# PERFORMANCE OF WIMAX IN RADIO OVER FIBER GIGABIT PASSIVE OPTICAL NETWORK ARCHITECHTURE

NOR AFFIDA M.ZIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

APRIL 2013

# ABSTRACT

The integration of wireless and optical network is a promising solution to support the growth of traffic demands in future access networks. The integrated network would provide high bandwidth (BW), flexibility, mobility and reliability. To meet the demand of future networks and provide wider service coverage, Gigabit Passive Optical Network (GPON) is chosen as the backbone of wireless distribution networks due to its high network capacity to be combined with WiMAX, today's most promising wireless network. In this GPON network, a Radio-over-Fiber (RoF) technology as the wireless transmission technique is deployed in the proposed optical-wireless hybrid architecture. This thesis focuses on the design, simulation and analysis works of WiMAX on RoF-GPON architecture based on physical and network layer simulation. At the physical level, to investigate the power and noise related measures, the network has been designed and simulated in the OptiSystem. The network was found to perform well at 30km of fiber with Bit Error Rate (BER) that was lower than $10^{-10}$. Next, a model was developed at the network layer to analyze the performance of wireless IEEE 802.16 medium access control (MAC) scheme when transmitting in the optical network architecture. The research also addressed the additional fiber delay imposed on existing MAC timing scheme which was done in the Network Simulator-2. Due to the fiber delay, analysis of the throughput, packet losses and end-to-end delay performances showed that throughput degradation was found to be 10% at 30km of fiber. In comparison to mathematical analysis, the network layer simulation can support up to 9000 users simultaneously with 1:32 GPON splitting ratio; which is almost 50% lower than the physical layer capacity due to the effect of real network characteristics such as packet losses.

# ABSTRAK

Integrasi di antara jaringan tanpa wayar dan optik menjanjikan harapan bagi menyokong peningkatan permintaan trafik untuk pencapaian jaringan masa hadapan. Jaringan integrasi ini akan menghasilkan lebar jalur (BW) yang tinggi, fleksibel, mobiliti dan boleh dipercayai. Bagi memenuhi keperluan jaringan di masa hadapan serta memberi skop perkhidmatan yang lebih luas, Jaringan Optik Gigabit Pasif (GPON) telah dipilih sebagai tulang belakang jaringan pengagihan tanpa wayar kerana kapasiti jaringannya yang tinggi untuk dikombinasikan dengan WiMAX, jaringan tanpa wayar terkini yang paling paling berjaya. Di dalam jaringan GPON ini, satu teknologi *Radio-over-Fiber* (RoF) iaitu teknik penyiaran tanpa wayar digunakan untuk seni bina hibrid optikal-tanpa wayar yang dicadangkan. Fokus tesis ini ialah reka bentuk, simulasi dan analisa kerja WiMAX ke atas seni bina RoF-GPON berdasarkan simulasi lapisan fizikal dan lapisan jaringan. Pada tahap fizikal, bagi mengkaji kuasa dan mengukur perkara berkaitan kebisingan, jaringan tersebut telah direka bentuk dan disimulasikan di dalam OptiSystem. Ia didapati mempunyai prestasi yang baik pada gentian 30km dengan kadar ralat bit (BER) kurang daripada $10^{-10}$. Seterusnya, satu model telah dibangunkan pada lapisan jaringan untuk menganalisa pencapaian medium kawalan akses (MAC) skim untuk IEEE 802.16 tanpa wayar bila dipancarkan di dalam seni bina jaringan optik. Kajian juga menjurus kepada penambahan kelewatan gentian kepada skim masa MAC sedia ada yang telah dibuat di dalam Network Simulator-2. Disebabkan kelewatan gentian ini, analisis terhadap prestasi penghasilan, kehilangan paket dan keseluruhan kelewatan menunjukkan bahawa penurunan penghasilan telah didapati di antara 10% pada gentian 30km. Dibandingkan dengan analisis matematik, simulasi lapisan jaringan boleh menyokong sehingga 9000 pengguna serentak dengan kadar betasan 1:32 GPON; iaitu hampir 50% lebih rendah daripada kapasiti lapisan fizikal disebabkan kesan keadaan jaringan sebenar seperti kehilangan paket.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $f$ | - | Frequency |
| $T_G$ | - | Guard time |
| $T_D$ | - | Data time |
| $T_S$ | - | Symbol time |
| $\Delta f$ | - | Subcarrier frequency spacing |
| $G$ | - | Cyclic prefix |
| $n$ | - | Sampling factor |
| $N_{FFT}$ | - | FFT magnitude |
| $Nused$ | - | Number of used subcarriers |
| $BW$ | - | Bandwidth |
| $f_S$ | - | Sampling frequency |
| $T_X$ | - | Transmitter |
| $R_X$ | - | Receiver |
| $\lambda$ | - | Wavelength |
| $D$ | - | Dispersion |
| $L$ | - | Fiber length |
| $B$ | - | Bit rate |
| $\tau_g$ | - | Time delay |
| $v_g$ | - | Group velocity |
| $\omega$ | - | Angular frequency |

| | | |
|---|---|---|
| $\beta$ | - | Propagation constant |
| $c$ | - | Velocity of light in vacuum |
| $N_{sub}$ | - | Number of data subcarriers |
| $N_{mod}$ | - | Number of uncoded bits per subcarriers |
| $N_{cod}$ | - | Coding rate |

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| RoF | - | Radio-over-Fiber |
| PON | - | Passive Optical Network |
| GPON | - | Gibabit Passive Optical Network |
| EPON | - | Ethernet Passive Optical Network |
| WiMAX | - | Worldwide Interoperability for Microwave Access |
| SCM | - | Subcarrier Multiplexing |
| WDM | - | Wavelength Division Multiplexing |
| CS | - | Control Station |
| SS | - | Subscriber Station |
| BS | - | Base Station |
| RAU | - | Remote Antenna Unit |
| PMP | - | Point-to-Multipoint |
| MAC | - | Medium Access Control |
| BER | - | Bit Error Rate |
| ISI | - | Intersymbol Interference |
| TDD | - | Time Division Duplexing |
| OFDM | - | Orthogonal Frequency Division Multiplexing |
| CP | - | Cyclic Prefix |
| OSNR | - | Optical Signal to Noise Ratio |
| NS2 | - | Network Simulatior 2 |

| | | |
|---|---|---|
| TDMA | - | Time Division Multiple Access |
| OLT | - | Optical Line Termination |
| ONU | - | Optical Network Unit |
| FTTH | - | Fiber-to-the-Home |
| RTD | - | Round Trip Delay |
| TTG | - | Transmitter Transmission Gap |
| RTG | - | Receiver Transmission Gap |
| FFT | - | Fast Fourier Transform |
| MZM | - | Mach Zehnder Modulator |
| LD | - | Laser Diode |
| PD | - | Photodetector |
| SMF | - | Single-mode fiber |
| MMF | - | Multi-mode fiber |
| UL | - | Uplink |
| DL | - | Downlink |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Integrating Wireless and Fiber Optics Technology

Over the decades, wireless communications have gained enormous popularity through the flexibility and high mobility connections. Inline with the maturity of wireless network, fiber optic technology also achieved more interests due to the high bandwidth offered (up to Tbits/s) with low attenuation characteristics (~0.2 dB/km) [1]. The future access networks are moving towards the integration of these wireless and optical communications in single network architecture. Moreover, this network integration also supported by the exponential growth in the number of traffic users with the demand for bandwidth-intensive applications such as online gaming and high definition (HD) video. The Passive Optical Network (PON) offers more opportunities for these services to be provided at higher connection speed per user of 100 Mb/s [2]. Enabled by the Radio-over-Fiber (RoF) technology to combine the features of flexibility and high mobility wireless networks with the advantageous PON network, has given a high focus in today's transmission technology.

### 1.1.1 The Future Access Networks

Internet communication has experienced a tremendous growth since the development in 40 years ago with 1.5 billion of users on the network being reported to-date compared to 1960s where only 350 users within the traffic [3]. The evolution was started from voice and text based services to video-based interactive and multimedia services. The estimation was also made in 2010 that approximately 50% revenue in the telephone company will be contributed by video-based services [4]. It is predicted that this growth will continue to rise due to more offerings on the wide-range of 'on-clicks' applications such as e-Commerce, social networking, multimedia services, and information centres, all supported by the advanced of computing technology.

In order to support the increasing traffic demands, the novel method that was investigated by the network operators is to extend the reach of fiber of the optical access network closer to the end users. Also, the significant cost reduction is expected to come from simplifying the distribution networks by eliminating the intermediate nodes. Thus, PON which use the low-cost unpowered passive splitter is an attractive solution in realizing these objectives. Compare to other PONs, Gigabit-PON (GPON) offers the most versatile architecture with all-optical based architecture that provides the high capacity, flexibility and Quality of Service (QoS) support for wired applications. GPON distribution network can reach up to 60 km, transmitted at gigabit speed and a better security [5-7].

Although the wired optical network can provide higher BW, the wireless communication services are still preferable due to the mostly recognized mobility features. Thus, today's technologies are seeking to combine the wireless and wired applications in one GPON access network. Obviously, this combined architecture can avoid the redundancy of expenditure involved since the deployment cost of running fiber to the home network is particularly high. To enable the transmission of the wireless services into this fiber network, RoF is the most suitable technology due to the simple hardware configurations, transparent against various modulation format and also practicing a centralized architecture, makes both GPON and wireless processing and termination points can be configured within the same stations [8-9]. It also can minimise the network installation and maintenance costs by using a simple Radio Antenna Unit (RAUs).

RoF is a technique to transmit the radio signal over the fiber medium which initially configured to support the picocellular wireless architecture and millimeter-wave (mm-wave) signal generations [8]. The works on RoF have been reported in many publications [8-14] which includes the theoretical and technical design aspects. The topics in RoF such as Subcarrier Multiplexing (SCM), modulation technique, and signal generation and transmission have been well exploited and promising results are presented. Thus, RoF indeed the most suitable solution to enable the convergence in the future access networks. Therefore, this project concerns with the distribution of wireless services through the GPON network by using the RoF transmission technique.

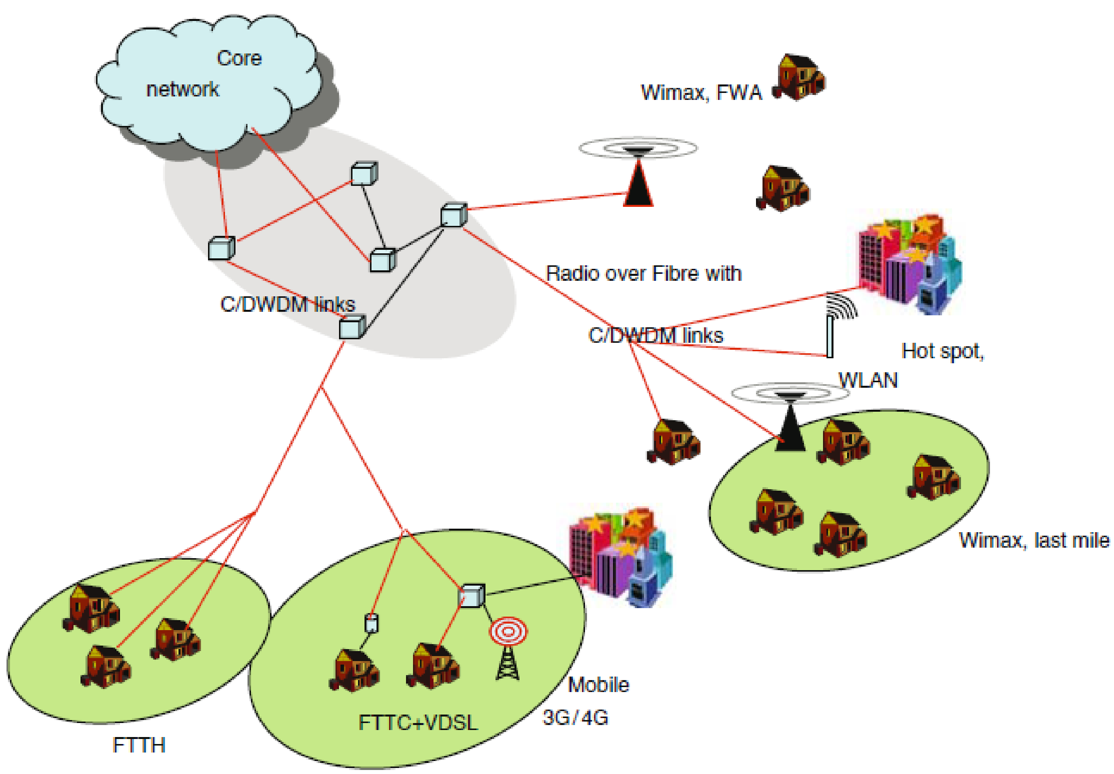


**Figure 1.1** The wireless and fiber common platform for the future access networks [7]

Figure 1.1 presents the wired and wireless technology sharing the same core network. For wired application, the options are Fiber-to-the-Home (FTTH), Fiber-to-the-Curb (FTTC) and high speed Very High Speed Digital Subscriber Line (VSDL). For wireless, there are mobile 3G/4G, WiFi and WiMAX. From this figure, it can be seen that RoF enables the WiMAX and other wireless schemes transported over a single fiber. The network also enabled by the powerful optical multiplexing scheme such as Coarse/Dense Wavelength Division Multiplexing (C/D WDM).

### 1.1.2 The Design Challenges

Integrating wireless and wired in single network is applicable in many areas such as shopping complex, airport, business building and residential homes and the existing GPON infrastructure is an appealing approach to give platform in transporting the wireless signals. An appropriate network configuration is needed for the connections which are directed from a central control station (CS) to several base stations (BSs). Therefore, in realizing this method, there are a few challenges that must be addressed to fully exploit the benefits of the fiber network.

#### 1.1.2.1 Low Cost Architecture

Developing smaller cells and using the high millimeter-wave as the carrier will increase the development costs. Some researchers prefer to develop a novel component such as Reflective Semiconductor Operational Amplifier (SOA) and broadband laser source then investigate the point-to-point (PP) connections to handle with the requirements of this new architecture [15]. Other approach is to use a simple and flexible architecture such as ring connections to distribute the signals to all end points. However, such connection mostly suffers from the complete breakdown if any point is fail. Therefore, a new architecture is needed to improve the tightness of expenses and address the related performance issues.

#### 1.1.2.2 Physical Layer Design

The second challenge is the physical/hardware configurations of the network in order to account the physical limitations such as attenuation level, bandwidth capacities, power budget and noise performance. Although this ‘transparent’ transport distributes a number wireless data into various optical channels which means low interference occurred, but the source of error comes from the different configurations such as the modulation format, and the noisy nature of the network components.

#### 1.1.2.3 Upper Layer Effect on Wireless Data Protocol

The work at the physical layer design has been well studied but the research in this area at the Medium Access Control (MAC) layer has received less concern. Most of the work concern with the impact of the additional propagation delay inserted by RoF and the impact on the MAC scheme and the degradation of network throughput [16-23]. They only presented a simple point-to-point scenario on RoF transmission of wireless data protocol. Thus, question that arises is about the performance of wireless MAC protocol by deploying RoF in this GPON architecture.

#### 1.1.2.4 Bandwidth Allocation Structure

By transporting wireless data into wired networks, one of the important challenges is the bandwidth allocation. The system must assure that the wired and wireless signals can coexist without interference and able to handle with the physical properties of the fiber such as attenuation and dispersion. As proposed in [24], the first option is to use the wavelength band allocated for analogue video distribution (1550 – 1560 nm). SCM technique can be easily used to transport several wireless channels by the optical carrier. Other than that, is digitizing the RoF signals and then transported within the same GPON data wavelength. However, this would require new hardware configurations such as Analogue/Digital Converters (ADC) to match with the high frequency of light carrier. The second option is by using the free wavelength bands but it suffers from high attenuation and needs new hardware developed to operate at this wavelength. Finally, this bandwidth allocation is also important in addressing the network users' capacities.

## 1.2 Research Background

Deploying RoF in transporting wireless on GPON network enables the convergence of wired and wireless access networks in a simple architecture. The number of wireless users can be increased significantly because of the high bandwidth offered by the fiber optic. In recent years, a lot of research works have been carried out to enable this new architecture. This part presents some of the related works that shows the progress of this technology and finally gives the direction of this research.

Among all of the network technologies for broadband wireless access, the standard IEEE 802.16, known as WiMAX is become popular both in industry and in academia due to the centralized protocol and wide coverage area. Compared to the distributed protocol such as IEEE 802.11 that suffers from a stronger limitation due to random-based and carrier sensing algorithms [22], IEEE 802.16 is particularly feasible to be integrated with the centralized RoF and GPON network.

Firstly, the physical distributions of WiMAX signals in a RoF-based scenario have been successfully reported in [25-26], just to name a few; considering the error vector measurement (EVM) and bit error rate (BER) performance. While in other works, [27-30], the interoperability of WiMAX with GPON networks are presented and also, they concentrate most on the physical layer performance. The works that reported on the MAC layer of this architecture can be found in [19][22][23][25][27]. A major issue that arises with transporting wireless over fiber links is the large propagation delay. This delay issue need to be addressed by protocols, which is related and responsible for packet synchronization and timeout. The centralized mechanism of the IEEE 802.16 medium access control (MAC) protocol makes an easier timing adjustment to support the long fibers, compared to the IEEE 802.11 which MAC timeout value are defined by the both wireless device vendors and the IEEE 802.11 standard; thus, it cannot be easily changed, and this limits the fiber length extension [31]. Therefore, in order to support a longer fiber reach, the main tuning in WiMAX is mainly related to the guard-time of Time Division Duplexing (TDD) technique and also the cyclic prefix of OFDM symbols [19][22].

This project focuses on the design, development and analysis the performance of WiMAX in RoF-GPON network infrastructure considering the MAC layer parameters which is mostly based on a discrete event simulation and real time data packets transmission. However, a performance analysis will be done earlier by a physical layer simulation using the variation of fiber length and the associated dispersion parameters to identify the physical reaches of the network. These parameters are used due to the fact that dispersion limits the fiber propagation delay and can be seen by the product of bandwidth (BW) and fiber length, L [32]. After that, an analysis of the system at both layers would give the significant results of the network performance especially the power measures and network capacities.

## 1.3 Problem Statement

This project proposed the integration of WiMAX in GPON network architecture by employing the RoF transmission technique. For this purpose, a detail understanding of the modeling and the performance parameters are needed to predict and calculate the system performance prior to network design and development. As a result, the system must be designed accordingly to address the performance at the MAC layer. Thus, the question that arises is “How the IEEE 802.16 protocol will perform in this RoF-GPON system?" This project also address the bandwidth utilization and users' capacities of such network considering the performance at both physical and MAC layer.

## 1.4 Research Objectives

The aims of this research are to enhance the capacity and transmission of wireless distribution network in the WiMAX-GPON integration using RoF transmission technique. In achieving this goal, the project is conducted with the following objectives:

a) To identify and simulate the performance of WiMAX on RoF-GPON system architecture through physical layer simulation considering the parameters of dispersion and fiber length.

b) To develop, simulate and analyze the performance of the network, IEEE 802.16 WiMAX over RoF-GPON system in a discrete event network layer simulation.

c) To analyze and compare the bandwidth utilization and network capacities theoretically and by using the simulation results in (b).

## 1.5 Significance of Research

The significant value of fiber optics have made the nation communicates easily around the world. Still, wireless network is chosen due to the flexibility and low-cost investment. However, the keep increasing traffic made the network providers looks for the convergence between these optical and wireless networks that promise many beneficial outcomes as stated in the discussion above. In designing such network, the performance at the physical layer provides the capabilities of the system mostly based on power budget, and noise related measures. Nevertheless, at upper layer, the wireless data protocol operates differently when transmitted in a high optical frequency and would fail when it reaches the delay or MAC timeout limits. For example, it would give effect to delay sensitive applications such as video conferencing which require a low delay, otherwise the sounds and pictures reached are not synchronized. Thus, the researchers must consider the MAC protocol scheme accordingly during the network design and development. In conclusion, the network must be designed in order to have a low end-to-end delay performance (high speed of connection), high throughput, optimum bandwidth utilization and network capacities.

## 1.6 Scope of Work

The scope of works in this project are specified below:

a) Literature study

A review on current progress and development of optical-wireless integration technology focusing on the architecture and performance testbed. The GPON network is based on the ITU-T G.984 standard while the wireless is based on IEEE 802.16 platform.

b) Modeling and Simulation

i) The network model that is proposed is an integration of WiMAX in GPON architecture using RoF technique. Physical layer analysis of this part will focus on variable parameters which are dispersion and fiber length and the output are BER, OSNR and power budget.

ii) The network layer simulation of the MAC parameters. The implementation in NS2 required an algorithm made to correctly simulate the WiMAX on RoF-GPON system considering the TTG parameters. Therefore, the understanding of the C++ and OTcl languages are necessary.

c) Mathematical analysis

An analysis on the network bandwidth utilization and potential capacity of users in the coverage that is carried out in Matlab Simulink.

d) Simulation tools

OptiSystem, Network Simulator-2 (NS2), and Matlab Simulink.

## 1.7 Research Methodology

The flow chart of the project methodology is shown in Figure 1.2. This research works began with a literature study on the current development of optical-wireless integration including the enabling technologies. A thorough understanding of the communication principle and a detail view of the international standard limitations, historical works, and theories about the topic were made. At the same time, the simulation tools which are OptiSystem and NS2 also were explored. The project started with a simulation in OptiSystem, to analyze the physical performance of the network in term of BER, OSNR and power budget. The identified parameters are the dispersion and fiber length. The next step is the simulation in NS2 which was the major part of this research. Firstly, the properties of the MAC layer were identified which mainly related to the timing properties limitations of the network. Then, the system was developed using the NS2 Otcl and C++ script to accommodate the WiMAX on RoF-GPON system. The output was measured in term of throughput and delay. If any problem occurred during the simulation, the necessary modification on the algorithm was made. After all of the results were obtained, an analysis on the system performance on the whole was made including the physical and MAC layer performance. A mathematical analysis on the system BW utilization and network capacities by using the physical and network layer simulation results has also been accounted in Matlab Simulink. Finally, the details reporting of the work is presented in this thesis.

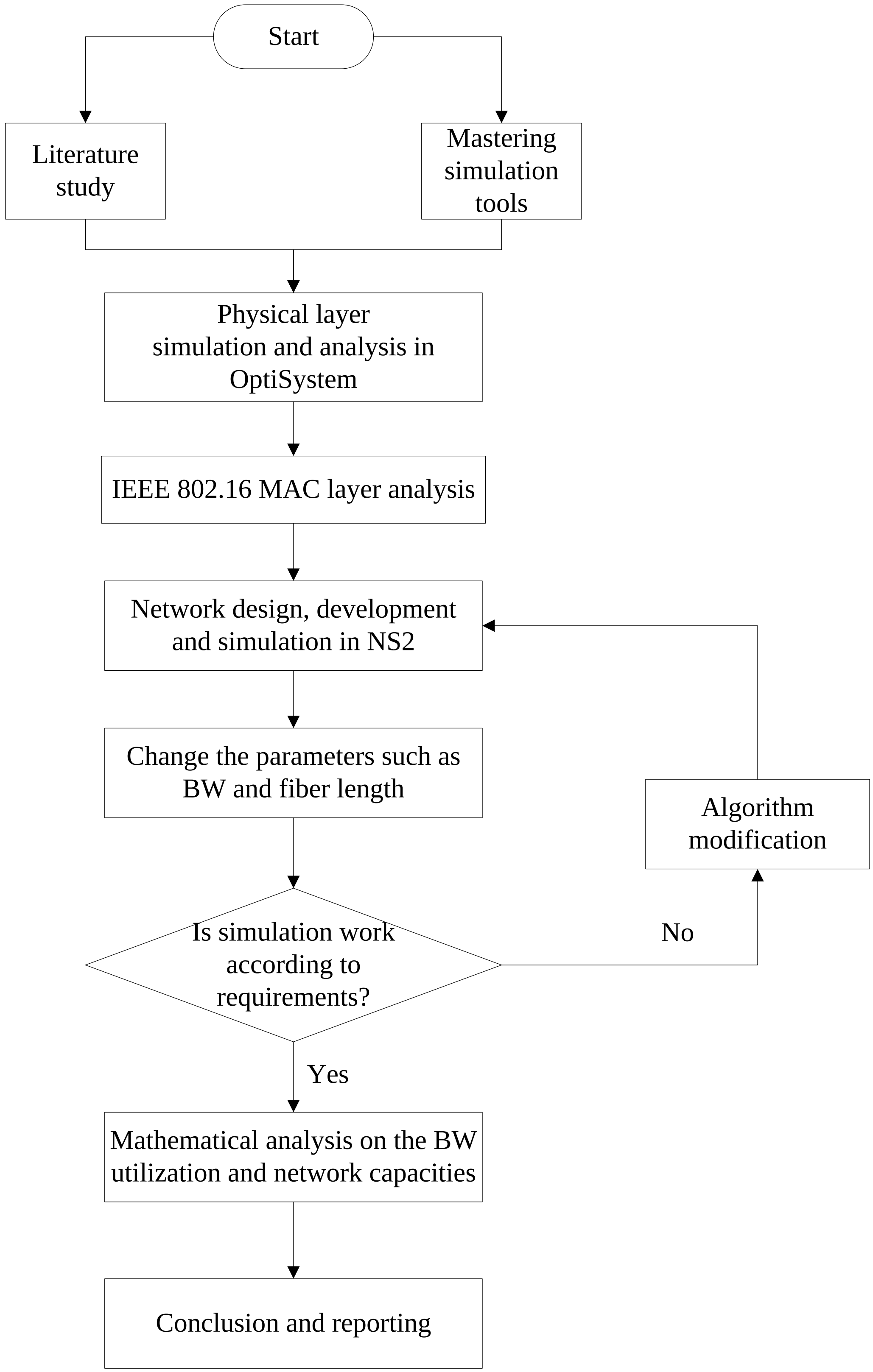


**Figure 1.2** Flow chart of the research methodologies

## 1.8 Thesis Outline

This thesis organized into various chapters in order to provide the necessary information for this research.

Chapter 1 outlines the general introduction about this project and address readers with the optical-wireless integration technology and the proposed work. The significance and goals of this research also been defined.

Chapter 2 discusses the theoretical review which started with a focus on the wireless IEEE 802.16 WiMAX standard and networks. Then, the discussion followed with the GPON standard and architecture. The RoF transmission technology is also presented subsequently. Finally, the chapter ends with the integration of the WiMAX on GPON network, the architecture, concept, previous works and the enabling technologies.

Chapter 3 is about an analysis of the fiber optic propagation delay which is related to the fiber dispersion characteristics and this can be seen by the product of the BW and the fiber length. The propagation delay of the RoF in term of TTG and RTG are also analyzed.

Chapter 4 presents the physical network modeling and analysis. The design and simulation made in OptiSystem is divided into transmitter model, distribution network model and receiver model with the configurations of all of the components used. The results for this simulation such as the eye diagram, BER, power budget and OSNR are presented and analyzed. Then, an analysis on the bandwidth utilization and potential network capacities are made using mathematical calculations.

Chapter 5 focuses on the network modeling and development in NS2 simulation which consists of network topology, algorithm used, and other design considerations. The simulation results of the network in this simulation such as throughput, packet losses and end-to-end delay are also presented and analyzed in detail.

Finally, chapter 6 summarizes all of the results and findings of this project. The contributions of this project are also stated and some feasible topics for the future research in this area have also been proposed.

# REFERENCES


1. John, M. S. Optical Fiber Communications: Principle and Practice. 3rd Edition. UK: Prentice Hall. ISBN 9780130326812. 2009.
2. Frank, E., David, C., Onn, H., Glen, K., Ruo Ding, L., Moshe, O. and Thomas, P. An Introduction to PON Technologies (Topics in Optical Communications). *IEEE Communication Magazine*.: IEEE 2007: S17-S25.
3. Miguel, A. T. Internet Marketing Method Revealed. US: Atlantic Publishing. ISBN139781601382658. 2007.
4. Lee, C. H., Wayne, V. S, and Kim, B. Y. Fiber to the Home Using a PON Infrastructure. *Journal of Lightwave Technology*. December 2006. 24(12): 4568-4683.
5. Chanclou, P., Cui, A., Geilhardt, F., Nakamura, H., and Nesset, D. Network Operator Requirements for the Next Generation of Optical Access Network. *IEEE Journals and Magazines.* 2012. 26(2): 8-14.
6. Ricciardi, S., Santos-Boada, G., Careglio, D., and Domingo Pascal, J. GPON and EP2P: A Techno Economic Study. *Proceeding of 17$^{th}$ International European Conference on Network and Optical Communications*. 2012: 1-6.
7. Carlos, B. et. al. Architecture of Future Access Networks. *Book Chapter of Next Generation FTTH Passive Optical Networks: Research towards unlimited bandwidth access by Josep Prat.* Spain: Springer. ISBN 9781402084690. 2008.
8. Hamed, A. R. and Shozo, K. Radio over Fiber Technologies for Mobile Communication Networks. Norwood: Artech House. ISBN 1580531482. 2002.
9. Kim, H. B., Radio over Fiber Based Network Architecture. *Master Thesis*, Technical University of Berlin. 2005.
10. Anthony, N., Radio-over-Fiber Technology for Broadband Wireless Communication Systems. *Doctor of Philosophy Thesis*. Eindhoven University of Technology. ISBN 9038617232. 2005.

11. Koonen, A. M. J. and García Larrodé, M. Radio-over-MMF Techniques-Part II: Microwave to Millimeter-Wave Systems. *Journal of Lightwave Technology*. August, 2008. 26(15).

12. García Larrodé, M., Koonen, A. M. J. et. al. Transparent Transport of Wireless Communication Signals in Radio-over-Fibre Systems, *Proceeding of 10$^{th}$ European Conference on Networks and Optical Communications*. July, 2005: 83-90.

13. Michael, S., Andrey, K., and Jacob, G. Radio over Fiber for Picocellular Network Architectures. *Journal of Lightwave Technology*. November, 2007. 25(11).

14. Cheng, H. W. et. al. Key Technologies and System Design for Various Radio over Fiber Applications. *Journal of China Universities of Posts and Telecommunications*: Elsevier. September, 2009. 29-34.

15. Chang, C. H., Lu, H. L., Su, H. S., Shih, C. L. and Chen, K. J. Broadband ASE Light Source based Full-Duplex FTTX/ROF Transport System. *Optic Express*: OSA. November, 2009. 17(24).

16. Bao, L. D. and Ignas, N. Analysis of IEEE 802.11 in Radio over Fiber Home Networks. *Proceedings of the IEEE Conference on Local Computer Networks.* 2005.

17. Bao L. D., Venkatesha Prasad., R. and Ignas, N. On the MAC Protocols for Radio over Fiber Indoor Networks. 2006.

18. Kalantarisabet, B. and Mitchell, J. E. MAC Constraints on the Distribution of 802.11 using Optical Fibre. *Proceedings of the 9th European Conference on Wireless Technolog.* September, 2006.

19. Linh Dang, B., Garcia Larrode, M., Venkatesha Prasad, R., Ignas, N. and Koonen, A.M.J. Radio-over-Fiber Based Architecture for Seamless Wireless Indoor Communication in the 60 Ghz Band. *Journal of Computer Communications*.: Elsevier. September, 2007.

20. Anjali, D., Majlinda, M., Anthony, N., and Nathan, J. G. Effects on IEEE 802.11 MAC Throughput in Wireless LAN Over Fiber Systems. *Journal of Lightwave Technology*. November, 2007. 25(11).

21. Kalantarisabet, B., Majlinda, M., Nathan, J. G., and Mitchell, J. E. Performance Impairments in Single-Mode Radio-Over-Fiber Systems Due to MAC Constraints. *Journal of Lightwave Technology*, August, 2008. 26(15).

22. Pedro, H. G., Nelson, L. S. da Fonseca, and Omar, C. B. Analysis of Performance Degradation in Radio-Over-Fiber Systems Based on IEEE 802.16 Protocol. *Proceeding of IEEE Latin-American Conference on Communications*. Sept, 2009: 1-6.

23. Feng, H., Joon Chae, C., Tran, A. V., Nirmalathas, A. MAC-layer Performances of Radio over Fiber and Basestation-based WiMax Pico-cell Networks. *Technical Digest of Opto-Electronics and Communications Conference*. July, 2010.

24. Sílvia, P., João, S., João, P., Paulo, M. and Henrique, S. On Supporting Radio over Fiber and Passive Optical Network Systems with a Common Fiber Plant: Compatibility Aspects. *Proceeding of International Conference on Transparent Optical Networks*, 2008.

25. Hoon Kim et. al. Radio-Over-Fiber System for TDD-Based OFDMA Wireless Communication Systems. *Journal of Lightwave Technology*. November, 2007. 25(11).

26. Ming-Li, Y., Anthony, N. and Michael, S. Performance Analysis of IEEE 802.16e WiMAX Radio-over-Fiber Distributed Antenna System. *Microwave Symposium Digest*. 2009: 197-200.

27. Gangxiang, S., Rodney, S. T., and Chang-Joon, C. Fixed Mobile Convergence Architectures for Broadband Access: Integration of EPON and WiMAX (Topics in Optical Communications). *IEEE Communications Magazine*. August, 2007.

28. Milos, M., Yuval, S., Pandelis, K. and John, M. S. Interoperability of GPON and WiMAX for Network Capacity Enhancement and Resilience. *Journal of Optical Networking*. 2009. 8(3): 285-294.

29 Alexey, V. O., Kamau, P. and Idelfonso, T. M. Converged Delivery of Wimax and Wireline Services over an Extended Reach Passive Optical Access Network. *Journal of Optical Fiber Technology*: Elsevier, 2010.

30. Abdou, R. A. Optical-WiMAX Hyrid Networks. *Doctor of Philosophy Thesis*, University of Western Ontario, 2011.

31. IEEE 802.11 Standard: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications. 1999.
32. Agrawal, G. P. Fiber-Optic Communication Systems. 4th Edition. New Jersey: John Wiley and Sons Inc. ISBN 9780470505113. 2010.
33. IEEE 802.16 Standard for Local and Metropolitan Area Networks: Air Interface for Fixed and Mobile Broadband Wireless Access Systems. 2004-2005.
34. WiMAX Forum, Regulatory Working Group, www.wimaxforum.org
35. Loutfi, N. WiMAX: Technology for the Broadband Wireless Access. England: John Wiley and Sons. ISBN 9780470028087. 2007.
36. Yee, T. S., Peter, M. and Sharif, H. R. WiMAX Security and Quality of Service: An End-to-End Perspective. UK: John Wiley and Sons Ltd. ISBN 9780470721971. 2010.
37. ITU-T Recommendation G.984 Series, Gigabit Passive Optical Network Standard. 2008 – 2009.
38. ITU-T Recommendation G.983 Series, APON and BPON Standard. 2005.
39. IEEE 802.3ah Standard: Ethernet Passive Optical Network Specifications. 2008.
40. Klaus, G. and Jörg-Peter, E. PON in Adolesence: From TDMA to WDM-PON (Topics in Optical Communications). *IEEE Communications Magazine*. January, 2008.
41. Hiroki, I., Jun, S., Yoshihiro, A. and Kenichi, S. High-definition IPTV Broadcasting Architecture over Gigabit-capable Passive Optical Network. *Proceeding of IEEE GLOBECOM*. 2007.
42. GPON Technology. www.flexsolvnetworks.com
43. Alex, V., Khaled, M., Heng, H. and Michel, S. Performance Characterization of PON Technologies. *Proceedings of SPIE - The International Society for Optical Engineering.* 2008,
44. Pulak, C., Biswanath, M., Suman, S., Glen, K., and Sudhir, D. Hybrid Wireless-Optical Broadband Access Network (WOBAN): Prototype Development and Research Challenges. *IEEE Network Magazine*. May/June, 2009.

45. Navid, G., Martin, M. and Chadi, M. A. Architecture_Fiber Wireless (FiWi) Access Networks: A Survey. Topics in Optical Communication. *IEEE Magazine*. Feb, 2009.

46. Wei, T. S., Shing, W. W., Ning, C., Xiaoqing, Z., Martin, M., Koussalya, B. and Leonid, G. K., Hybrid Architecture and Integrated Routing in a Scalable Optical-Wireless Access Network. *Journal of Lightwave Technology*. Nov, 2007. 25(11).

47. Yuanqio, L., Ting, W., Steve, W., Milorad, C. and Shinya, N. Integrating Optical and Wireless Services in the Access Networks. *Proceeding of Optical Fiber Communication Conference.* 2006.

48. Milos, M., Pandelis, K., Ali, G. and John, M. S. Advanced PON Topologies with Wireless Connectivity. *Proceeding of 11th International Conference on Transparent Optical Networks*. 2009.

49. Arshad, C., Hung, C. C., Yu-Ting, H. and Gee-Kung, C. Advanced System Technologies and Field Demonstration for In-building Optical-Wireless Network with Integrated Broadband Services. *Journal of Lightwave Technology*. June, 2005. 27(12).

50. Moradpoor, N., Parr, G., McClean, S., Scotney, B., and Owusu, G., Hybrid Optical and Wireless Technology Integrations for Next Generation Broadband Access Networks. *Proceeding of International Workshop on Broadband Convergence Network*. 2011.

51. Yu-Min, L. and Po-Lung, T. Next-Generation OFDMA-Based Passive Optical Network Architecture Supporting RoF *IEEE Journal on Selected Areas in Communications*. August 2010. 28(6).

52. Suman, S., Biswanath, M., and Sudhir, D. Optimum Placement of Multiple Optical Network Units (ONUs) in Optical-Wireless Hybrid Access Networks. *Proceedings of Optical Fiber Communication Conference.* 2006.

53. Redwan, Q. S. and Abu, B. M. Bandwidth Efficient Hybrid Wireless-Optical Broadband Access Network Based on OFDM Transmission. *IEEE Photonics Society Lecture Series*. Universiti Teknologi Malaysia. Oct, 2011.

54. Telchemy. Impact of Delay in Voice over IP Services. VoIP Performance Management. Jan, 2006.

55. Bo, Z., Eugene, N., Animesh, N., Rudolf, R., Peter, D., and Guohui, W. Measurement Based Analysis, Modeling and Synthesis of the Internet Delay Space. *Proceeding of Internet Measurement Conference*. Oct, 2006.

56. ITU-T Recommendation G.652 Standard. Characteristics of Single Mode Optical Fibre and Cable. 2009.

57. Stephen, S. Optical Fibers. Lecture Notes. Electrical and Computer Engineering Department. Brigham Young University. 2005. schultz@ee.byu.edu

58. Ziad, N. and Loutfi, N. Simple Capacity Estimations in WiMAX/802.16 System. *Proceeding of IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*. 2006.

59. Aymen, B. and Loutfi, N. WiMAX Capacity Estimations and Simulation Results. *Proceeding of Vehicular Technology Conference*. May, 2008.

60. Amir, M. Capacity and Cell-Range Estimation for Multitraffic Users in Mobile WiMAX. *Masters' Thesis*. University College of Boras. 2008.

61. Xinbing, W., Shen, G., Yuan, W., and Jiajing, W. QoS Simulation and An Enhanced Solution of Cell Selection for WiMAX Network. *WiMAX Security and Quality of Service: An End-to-end Perspective*. UK: John Wiley and Sons. ISBN9780470721971. 2010. 337-364.

62. Network Simulator-2. *www.isi.edu/nsnam/ns*

63. Teerawat, I. and Ekram, H. Introduction to Network Simulator NS2. 2nd Edition. New York: Springer: ISBN9781461414056. 2012.

64. National Institute of Standards and Technology. Seamless and Secure Mobility: Tools. *www.nist.org*

65. Corning Incorporated. Corning® SMF-28™ Product Information Datasheet. *www.corning.com*

66. Roithner LaserTechnik GmbH. RLTMDL-1550R 1-200 mW. Round Spot Beam Profile. *www.roithner-laser.com*

67. Tmi Optics Sales Company. Datasheet of Nitta Optical Power Splitter *tmioptics.com*