POWER CONSUMPTION MODELING IN INTEGRATED OPTICAL-WIRELESS ACCESS NETWORK

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To my patience and understanding husband, Wan Mohamad Maulana Wan Aris, to our precious daughter and son, Wan Dzaira Amani and Wan Dzahin Ammar.

~Our family is a circle of strength and love~

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ABSTRACT

The access segments of both optical and wireless networks are well known for their domination over the network's total power consumption. Therefore, the study on energy consumption particularly in integrated optical-wireless access networks is crucial as energy consumption issue is increasingly vital nowadays. Existing works to date largely addressed the physical characteristics of integrated devices and algorithms for layer 2 and layer 3, where the study in power consumption modeling was often ignored. Hence, this thesis focuses on developing a power consumption model for integrated optical-wireless access networks and investigates the energy efficiency of such networks. Gigabit Passive Optical Network (GPON) as the optical backhaul and Worldwide Interoperability Microwave Access (WiMAX) and Long-Term Evolution (LTE) with femtocell application for the wireless network are considered. First, the power consumption model of the integrated network involving Optical Line Terminal (OLT) and integration between Optical Network Unit (ONU) and Base Station (BS) known as Integrated ONU-BS (IOB) are developed. Then, the power consumption behavior of ONU under different traffic loads has been investigated to model the total power consumption of integrated access networks. An empirical approach has been proposed to characterize the power consumption of the ONU by using real GPON testbed and to develop the power consumption model of ONU based on experimental results. This is followed by the extensive analyses that have been conducted to investigate the impact of various parameters such as split ratio, Femtocell Base Station (FBS) cell range, broadcast factor, and modulation and coding scheme into the total network power consumption and energy efficiency. It has been observed that GPON-LTE has the worst energy efficiency performance when compared to GPON-WiMAX, even though it offers the highest data rates. The study has been further extended by including energy saving aspects where sleep mode techniques have been applied (i.e. power shedding for the ONU and idle mode procedure for FBS) based on the user behavior from the traffic profile pattern in Cyberjaya municipal broadband access networks. The implementation of energy saving techniques have shown further significant improvement of 15% lower energy consumption for the integrated access network.

ABSTRAK

Segmen capaian bagi kedua-dua rangkaian optik dan wayarles adalah diketahui mendominasi jumlah keseluruhan penggunaan kuasa rangkaian. Oleh itu, kajian ke atas penggunaan tenaga khususnya di dalam rangkaian capaian optik-wayarles bersepadu adalah penting disebabkan isu penggunaan tenaga yang semakin penting pada masa kini. Kerja-kerja yang sedia ada kebanyakannya menujukan kepada ciri-ciri fizikal peranti bersepadu dan algoritma untuk Lapisan 2 dan Lapisan 3, di mana kajian di dalam model penggunaan kuasa kebiasaanya diabaikan. Oleh itu, tesis ini fokus kearah membangunkan model penggunaan kuasa untuk rangkaian capaian optik-wayarles bersepadu dan menyiasat kecekapan tenaga rangkaian ini. Rangkaian Optik Pasif Gigabit (GPON) sebagai optik angkut balik dan *Worldwide Interoperability Microwave Access* (WiMAX) dan Evolusi Jangka-Panjang (LTE) dengan aplikasi sel-femto bagi rangkaian wayarles telah dipertimbangkan. Pertama, model penggunaan kuasa bagi rangkaian capaian bersepadu melibatkan Terminal Talian Optik (OLT) dan penyepaduan antara Unit Rangkaian Optik (ONU) dan Stesen Utama (BS) dikenali sebagai ONU-BS Bersepadu (IOB) telah dibangunkan. Kemudian, ciri-ciri penggunaan kuasa ONU di bawah beban trafik yang berlainan telah dikaji untuk memodelkan penggunaan kuasa keseluruhan bagi rangkaian capaian bersepadu. Pendekatan empirik telah dicadangkan untuk mencirikan penggunaan kuasa ONU menggunakan tapak uji GPON yang sebenar dan untuk membangunkan model penggunaan kuasa ONU berdasarkan keputusan eksperimen. Ini diikuti dengan analisis meluas yang telah dijalankan untuk menyiasat impak pelbagai parameter seperti nisbah perpecahan, jarak stesen utama sel-femto (FBS), faktor siaran dan modulasi dan pengekodan kepada jumlah keseluruhan penggunan kuasa rangkaian dan kecekapan tenaga. Didapati bahawa GPON-LTE mempunyai kecekapan tenaga yang paling rendah apabila dibandingkan dengan GPON-WiMAX walaupun ia menawarkan kadar data yang paling tinggi. Kajian dilanjutkan dengan mengambil kira aspek penjimatan tenaga di mana teknik mod tidur telah digunakan (iaitu teknik penyisihan kuasa bagi ONU dan prosedur mod melahu bagi FBS) berdasarkan tingkah laku pengguna daripada corak profil trafik rangkaian capaian jalur lebar di Cyberjaya. Pelaksanaan teknik penjimatan tenaga telah menunjukkan penambahbaikan ketara sebanyak 15% penggunaan kuasa lebih rendah bagi rangkaian capaian bersepadu.

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LIST OF ABBREVIATIONS

1G	-	First Generation
2G	-	Second Generation
3G	-	Third Generation
3GPP	-	Third Generation Partnership Project
4G	-	Fourth Generation
5G	-	Fifth Generation
AC/DC	-	Alternating Current/Direct Current
AON	-	Active Optical Network
AP	-	Access Point
ATM	-	Asynchronous Transfer Mode
BM-CDR	-	Burst Mode-Clock and Data Recovery
BS	-	Base Station
CFB	-	Core Functional Block
CO	-	Central Office
CPE	-	Customer Premise Equipment
DC	-	Direct Current
DFB	-	Distributed Feedback
DS	-	Downstream
DSP	-	Digital Signal Processing
EDC	-	Electronic Dispersion Compensation
EEE	-	Energy Efficient Ethernet
EPON	-	Ethernet Passive Optical Network
FBS	-	Femtocell Base Station
FEC	-	Forward Error Correction
FiWi	-	Fiber-Wireless

FTTX	-	Fiber-to-the-x
GBA	-	Green Bandwidth Allocation
GbE	-	Gigabit Ethernet
GPON	-	Gigabit Passive Optical Network
GSM	-	Global System for Mobile Communication
HBT	-	Heterojunction Bipolar Transistor
HOWAN	-	Hybrid Optical Wireless Access Network
ICT	-	Information and Communication Technology
IDE	-	Integrated Development Environment
IEEE	-	Institute of Electrical and Electronics Engineers
IF	-	Intermediate Frequency
IM	-	Implementation Margin
IOB	-	Integrated ONU-BS
IoT	-	Internet of Things
IP	-	Internet Protocol
IPTV	-	Internet Protocol Television
ITU-T	-	International Telecommunication Union-Telecommunication
L2SW	-	Layer 2 Switch
LO	-	Local Oscillator
LTE	-	Long-Term Evolution
MAC	-	Medium Access Control
MCS	-	Modulation and Coding Scheme
MIMO	-	Multiple Input Multiple Output
MMIC	-	Monolithic Microwave Integrated Circuit
NG-PON	-	Next Generation Passive Optical Network
OA	-	Optical Amplifier
ODN	-	Optical Distribution Network
OFDM-PON	-	Orthogonal Frequency Division Multiplexed-PON
OLT	-	Optical Line Terminal
ONU	-	Optical Network Unit

PA	-	Power Amplifier
PC	-	Power Consumption
PHY	-	Physical Layer
PON	-	Passive Optical Network
POTS	-	Plain Old Telephone Service
PtM	-	Point-to-Multipoint
PtP	-	Point-to-Point
QoS	-	Quality of Service
RN	-	Remote Node
RoF	-	Radio-over-Fiber
SAS	-	Sort-and-Shift Scheme
SDH/SONET	-	Synchronous Digital Hierarchy/Synchronous Optical Networking
SFB	-	Specific Functional Block
SINR	-	Signal-to Interference plus Noise Ratio
SLIC	-	Subscriber Line Interface Circuit
SNR	-	Signal-to-Noise Ratio
SoC	-	System-on-Chip
SPW	-	Sleep and Periodic Wake Up
SSR	-	Solid-State Relay
TCP	-	Transmission Control Protocol
TDMA	-	Time Division Multiple Access
TU	-	Terminal Unit
TWDM-PON	-	Time and Wavelength Division Multiplexed-PON
UDP	-	User Datagram Protocol
UE	-	User Equipment
UMTS	-	Universal Mobile Telecommunication System
UNI	-	User Network Interface
US	-	Upstream
USB	-	Universal Serial Bus
VCSEL	-	Vertical-Cavity Surface-Emitting Laser

VoIP	-	Voice-over-Internet Protocol
WDM-PON	-	Wavelength Division Multiplexed-PON
WiFi	-	Wireless Fidelity
WiMAX	-	Worldwide Interoperability Microwave Access Network
WLAN	-	Wireless Local Area Network
WOBAN	-	Wireless Optical Broadband Access Network

LIST OF SYMBOLS

A	-	Cell coverage area
B	-	Broadcast factor
BW	-	Channel bandwidth
EE	-	Energy efficiency
E_{1-x}	-	Energy consumption of IOB that in sleep mode in a day
E_{PS}	-	Energy consumption of IOW with PS configuration
E_{WPS}	-	Energy consumption of IOW without power saving mode
E_x	-	Energy consumption of IOB that remain on in a day
$f(t)$	-	Traffic load
M	-	Number of OLT
M_{RN}	-	Number of Remote Node
M_{TU}	-	Number of Terminal Unit
N	-	Number of ONU
PS	-	Power saving configuration mode
$P_{control}$	-	Power consumption of OLT general function
P_{CPE}	-	Power consumption of Custome Premise Equipment
P_{FBS}	-	Power consumption of FBS
P_{IOB}	-	Power consumption of Integrated ONU-BS
P_{IOB-S}	-	Power consumption of IOB in saving mode
P_{IOW}	-	Power consumption of Integrated Optical-Wireless
P_{OLT}	-	Power consumption of OLT
P_{ONU}	-	Power consumption of ONU
P_{ports}	-	Power consumption of OLT PON ports
P_{RN}	-	Power consumption of Remote Node
P_{TU}	-	Power consumption of Terminal Unit
P_{UL}	-	Power consumption of OLT uplink port
P_{user}	-	Power per user

R	-	FBS cell radius
R_o	-	Bidirectional data rate of GPON
r_o	-	ONU access data rate
r_{DS}	-	GPON downstream data rate
r_{US}	-	GPON upstream data rate
r_w	-	FBS access data rate
r_w^L	-	Data rate of LTE
r_w^W	-	Data rate of WiMAX
S	-	Coverage area
SF	-	Site factor
SR	-	Splitting ratio
x	-	Number of active IOBs
α	-	IOB load dependent power consumption
α_o	-	Power consumption of ONU to transmit 1 bit
α_w	-	Power consumption of FBS to transmit 1 bit
γ	-	IOB fixed power consumption
γ_o	-	ONU idle power consumption
γ_w	-	FBS idle power consumption
η	-	Fudge factor
η_{BW}	-	Bandwidth efficiency
$\eta_{DC/DC}$	-	Power conversion efficiency
η_{SNR}	-	SNR efficiency
θ	-	Energy saving using PS configuration
σ	-	Overhead factor

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Over the last three decades, research and technology on Passive Optical Network (PON) have been explored rapidly, resulting in the wide deployment of this technology to implement various Fiber-to-the-x (FTTx) solutions. These solutions aim to deliver high bandwidth to the users at significantly reduced cost and low energy per bit. Research on PON continues at a remarkable pace where in 2007 International Telecommunication Union-Telecommunication Sector (ITU-T) and Institute of Electrical and Electronics Engineers (IEEE) recommended the future solution for PON with extended data rates in order to meet broadband consumer demand [1, 2]. They proposed next generation PON (NG-PON) where the planning was divided into two phases; NG-PON1 and NG-PON2. NG-PON1 is expected to deliver data rates up to 10 Gbps based on the existing Gigabit-capable PON (GPON) legacy whereas NG-PON2 include the research area of time and wavelength division multiplexed PON (TWDM-PON) as its most promising candidate which is capable to provide data rates no less than 40 Gbps.

In addition to the high bandwidth demand, increasing mobility requirements for access networks also present new challenges for service providers. Mobility is highly desirable for users because it enables access to the Internet regardless of location. Wireless access technologies offer the features of mobility and untethered access which provide ease of deployment and cost effectiveness. According to surveys, mobile data traffic has grown 4000-fold over the past 10 years and will be increased nearly eightfold between 2015 and 2020 [3]. Moreover, as the Internet of Things (IoT) becomes a reality, there will be massive growth in the number of connected devices which is expected to be around 12 billion devices by 2020.

The integration of optical and wireless networks is a promising solution to improve both problems due to their complementary features of wide bandwidth and user mobility, respectively. However, due to the expansion of network connectivity and the increment of network data rate, power consumption is expected to increase. The optical access network consumes 60-80% of the total power consumed by wired networks [4, 5, 6, 7] where the power consumption is dominated by the Optical Network Units (ONUs). On the other hand, wireless access network consumes 9% of ICT power consumption [8] where 80% of the power is consumed by the Base Stations (BSs) [9]. Therefore, study on the energy consumption of such network will allow energy performance optimization, network architecture improvement and other network parameter enhancements to be applied. Thus, the power consumption and energy efficiency of the integrated access network become the ultimate goals of the current research direction.

1.2 Problem Statement

The works and research on the integration of optical and wireless access networks have begun since the year of 2009. Alcatel-Lucent considered to leverage GPON for mobile backhaul network [10] due to the growing demand for bandwidth hungry applications and services which results in significant increase in the cost of deployment. This is because current mobile backhaul network (e.g. copper cable) is not cost effective since the cost scale linearly with bandwidth. Although advanced copper-based technologies (such as G.fast) are able to offer rates of few Gbps, it can only cover short distance [11]. Thus, this technology is suitable to be used for the network with low bit options or short distance applications. Since 3G applications, the deployment of cost effective solutions are discussed for backhaul network in order to accommodate the higher demand in data rates as well as to prepare for Long-Term Evolution (LTE) network. These solutions leverage the integration of GPON triple play network and wireless technologies to provide effective tetherless connectivity and cost effective at high bandwidth transmission. Such integration will also provide the advantages of optical fiber capacity and wireless communication mobility [12, 13, 14].

Most of the research in the integrated optical and wireless access networks focuses on the physical (PHY), medium access control (MAC) and network layers with the goal to develop and investigate low cost enabling technologies as well as Layer 2 and 3 protocols and algorithms. However, as access networks have been reported to dominate the energy consumption of the Internet thus gives significant contribution in greenhouse footprint, the design of energy efficient "green" optical wireless access networks has gained the scholarly attention. Unfortunately, the potential of the integration wireless with the existing fiber based PON in terms of power consumption in the physical layer remains largely unexplored. Most published works consider the optical and wireless access networks in terms of energy consumption separately where some compare the energy performances between both access networks. The network energy modeling can provide information on energy consumption of the considered access technologies thus energy performance optimization, network architecture improvement and other network parameters enhancement can be applied to those particular access technologies. To the best of our knowledge, only few publications [15, 16] have addressed the task at modeling the energy consumption of integrated optical wireless networks, in which [16] provide energy model for RoF network instead of optical network as a wireless backhaul.

1.3 Objectives of Research

This research focuses on developing power consumption model of the integrated optical-wireless access network. Based on the above mentioned research problem statement, the research objectives can be specified as:

i. To model and simulate the power consumption of the integrated ONU-BS (IOB) and the whole integrated optical-wireless access networks.
ii. To propose a power consumption model for the ONU through experimental work utilizing GPON testbed.
iii. To analyze the energy performance of the integrated access network and investigates the effect of power saving mode based on user behavior.

1.4 Scopes of Research

Based on the objectives of the study stated above, few research scopes of work were formulated:

i. Development of power consumption model for the integrated access technologies.

- The structure and functional blocks of the network elements, i.e. Optical Line Terminal (OLT), ONU and Femtocell Base Station (FBS) in the integrated access network were identified.
- The integrated access network was dimensioned and the power consumption model was developed which is the sum of contribution from the power consumed by each network elements. The power consumption model for the ONU was based on the experimental measurements.

ii. Experimental setup for the ONU power consumption characterization.

- Experiment tools such as traffic generator, client and server were set up on the GPON tesbed.
- Power consumption of the ONU was monitored based on Arduino-based power meter where the measurement is limited to a maximum access data rate of 100 Mbps due to the limitation in the sampling rate of the power meter device.
- Comparison with theoretical power consumption modeling was conducted for validation purpose.

iii. Energy performance evaluation and implementation of power saving mode based on user behaviour.

- Various parameters were considered in order to investigate their effect to the energy performance of the integrated GPON with LTE and WiMAX access network. Two energy metrics were used in order to quantify the energy performance; total network power consumption and energy efficiency.
- The traffic profile from Cyberjaya municipal was used to represent the user behaviour of the network.
- Power saving modes were applied to the ONU and FBS which are power sheeding for ONU and idle mode procedure for FBS and its effect to the energy performance was studied.

1.5 Research Methodology

In order to achieve research objectives presented in the previous section, the study was classified into three phases namely; modeling approach, experimental design and user behavior dimensioning.

1.5.1 Modeling Approach

The energy efficiency of the integrated optical-wireless access network is implemented as depicted in Figure 1.1. First of all, the network was dimensioned by defining some technology and topology related parameters and limitations such as coverage area need to be considered, cell range of the FBS and split ratio for GPON. Then, the total power consumption model of the integrated access network was formulated by summing up the power consumption (PC) values of all active network elements such as OLTs and IOBs. For that reason, the power consumption of the ONU was modeled based on the experimental measurement in which the relationship between instantenous ONU power consumption and traffic load was considered. Power consumption model for the OLT and FBS are based on previously reported works [17, 18]. In the meantime, the user demand was also defined which will be used to determine the achievable data rate. Finally, the end product would be the energy efficiency which is obtained by dividing the resulting data rate by the total network power consumption.

1.5.2 Experimental Design

The goal of the experiment was to measure the power consumption of the ONU and investigate its relationship with traffic load. The experimental testbed is a GPON which consists of one OLT chasis, one 1:32 passive splitter and several ONUs. The devices are commercial products of market leading companies. The OLT was connected to the splitter with 20 km optical fiber link. Figure 1.2 depicts the experimental setup utilized in the measurement work.

An *iPerf* traffic generator injected a UDP traffic to the ONU 2 where the transmit data rate was varied from 0 to 100 Mbps. Then the traffic was transmitted to the OLT in which the OLT re-transmit the UDP traffic to the ONU 1. When the ONU 1 received the traffic, the Arduino-based power meter was utilized to monitor and measure the real time power consumption when the ONU acting as a receiver. The power meter is a plug load power meter that comprises DC power supply, voltage sensor, current sensor and solid state relay. It has the advantages of low cost, easy integration into a desktop and laptop and provide real time power consumption monitoring. The computed average power consumption will be displayed by the serial monitor from the Arduino IDE where the reading was transmitted by the Arduino microcontroller. The resulting experimental measurement will be used to develop the ONU power consumption modeling. The comparison between the developed ONU power consumption model and the theoretical power consumption model will be performed in order to validate the developed model. The details on the ONU power consumption model based on experimental measurement will be presented in detail in Chapter 4.

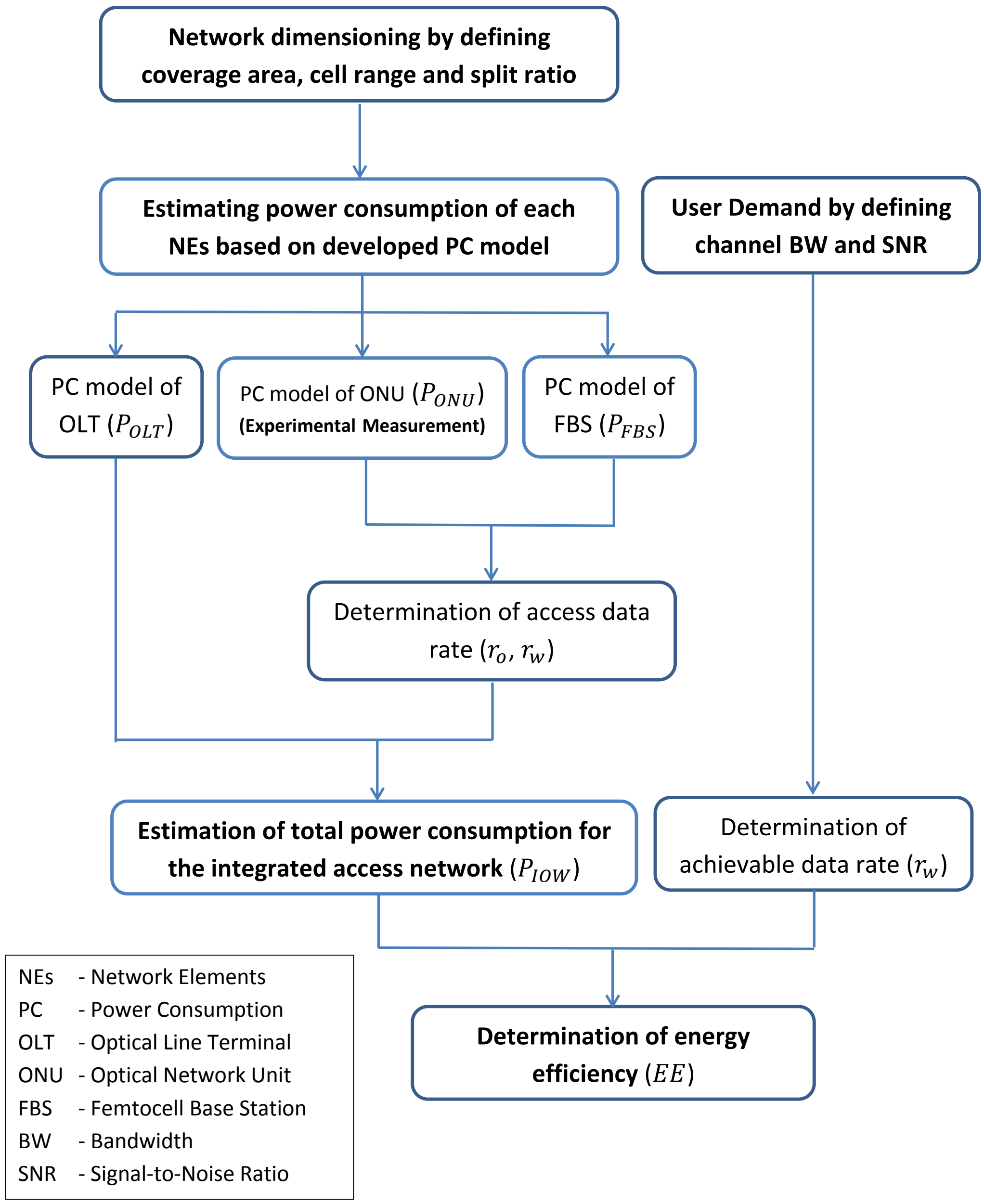

Figure 1.1: Overview of modeling approach

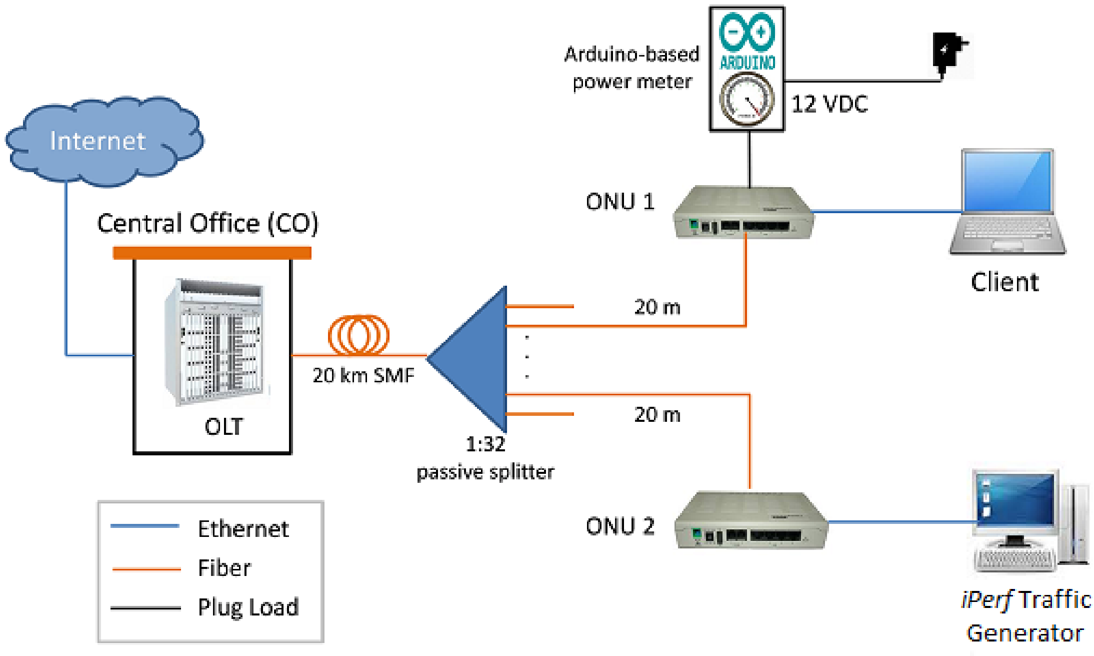

Figure 1.2: The experimental testbed

1.5.3 User Behavior Dimensioning

The energy performance of the integrated access network was further investigated by considering user behavior dimensioning. The modeling approach can be found in Figure 1.3. User behavior was represented by a realistic daily traffic profile from Cyberjaya municipal. Then, the number of active IOBs during low traffic was defined. Following that, the implementation of power saving modes for the IOBs was considered so that energy reduction can be achieved. The performance of the integrated access network was investigated by assuming several power saving schemes. Details explanation in this approach is presented in Chapter 5.

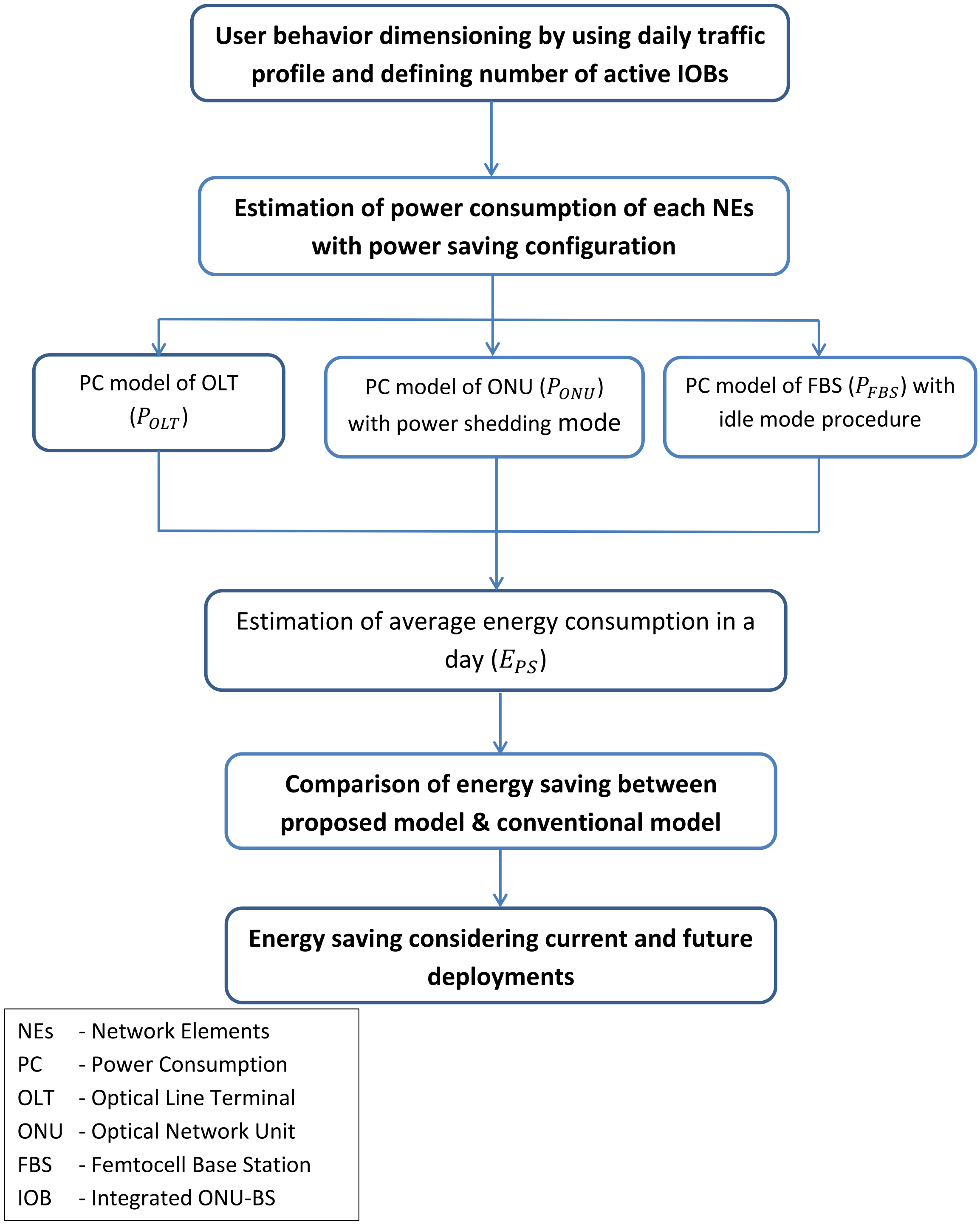

Figure 1.3: Overview of modeling approach considering user behavior dimensioning

1.6 Research Contribution

The main contributions of this thesis are:

i. Development of the power consumption model for the IOB and the whole integrated optical wireless access network.

ii. Proposal of a more realistic power consumption model for the ONU which is validated by experimental measurement with real GPON testbed.

iii. Implementation of network user behavior in order to assess the power saving application for reducing energy consumption of the integrated access networks.

1.7 Thesis Outline

This thesis is composed of six chapters, which are organized as follows. Chapter 2 provides an introduction to the optical access networks, wireless access networks which include their infrastructures and their evolutions. PONs are widely examined and different standards are summarized. The evolution of wireless networks and the associated standards are given and the optical-wireless access networks' architectures are described. The advantages of the integrated access networks are listed. Then, the related works on power consumption model for both optical and wireless network whether independent or as a converged network as well as energy efficiency efforts are described.

The mathematical models for the power consumption of the IOB and the whole integrated access network were presented in Chapter 3. The generic structures of each network element in the integrated access networks are presented. The ONU power consumption model will be based on the experimental measurement proposed in the following chapter. Additionally, the power saving techniques implemented to reduce the power consumption of the integrated access networks were also described. A daily traffic profile will be used to represent the network user behavior in which the power saving applied will be based on this traffic pattern.

Chapter 4 investigates the power consumption behavior of ONU with different traffic loads. An Arduino-based power meter was utilized which provides real time power monitoring to characterize the ONU from an energy consumption standpoint.

The real GPON testbed was exploited in the experiment for monitoring, measurement and analysis of the power consumption patterns of the ONU. The measurement results show that the power consumption of the ONU exhibits a linear dependence on the traffic loads.

Chapter 5 focuses on the simulation results and analysis of the total power consumption and energy efficiency of the integrated access network. Different simulation scenarios were considered in order to analyze the energy performance of such network. The real traffic profile which is based on user behavior in Cyberjaya municipal was also considered in the implementation of power saving techniques to the network.

Finally, Chapter 6 concludes the thesis with summary of the main topics, followed by some perspectives about future works.

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