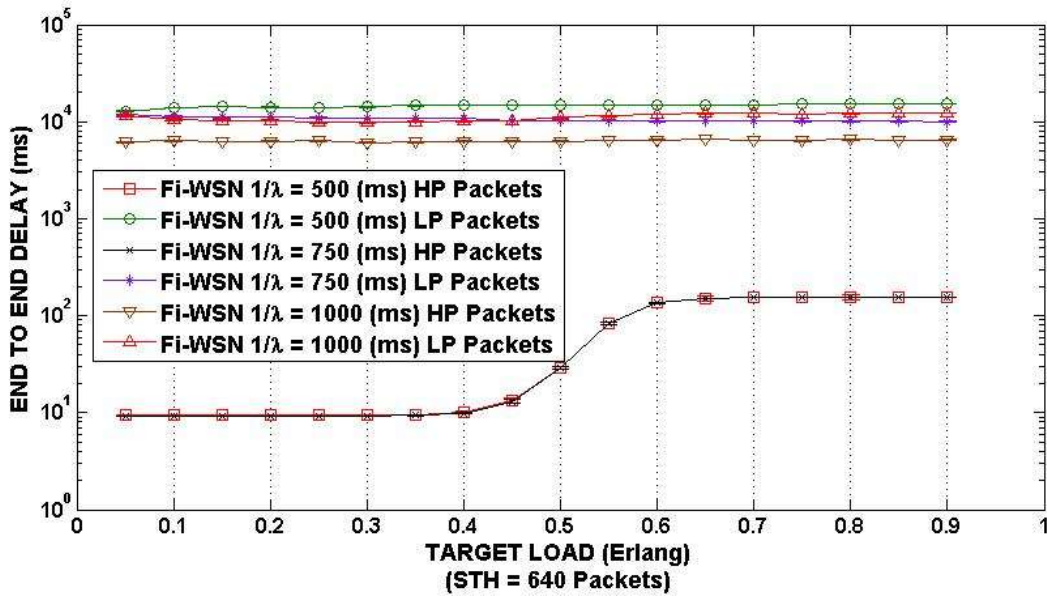


Figure 4.12 End To End Delay vs. Target Load

As we have explained earlier, the E2E delay increases for the high priority packets by increasing the inter-arrival times that leads decreasing the number of generated WSN packets totally. Consequently, the packet bursting aggregation decreases at the ONU-WSN gateway. It is certainly true that the E2E delay increases for the low priority packets by increasing the number of WSN packets at the SN in the integrated network. The main reason for this phenomenon is that low priority packets experience higher delay in comparison to the high priority packets. Although, as we can see in Figure 4.12, the E2E delay is not changed significantly for low priority packets, compared to the significant decreasing the E2E delay for the high priority packets.

The performance measurements in Figures 4.13, 4.14 and 4.15 show that adding WSN traffic in terms of a hybrid network does not disrupt the MAX-DLY for FTTX traffic with the varying inter-arrival times (500ms, 750ms and 1000ms). All aforementioned behaviors for the E2E delay performance factor, under the different considered parameters, are the same for the maximum

delay factor as well. Furthermore, Glen Kramer in [57] has shown the same behavior for EPON traffics in absence of the WSN packets.

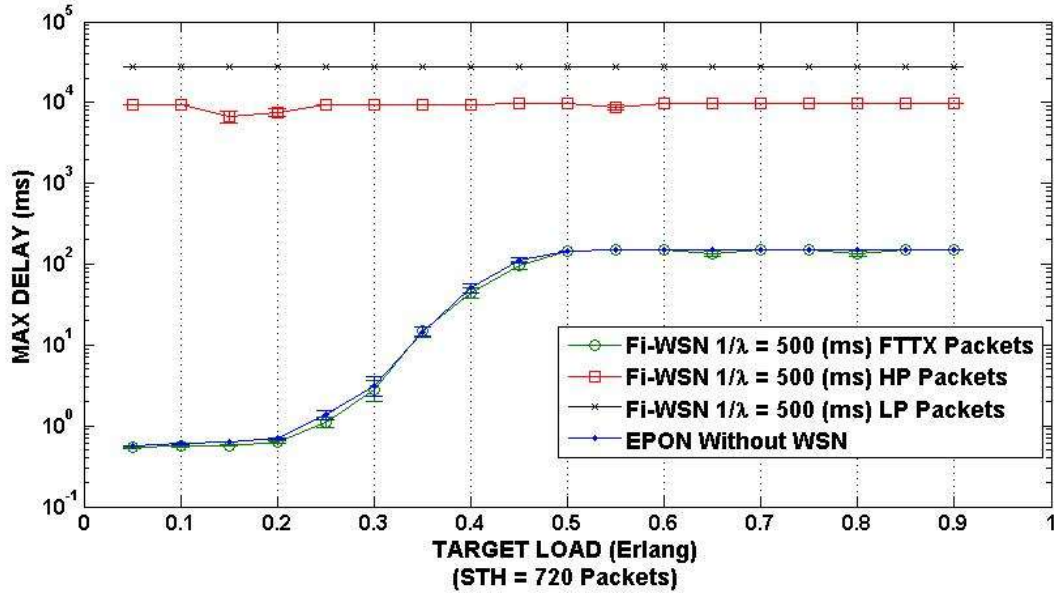


Figure 4.13 Maximum Delay vs. Target Load

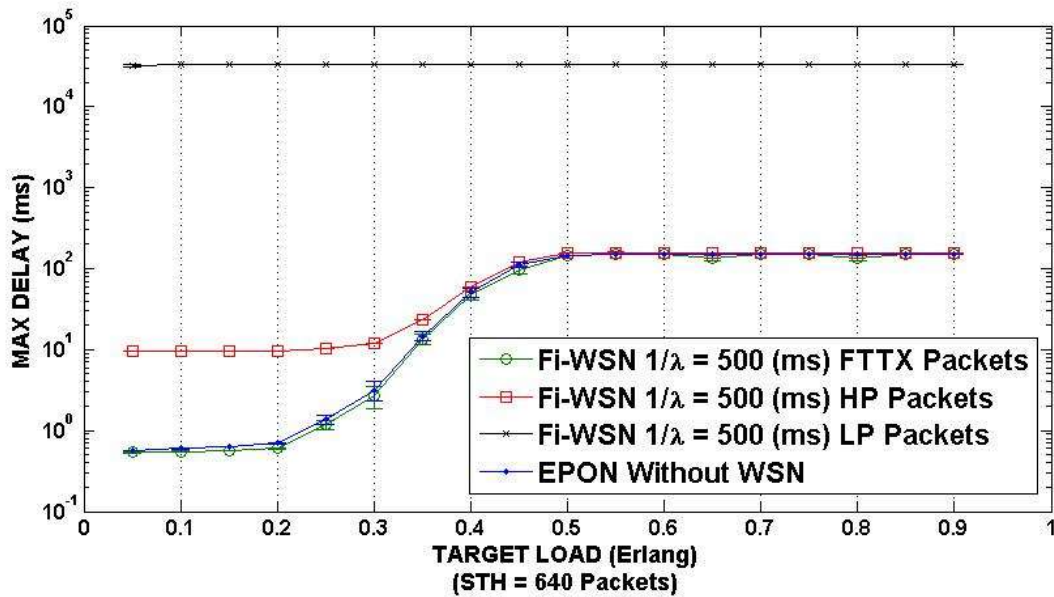


Figure 4.14 Maximum Delay vs. Target Load

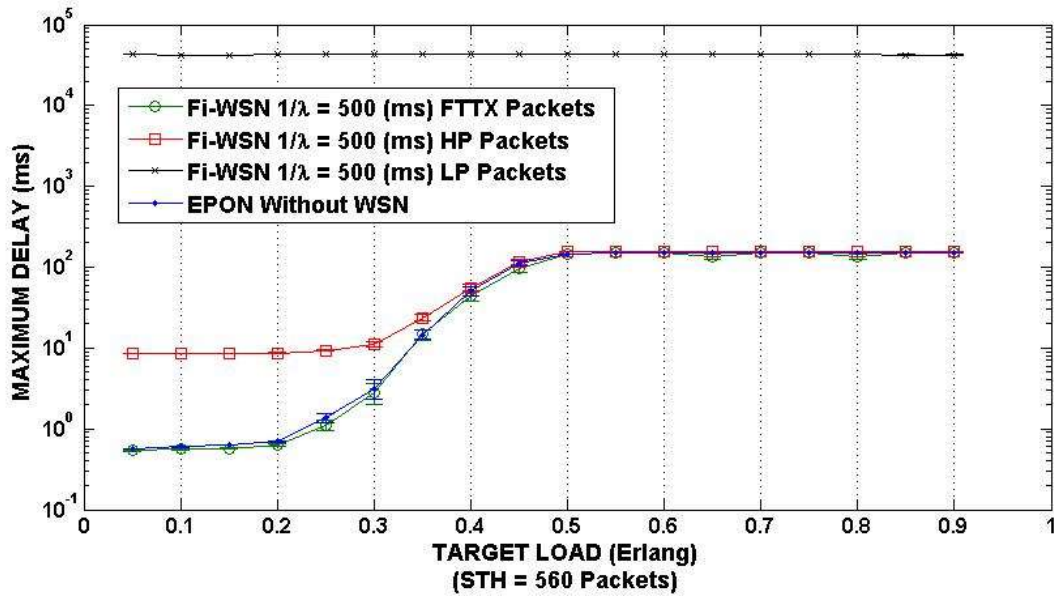


Figure 4.15 Maximum Delay vs. Target Load

To provide a comparison with the existing literature, we refer to the study in [33] where the authors have investigated EPON and WiMAX integration. The underlying communication technologies used in that paper are different than our work. Therefore, it is not straightforward to compare the outputs of simulations while the trends in E2E delay provide insights for the behavior of our proposed scheme. Similar to [33], there are three regions in our simulation results. These regions include light, medium and high traffic loads. The range of light, medium and high traffic load are 0-0.3, 0.3-0.8, and 0.8-1 Erlang respectively. The E2E delay increases slowly in the light traffic region. It increases significantly in the medium region. Finally, it exhibits very slow increment in the high traffic region. However, our delay values are higher than [33] since we consider the WSN integration which incurs additional delay in the overall E2E delay measurements.

Figure 4.16 shows the impact of the Fi-WSN gateway design on the packet loss probability due to contention at the ONU. In fact, various STH are tested with the inter-arrival time of 0.5s.

Simulation results confirm that the Fi-WSN gateway design scheme does not increase the packets loss probability in the presence of the WSN traffic. Moreover, STH does not have a significant impact on the PLR.

The main reason for this phenomenon is that the FTTX and WSN packets share the same buffer in the back-end, and even though a portion of the ONU buffer which is reserved for the WSN traffic, it can still be utilized by the FTTX packets when it cannot fully be utilized by the WSN packets.

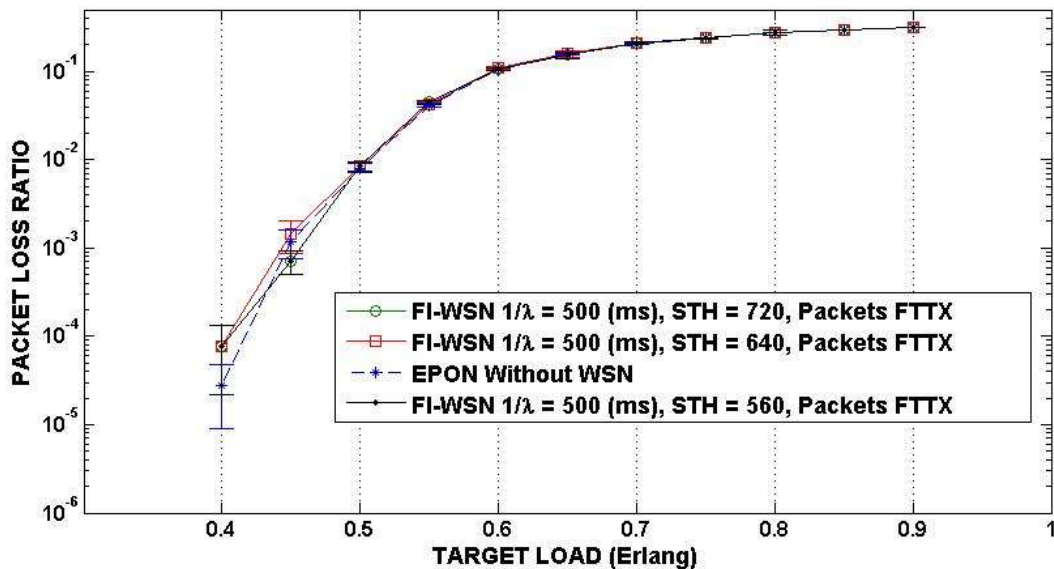


Figure 4.16 Packet Loss Ratio vs. Target Load

In addition, the measured values for WSN packets, whether the WSN packets have a high or low priority, have the same behaviors for the FTTX traffic as Glen Kramer has simulated in [57] for EPON traffics without WSN packets.

Generally, by selecting a suitable threshold for priority queues at the SN, the average delay does not increase for FTTX traffic in presence of WSN packets. Moreover, we have observed that injecting the WSN packets do not degrade the QoS levels for FTTX users. As we have stated in Section 4.2, we present more simulation results under different percentages for high and low priority packets, 30% and 70% respectively, based on different values within the aforementioned parameters in Appendix A.

4.4 Summary

In this chapter we have presented simulation settings and assumptions for the performance evaluation of the adopted broadband access network architecture under the proposed Fi-WSN Gateway. We have considered various parameters as well as different related values for each parameter. Finally, we have analyzed the simulation results and we have identified the most suitable values of the WSN packet inter-arrival times and the STH for the low-priority packets.

Chapter 5

Conclusion and Future Work

5.1 Concluding Remarks

This thesis has focused on the communication system for the smart grid application by adopting a two-way, secure, fast and flexible communication infrastructure with ICT capabilities. For this purpose, we have first considered the conventional power grid structure and explored the potential importance of introducing the smart grid technology, in order to decrease GHG emissions and provide energy efficient power consumption through the use of smart metering and effective energy management systems. We have found that the smart distribution monitoring infrastructure is an essential tool for optimizing the power grid, profile shaping for peak-time demand reduction, and achieving reliability of the power grid. According to the aforementioned features for the power grid, we have reviewed enabling wireless and optical access network technologies and their advantages and weaknesses as separate communication network infrastructures for the smart grid applications. To exploit the strength of each of the wireless and optical network technology, we have investigated the FiWi network. Considering all the factors we have discussed, one is drawn to conclude that the FiWi network provides significant promises for the communication infrastructure in the smart grid application.

We have discussed FiWi enabling technologies including RoF and R&F schemes and the differences between carrying out a wireless signal via an analog fiber link compared to optical-wireless networking. Hence, we adopted the Fi-WSN architecture with EPON as the backhaul access network integrated to the front-end wireless access network based on the R&F approach on top of it, aimed to provide an integrated broadband access network. Indeed, we have proposed the Fi-WSN Gateway interface for applying EPON technology as the shared medium for both smart metering and FTTX traffic, besides using the wireless access network as a low cost implementation technology at the premises. In addition, we discussed the advantages and challenges, as well as summarized the state of the art, for FiWi network architectures from recent publications.

Next, we have classified the premises by smart homes, smart farms and substations, as different services at the application level, based on the utilization and energy generation rate of the appliances and generators. Then we adopted the GR mechanism to collect data from embedded sensors in smart appliances, power generators and critical equipment in the smart grid.

The main focus of this thesis was to introduce the Fi-WSN Gateway interface based on the interconnection of the WSN gateway or wireless routers to ONUs. In fact, we have considered Fi-WSN to provide interconnection between end users, the power consumers and utilities, in both directions through the secure and fast smart grid communication network.

Finally, we have provided a simulation environment and assigned the settings and assumptions for performance analysis of the applied Fi-WSN gateway interface. The simulation environment covered the entire adopted broadband access network, based on the average E2E delay, MAX-DLY and PLR network performance factors. Our simulation results, based on varying parameters

for STH and packet inter-arrival times, have shown that decreasing the time interval between packet arrivals at the ONU-WSN gateway improves the E2E delay for high priority packets. We observed the best behavior for this parameter in half-second time intervals and with the decrease of the STH to 560 packets. As we have stated in Chapter 4, the reason for this behavior is that with smaller SN buffer size threshold and larger packet inter-arrival times in the integrated network, the number of times burst generation happens increases at the SN.

We have observed an increase in the E2E delay with the increase of the packet inter-arrival times versus the increase of the network load for the low priority packets. However, the measured performance degradation was not significant compared to the impressive decrease in the E2E delay for high priority packets.

According to the simulation results, the overall conclusion is that selecting a suitable threshold for the priority queues at the sink node introduces low-delay for high priority messages and does not disrupt the FTTX user traffic. Furthermore, the Fi-WSN gateway scheme maintains the desired QoS levels for FTTX users without compromising the reliability of the WSN.

5.2 Future Research Work

FiWi networks are a promising solution for future broadband access networks. Their combination of wider bandwidth in the optical network and mobility and flexibility of wireless technology has been actively studied.

Despite the recent advancements at the FiWi physical layer, we still witness layer 2 related issues such as inefficient path selection protocols and algorithms for this new integrated technology

[19]. It is essential to consider the layer 2 FiWi networking from a QoS standpoint including resource management, class mapping and scheduling [19].

The design of energy efficient network infrastructures is of interest to providers for the future of green network technologies [34]. For this purpose, an energy efficient hybrid MAC protocol should be defined as a point of future work. In fact, it is important to focus on the Green Broadband Access Network Technology (GBANT) to provide energy efficient solutions for this type of integrated telecommunication network.

An interesting topic to be developed in the future is to consider the RoF technology for this form of broadband hybrid networks. In fact, it is important to define some suitable solutions to enhance QoS issues. For instance, the major limitation of the WLAN-based RoF technology is that the CO becomes a bottleneck for data processing and that degrades the reliability aspect. Furthermore, the additional propagation delays caused by distributed MAC protocols limit the optical fiber range and also degrade the integrated network performance.

Bibliography

- [1] M. Erol-Kantarci and H. T. Mouftah, "Wireless multimedia sensor and actor networks for the next generation power grid", ELSEVIER Journal of Ad Hoc Networks, vol. 9, no. 4, June 2011, pp. 542-551.
- [2] M. Maier, "Fiber-wireless sensor networks (Fi-WSNs) for smart grids", in Proceedings IEEE International Conference on Transparent Optical Networks (ICTON), Stockholm, Sweden, June 2011, pp.1-4.
- [3] B. Kantarci and H. T. Mouftah, "Energy efficiency in the extended-reach fiber-wireless access networks," IEEE Network, vol. 26, no. 2 , March-April 2012, pp. 28 - 35.
- [4] M. Erol-Kantarci and H. T. Mouftah, "Wireless Sensor Networks for Cost-Efficient Residential Energy Management in the Smart Grid," IEEE Transactions on Smart Grid, vol. 2, no. 2, June 2011, pp. 314-325.
- [5] V. Gungor, B. Lu and G. Hancke, "Opportunities and Challenges of Wireless Sensor Networks in Smart Grid", IEEE Transactions on Industrial Electronics, vol. 57, no. 10, 2010, pp. 3557 - 3564.
- [6] "EPON-OLT Configuration," H3C Technologies Co., Limite, [Online]. Available: <http://www.h3c.com>. [Accessed 25 09 2012].
- [7] B. L. S. P. Bratley, A guide to Simulation: Springer-Verlag, New York, 1987.
- [8] M. Hashmi, S. Hanninen and K. Maki, "Survey of smart grid concepts, architectures, and technological demonstrations worldwide", in Proceedings IEEE PES Conference on Innovative Smart Grid Technologies (ISGT Latin Americas), October 2011, pp. 1-7.
- [9] X. Fang, S. Misra, G. Xue and D. Yang, "Smart Grid — The New and Improved Power Grid: A Survey", IEEE Communications Surveys & Tutorials, vol. PP, no. 99, 2011, pp. 1-37.
- [10] Y. Yan, Y. Qian and H. Sharif, "A secure and reliable in-network collaborative communication scheme for advanced metering infrastructure in smart grid", in Proceedings IEEE Wireless Communications and Networking Conference (WCNC), Cancun, Mexico, March, 2011, pp. 909-914.
- [11] B. Kantarci, N. Naas and H. T. Mouftah, "Energy-efficient DBA and QoS in FiWi networks constrained to metro-access convergence," in Proceedings IEEE International Conference on Transparent Optical Networks (ICTON), Coventry, England, July 2012, pp.1-4.

- [12] B. Xiao-min, M. Jun-xia and Z. Ning-hui, "Functional analysis of advanced metering infrastructure in smart grid", in Proceedings IEEE International Conference on Power System Technology (POWERCON), Hangzhou, China, October 2010, pp. 1-4.
- [13] A. Singhal and R. Saxena, "Software models for Smart Grid," in Proceedings IEEE International Workshop on Software Engineering for the Smart Grid (SE4SG), Zurich, Germany, March 2012, pp. 42-45.
- [14] H. Y. Tung, K. F. Tsang and K. L. Lam, "ZigBee sensor network for Advanced Metering infrastructure", in Proceedings IEEE International Conference on Consumer Electronics (ICCE), Hong Kong, South Korea, January 2010, pp. 95-96.
- [15] S. Mak, "Smart meters serving as synchro-sensors for Smart Distribution Grid applications", in Proceedings IEEE Power and Energy Society General Meeting, Detroit, USA, July 2011, pp.1-3.
- [16] N. Ghazisaidi and M. Maier, "Fiber-wireless (FiWi) access networks: Challenges and opportunities", IEEE Network, vol. 25, no. 1, January-February 2011, pp. 36 - 42.
- [17] Y. Liu, C. Zhou and Y. Cheng, "Integrated BS/ONU Placement in Hybrid EPON-WiMAX Access Networks", in Proceedings Global Telecommunication Conference (GLOBECOM), Honolulu, USA, November-December 2009 , pp. 1-6.
- [18] N. Ghazisaidi, M. Maier and C. Assi, "Fiber-wireless (FiWi) access networks: A survey", IEEE Communications Magazine, vol. 47, no. 2, February 2009, pp. 160 - 167.
- [19] M. Maier and N. Ghazisaidi, "QoS-Aware Radio-and-Fiber (R&F) Access-Metro Networks", in Proceedings Wireless Communications and Networking Conference Workshops (WCNCW), Sydney, Australia, April 2010, pp. 1-6.
- [20] Y. Li, J. Wang, C. Qiao, A. Gumaste, Y. Xu and Y. Xu, "Integrated Fiber-Wireless (FiWi) Access Networks Supporting Inter-ONU Communications", IEEE Journal of Lightwave Technology, vol. 28, no. 5, March 2010, pp. 714-724.
- [21] V. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati and G. Hancke, "Smart Grid Technologies: Communication Technologies and Standards", IEEE Journal of Industrial Informatics, vol. 7, no. 4, November 2011, pp. 529 - 539.
- [22] S. Tozlu, " Feasibility of Wi-Fi enabled sensors for Internet of Things", in Proceedings IEEE International Wireless Communications and Mobile Computing Conference (IWCMC), Istanbul, Turkey, July 2011, pp. 291-296.
- [23] M. Levesque and M. Maier, "The Über-FiWi network: QoS guarantees for triple-play and future Smart Grid applications", in Proceedings IEEE International Conference on Transparent Optical Networks (ICTON), Coventry , England, July 2012, pp. 1-4.

- [24] P. Yi, A. Iwayemi and C. Zhou, "Developing ZigBee Deployment Guideline Under WiFi Interference for Smart Grid Applications", *IEEE Transactions on Smart Grid*, vol. 2, no. 1, March 2011, pp. 110-120.
- [25] L. Kazovsky, S.W. Wong, T. Ayhan, K. Albeyoglu, M. Ribeiro and A. Shastri, "Hybrid Optical–Wireless Access Networks", *Proceedings of the IEEE*, vol. 100, no. 5, May 2012, pp. 1197 - 1225.
- [26] "Ericsson Canada Company", July 2012. [Online]. Available: www.ericsson.com.
- [27] S.W. Luan, J.H. Teng, S.Y Chan, L.C Hwang , "Development of a smart power meter for AMI based on ZigBee communication", in *Proceedings IEEE International Conference on Power Electronics and Drive Systems (PEDS)*, Taipei, Taiwan, November 2009, pp. 661-665.
- [28] M. Maier, N. Ghazisaidi and M. Reisslein, "The Audacity of Fiber-Wireless (FiWi) Networks", in *Proceedings IEEE International Conference on Access Nets*, Las Vegas, USA, October 2008, pp. 16-35.
- [29] H. Song, A. Banerjee, B.-W. Kim and B. Mukherjee, "Multi-Thread Polling: A Dynamic Bandwidth Distribution Scheme in Long-Reach PON", *IEEE Journal of Selected Area in Communications*, vol.27, no.2, February 2009, pp. 134-142.
- [30] B. Kantarci and H. T. Mouftah, "Bandwidth Distribution Solutions for Performance Enhancement in Long-Reach Passive Optical Networks," *IEEE Communications Surveys & Tutorials*, vol. 14, no. 3, Third Quarter 2012, pp. 714 - 733.
- [31] A. Sreesha, S. Somal and I.-T. Lu, "Cognitive Radio Based Wireless Sensor Network architecture for smart grid utility", in *Proceedings IEEE Long Island Systems, Applications and Technology Conference (LISAT)*, Farmingdale, USA, May 2011, pp. 1-7.
- [32] M. Souryal, C. Gentile, D. Griffith, D. Cypher and N. Golmie, "A Methodology to Evaluate Wireless Technologies for the Smart Grid" in *Proceedings IEEE Smart Grid Communications (SmartGridComm)*, New York, USA, October 2010, pp. 356-361.
- [33] B. Jung, J. Choi, Y. Han, M. Kim and M. Kang, "Centralized Scheduling Mechanism for Enhanced End-to-End Delay and QoS Support in Integrated Architecture of EPON and WiMAX", *IEEE Journal of Lightwave Technology*, vol. 28, no. 16, August 2010, pp. 2277 - 2288.
- [34] G. Schutz and N. Correia, "Design of QoS-aware energy-efficient fiber-wireless access networks", *IEEE/OSA Journal of Optical Communications and Networking*, vol. 4, no. 8, August 2012, pp. 586 - 594.
- [35] M. Maier and N. Ghazisaidi, *FiWi Access Networks*: Cambridge University Press, Montreal, 2011.

- [36] A. Stöhr, A. Akrouf, R. Buß, B. Charbonnier, F. van Dijk, A. Enard, S. Fedderwitz, D. Jäger, M. Huchard, F. Lecoche, J. Marti, R. Sambaraju, A. Steffan, A. Umbach and M. Weiß, "60 GHz radio-over-fiber technologies for broadband wireless services [Invited]" , IEEE/OSA Journal of Optical Networking, vol. 8, no. 5, 2009, pp. 471-487.
- [37] S. Arismar Cerqueira, D. Valente e Silva, M. Fortes, L. da Silva, O. Branquinho and M. Abbade, "Radio over Fiber system applied to IEEE 802.15.4 standard", in Proceedings IEEE Microwave and Optoelectronics Conference (IMOC), Belem, Brazil, November 2009, PP. 838-840.
- [38] N. Ghazisaidi and M. Maier, "Techno-economic analysis of EPON and WiMAX for future Fiber-Wireless (FiWi) networks," IEEE Network, vol. 54, no. 15, 2010, pp. 2640-2650.
- [39] J. Tang, X. Jin, Y. Zhang, X. Zhang and W. Cai, "A Hybrid Radio Over Fiber Wireless Sensor Network Architecture", in Proceedings IEEE Wireless Communications, Networking and Mobile Computing, Shanghai, China, September 2007, pp. 2675 - 2678.
- [40] T. Tsagklas and F. Pavlidou, "A Survey on Radio-and-Fiber FiWi Network Architectures", IEEE Journal of Selected Area in Communications (JSAC), 2011, pp. 18-24.
- [41] P. Chowdhury, B. Mukherjee, S. Sarkar, G. Kramer and S. Dixit, "Hybrid wireless-optical broadband access network(woban) : prototype development and research challenges", IEEE Network, vol. 23, no. 3, 2009, pp. 41 - 48.
- [42] M. Maier, M. Levesque and L. Ivanescu, "NG-PONs 1&2 and beyond: the dawn of the uber-FiWi network", IEEE Network, vol. 26, no. 2, March-April 2012, pp. 15 - 21.
- [43] N. Ghazisaidi, M. Scheutzow and M. Maier, "Survivability Analysis of Next-Generation Passive Optical Networks and Fiber-Wireless Access Networks", IEEE Transactions on Reliability, vol. 60, no. 2 , June 2011, pp. 479 - 492.
- [44] B. Kantarci and H. T. Mouftah, " Towards energy-efficient hybrid Fiber-Wireless Access Network", in Proceedings IEEE International Conference on Transparent Optical Networks (ICTON), Stockholm, Sweden, June 2011, pp. 1-4.
- [45] B. Kantarci and H. T. Mouftah, "ELEGANT: EPON-LTE deployment for a green access network," IET Optoelectronics, special issue on green photonics, 10.1049/iet-opt.2010.0112.
- [46] M. Erol-Kantarci and H. T. Mouftah, "Suresense: sustainable wireless rechargeable sensor networks for the smart grid," IEEE Journal of Wireless Communications, vol. 19, no. 3, June 2012, pp. 30-16.
- [47] "ZigBee Alliance," ZIGBEE BUILDING AUTOMATION, 2011. [Online]. Available: <http://www.zigbee.org/Standards/ZigBeeSmartEnergy/Version20Documents.aspx>. [Accessed 27 09 2012].

- [48] L. Shen, H. Wang, X. Duan and X. Li, "Application of Wireless Sensor Networks in the Prediction of Wind Power Generation," in Proceedings IEEE International Conference on Wireless Communications, Networking and Mobile Computing, Dalian, China, October 2008, pp. 1-4.
- [49] Y. Wang, W. Lin and T. Zhang, "Study on security of Wireless Sensor Networks in smart grid", in Proceedings IEEE International Conference on Power System Technology (POWERCON), Hangzhou, China, October 2010, pp. 1-7.
- [50] A. Nasipuri, R. Cox, J. Conrad, L. Van der Zel, B. Rodriguez and R. McKosky, "Design considerations for a large-scale wireless sensor network for substation monitoring", in Proceedings IEEE International Conference on Local Computer Network (LCN), Denver, USA, October 2010, pp. 866 – 873.
- [51] D. DeBlasio, T. Prevost and B. Grow, "IEEE standard Association," 21 9 Last Modified 2011. [Online]. Available: http://grouper.ieee.org/groups/scc21/2030/2030_index.html. [Accessed 24 9 2012].
- [52] Y.-h. Zhu, H. Qi and G.-x. Wang, "Temperature Characteristic of Fiber Bragg Grating," in Proceedings IEEE International Conference on Electronic and Mechanical Engineering and Information Technology (EMEIT), Harbin, China, August 2011, pp. 4020 - 4022.
- [53] N. Bressan, L. Bazzaco, N. Bui, P. Casari, L. Vangelista, M. Zorzi, "The deployment of a smart monitoring system using wireless sensors and Actuator Network", in Proceedings IEEE International Conference on Smart Grid Communications, Gaithersburg, USA, October 2010, pp. 49 - 54.
- [54] P. W. Shumate, "Fiber-to-the-Home: 1977–2007," IEEE Journal of Lightwave Technology, vol. 26, no. 9, 2008, pp. 1093-1103.
- [55] M. Hajduczenia, H. da Silva and P. Monteiro, "Extended GATE/REPORT MPCP DUs for EPONs," in Proceedings IEEE Symposium on Computers and Communications (ISCC), Cagliari, Italy, June 2006, pp. 554 - 559.
- [56] P. Peschlow and P. Martini, "A discrete-event simulation tool for the analysis of simultaneous events", in Proceedings ACM 2nd international conference on Performance evaluation methodologies and tools, Nantes, France, October 2007, pp. 1-9.
- [57] G. Kramer, "Discrete Event Simulation Library," [Online]. Available: <http://glenkramer.com>. [Accessed 01 08 2012].
- [58] M. S. Taqqu, W. Willinger and R. Sherman, "Proof of a fundamental result in self-similar traffic modeling," ACM SIGCOMM Computer Communication Review, vol. 27, no. 2, 1997, pp. 5-23.
- [59] G. Kramer and G. Pesavento, "Ethernet passive optical network (EPON): building a next-generation optical access network," IEEE Communications Magazine, vol. 40, no. 2 , April

2002, pp. 66 - 73.

- [60] M. Maier and N. Ghazisaidi, "QoS Provisioning Techniques for Future Fiber-Wireless (FiWi) Access Networks," MDPI Journal of Future Internet, vol. 2, April 2010, pp. 126-155.
- [61] "European Commission: Energy", [Online]. Available: www.ec.europa.eu. [Accessed 10 09 2012].
- [62] "IEEE 2030 Draft Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), and End-Use Applications and Loads ", [Online]. Available: http://grouper.ieee.org/groups/scc21/2030/2030_index.html. [Accessed 2 09 2012].
- [63] H. Farhangi, "Intelligent Micro Grid Research at BCIT", in Proceedings IEEE Electric Power and Energy Conference (EPEC), Vancouver, Canada, October 2008, pp.1-7.
- [64] V. Srivastava and M. Motani, "Cross-layer design: A survey and the road ahead," IEEE Communications Magazine, vol. 43, no. 12, December 2005, pp. 112–119.
- [65] "Capital expenditure ",[Online]. Available: http://en.wikipedia.org/wiki/Capital_expenditure [Accessed 22 01 2013].
- [66] "Operating expense ", [Online]. Available: http://en.wikipedia.org/wiki/Operating_expense [Accessed 22 01 2013].

Appendix A

Result Graphs

The following results have 70% of the WSN packets as high priority, while 30% are low priority.

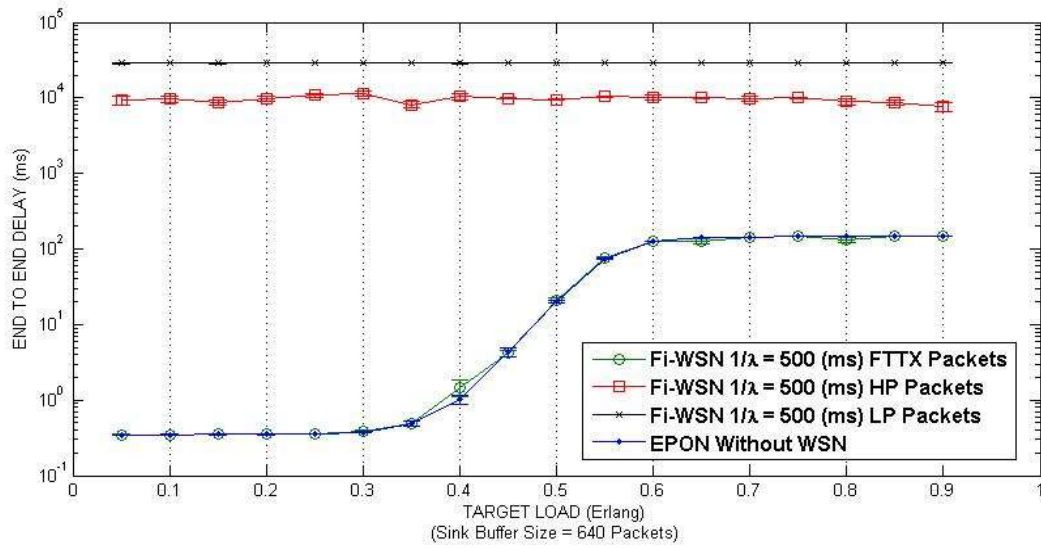


Figure A.0.1 End to End Delay vs. Target Load

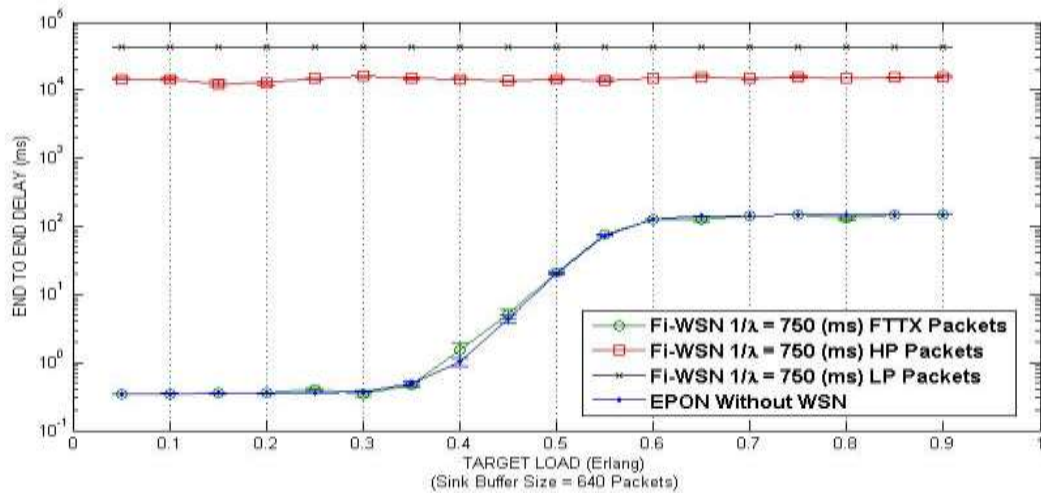


Figure A.0.2 End to End Delay vs. Target Load

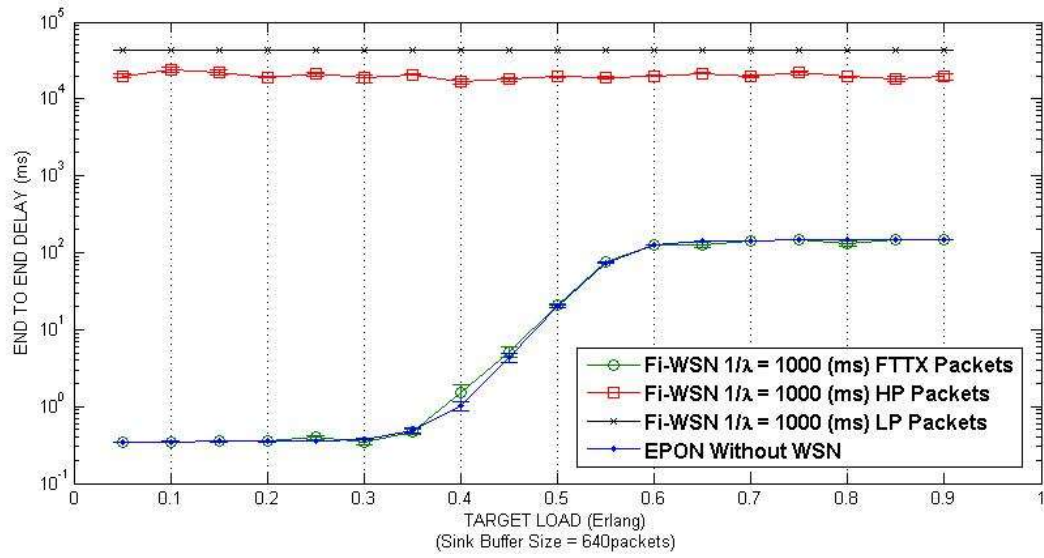


Figure A.0.3 End to End Delay vs. Target Load

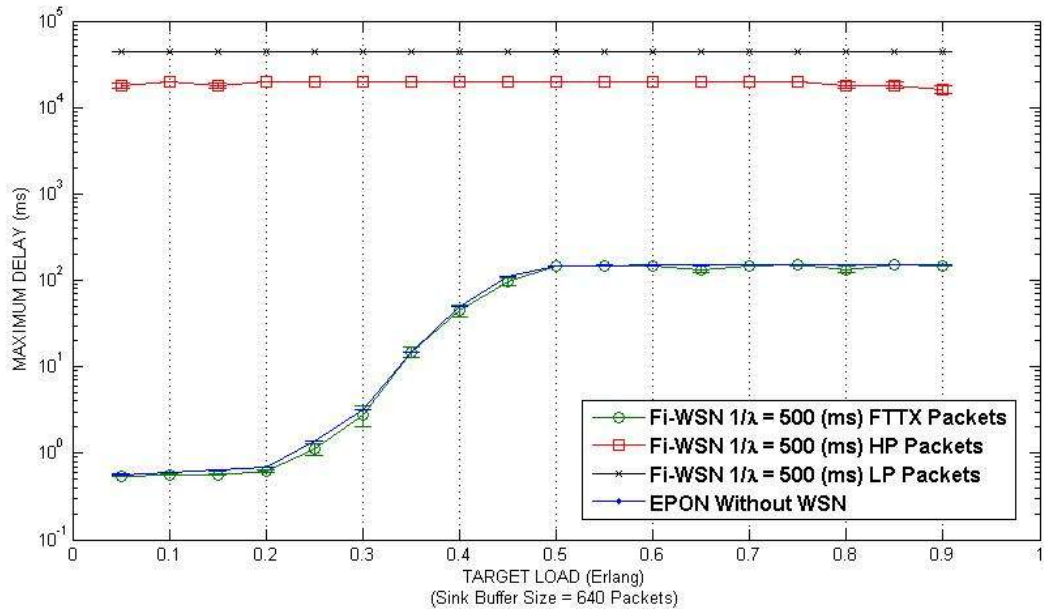


Figure A.0.4 Maximum Delay vs. Target Load

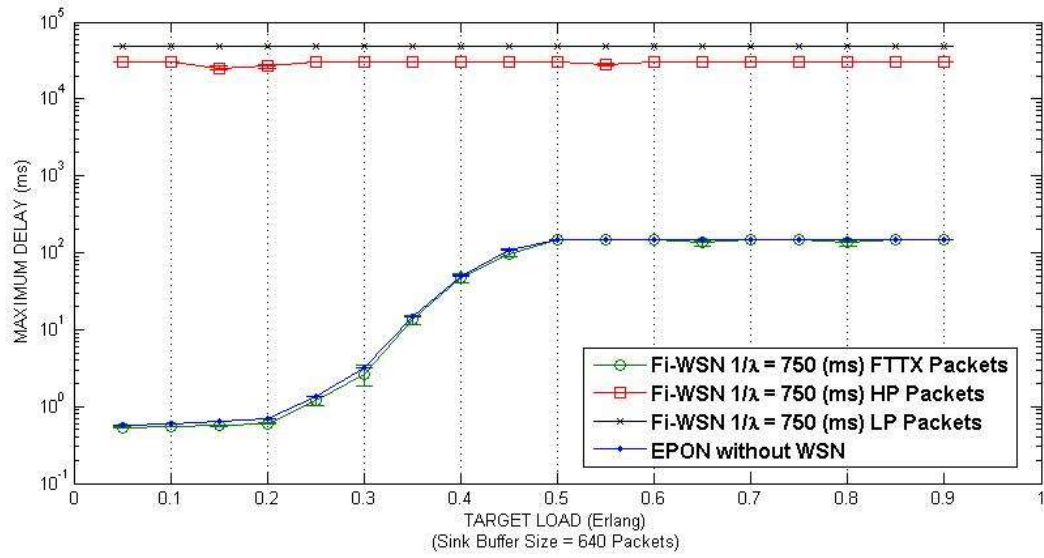


Figure A.0.5 Maximum Delay vs. Target Load

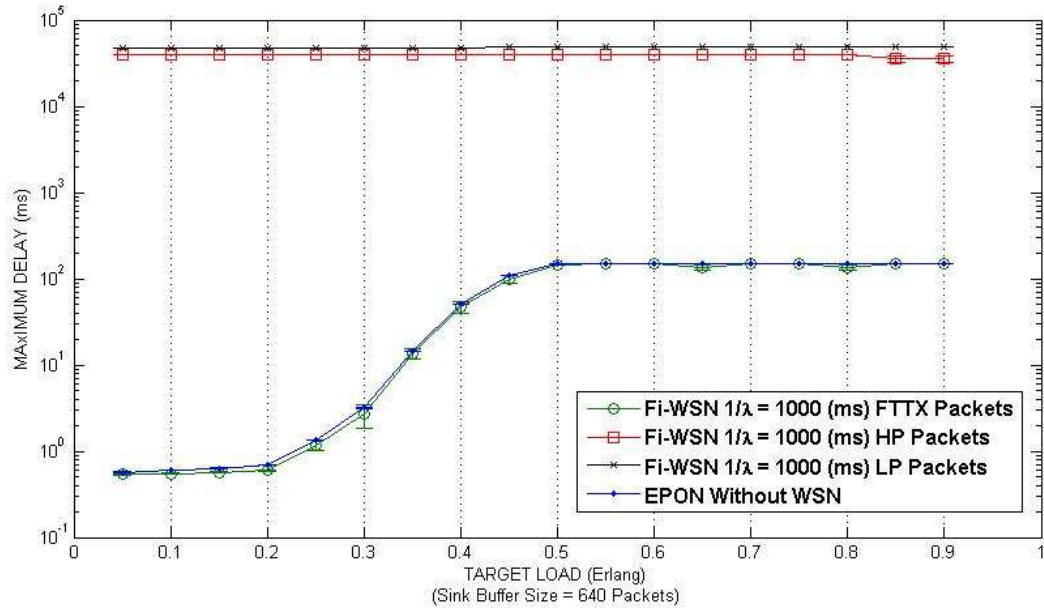


Figure A.0.6 Maximum Delay vs. Target Load

Appendix B

Confidence Interval

The Confidence Interval (CI) calculates an estimated range for uncertain quantities based on a set of collected sample data. The CI technique is one of the main applications of statistics in engineering, especially for computer simulations that have statistical behaviors. Suppose we run the simulation n times, independently from each other, with $R_1, R_2, \text{ and } R_3 \dots R_n$ different results, and then we calculate the mean value, such as the average end-to-end delay, maximum delay, and network throughput. We assume that R_i is obtained as the average end-to-end delay from the simulation iteration i :

$$M = \frac{1}{n} \sum_{i=1}^n R_i \quad (\text{B.1})$$

Where M is the sample average.

However, in the analytical statistics systems, such as computer simulations, we cannot provide a single value for the expected mean value (μ). Therefore, we provide a CI for the verification of our simulation results. First we need to use another parameter, named the standard variation, before calculating the confidence interval.

$$\text{The standard deviation } \sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (R_i - M)^2} = V_R \quad (\text{B.2})$$

Where V_R is the variance, $1 - \alpha$ is the confidence and α is the significance level.

The CI is provided to make sure that the populated result values are contained within the calculated interval based on the specific probability percentage e.g., 90%, 95% and so on.

Therefore, due to required confidence interval, we need to calculate the upper and lower limit bound which are calculated using the following statistical formula at the second stage:

$$\text{Lower Bound L (B)} = M - \frac{\sigma t[1 - \frac{\alpha}{2}, n-1]}{\sqrt{n}} \quad (\text{B.3})$$

$$\text{Upper Bound U (B)} = M + \frac{\sigma t[1 - \frac{\alpha}{2}, n-1]}{\sqrt{n}} \quad (\text{B.4})$$

Where the value of $t[1 - \frac{\alpha}{2}, n - 1]$ is found from the t-distribution table based on the number of times the simulation has been run for each other iteration.

Run Times	$\alpha = 0.01$ (two tails)	$\alpha = 0.02$ (two tails)	$\alpha = 0.05$ (two tails)	$\alpha = 0.1$ (two tails)	$\alpha = 0.2$ (two tails)	$\alpha = 0.5$ (two tails)
8	3.355	2.896	2.306	1.860	1.397	.706
9	3.250	2.821	2.262	1.833	1.383	.703
10	3.169	2.764	2.228	1.812	1.372	0.700

Table B.1 The t-distribution

For this thesis, we considered 95% as the CI, which means the provided simulation results fall within the calculated interval. In addition, we collect the average results based on 10 independent simulation runs where significance level (α) will be 0.05 as two tails, where $(1 - 0.05) * 100$ is equal to 95% CI. Therefore, the observed results are with a probability of 95% between $L(B) \leq \mu \leq U(B)$.

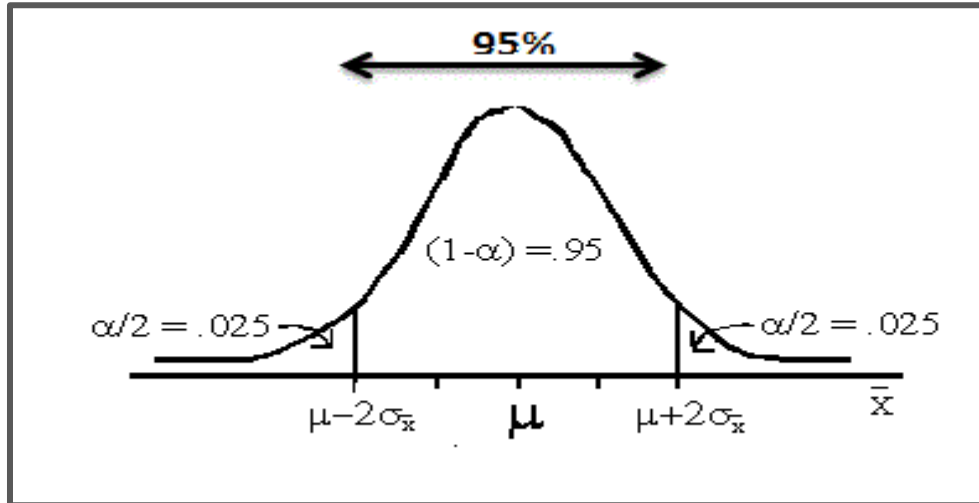


Figure B.0.1 Normal sampling distribution by 95% Confidence Interval

However, we accept that there is 5% probability that the mean value of the result is out of this interval.

The length of the calculated interval has an inverse relationship with the accuracy of the obtained result. Hence, for providing more accurate intervals in the normal distribution population, we can increase the number of independent simulation runs, which leads to an increase in the number of samples and a decrease in the standard deviation, providing a smaller interval for higher verification of the results.