

# **Design and Development of Dynamic Bandwidth Allocation Algorithms for Power Efficient Optical Access Networks**

Sukriti Garg



Bharti School of Telecommunication Technology and Management  
Indian Institute of Technology Delhi, New Delhi

October 2022

# **Design and Development of Dynamic Bandwidth Allocation Algorithms for Power Efficient Optical Access Networks**

Dissertation submitted in fulfilment  
of the requirements for the degree of

*Doctor of Philosophy*

by

**Sukriti Garg**

Under the guidance of  
**Prof. Abhishek Dixit**



Bharti School of Telecommunication Technology and Management  
Indian Institute of Technology Delhi, New Delhi

October 2022

© Indian Institute of Technology Delhi (IITD), New Delhi, 2022.

*To family and friends*



# Certificate

This is to certify that the dissertation entitled “**Design and Development of Dynamic Bandwidth Allocation Algorithms for Power Efficient Optical Access Networks**” submitted by **Sukriti Garg** (2016BSZ8041) for the award of the degree of **Doctor of Philosophy**, is a record of bonafide research work carried out by her at Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi, New Delhi, India, during the academic session 2016-2021 under my supervision and guidance. The results contained in this dissertation have not been submitted either in part or in full to any other University or Institute for award of any other degree. In my opinion, this dissertation is of standard required for the award of the degree of Doctor of Philosophy.

**Prof. Abhishek Dixit**

Department of Electrical Engineering  
Indian Institute of Technology Delhi  
Hauz Khas, New Delhi, 110016, India

Date:

Place: New Delhi



# Acknowledgements

Enumerating and enlisting all the individuals whose contributions went into the making of the dissertation is a very difficult task.

Foremost, very sincere and honest words of thanks for Prof. Abhishek Dixit, my PhD supervisor at Indian Institute of Technology Delhi, for his invaluable suggestions and ideas during my PhD. It is his wisdom, clarity of thoughts, and support that motivated and guided me to bring this dissertation in its present state. His immense knowledge and plentiful experience has encouraged me in all the time of my academic research and daily life. He has not only taught the fundamentals essential for presenting such a dissertation but has also helped me to develop as an individual. The values inculcated and the management skills imparted by him have been of immense help at every point of my career.

I would like to thank my student research committee members, Prof. Vivek Venkatraman, Prof. Subrat Kar, and Prof. R. K. Varshney for their valuable feedback and suggestions during my end semester presentations. I have benefited greatly from their wealth of knowledge.

I have been fortunate to meet many good friends at IIT Delhi. The long and painful hours spent on this dissertation became an entertainment with Sonali and Kshitiza. Without their support this work would not have been completed. I am thankful to them for having valuable discussions and giving encouragement whenever I needed. I would like to thank Rishu and Nitin sir for helping me in every possible way. I am also thankful to all friends who made my IIT journey unforgettable one. I would also like to thank Rajesh sir, Neeru ma'am, and Negi sir, the staff of Photonics lab and Optical communication lab here at IIT Delhi for maintaining a research friendly and secure atmosphere in the lab even during the tough covid times.

Lastly, I would like to express my heartfelt appreciation to my husband Saurabh for his

love, understanding, and generous support during these years. I am grateful to him for being besides me in my lows and highs and for the sacrifices he made in order for me to pursue a PhD degree. I am also thankful to my family (my mother, father, brother and in-laws) for their indispensable support, blessings and encouragement in every decision that I take in my life.

Sukriti Garg

# Abstract

With the increase in the subscribers of high-definition multi-media applications, mobile back-hauling, and content-rich cloud services, the data rate requirement of the access network is increasing exponentially. Passive optical networks (PONs) are becoming a prominent solution due to their high data rate support and economic nature. At this moment, there are several PON flavors – time division multiplexed (TDM) PON (such as Ethernet PON (EPON), Gigabit PON (GPON)), wavelength division multiplexed (WDM) PON, and time and wavelength division multiplexed (TWDM) PON. Power efficiency is an essential attribute of these PON technologies, not only for reducing operational expenditures but also for the carbon footprint. In this dissertation, we keep power efficiency as the foremost attribute and optimize the most power-efficient PON for other performance parameters like delay and packet loss rate.

Thus, the first task in the dissertation is to search for the most power-efficient PON solution, which is accomplished by evaluating the currently available power-efficient mechanisms. The power efficiency of a PON solution can be minimized in several ways, e.g., optimal PON dimensioning, sleep modes, and designing next-generation power-efficient PON candidates, like bit-interleaved PON (Bi-PON), wavelength split TWDM-PON, and wavelength-switched TWDM-PON. Some of these efforts can also be combined. A natural question thus arises what are the power savings of these various mechanisms, and are there some synergy gains if these efforts are combined?

In this dissertation, we propose analytical models for evaluating the power-saving potentials of optimal PON dimensioning, sleep modes, and next-generation PON candidates like Bi-PON, wavelength split, and wavelength switched TWDM-PON. For optimal PON dimensioning, we consider a promised grade of service to the users. Additionally, to explore the sleep mode functionality, we consider state-of-the-art dynamic bandwidth allocation (DBA)

algorithms like sleep mode aware (SMA) and hybrid sleep mode aware (HSMA). We then propose the power models to assess the power efficiency of sleep modes in combination with the optimal dimensioning. In addition, we further extend these mechanisms to the next-generation PON candidates and evaluate the power-saving potentials. Furthermore, we validate all these analytical models with the simulation results to show the proposed models' accuracy. After comparing the power consumption of all these technologies, we found that architectures using TWDM-PON technology are the most power-efficient.

Super passive optical network (Super-PON, Ethernet counterpart of TWDM-PON), a prominent next-generation Ethernet PON (NG-EPON) candidate, is envisaged to provide high data rate and low latency. To support such requirements, Super-PON employs multiple wavelengths. The over-and under-utilization of these wavelengths impacts the network performance. Hence, there is a need to manage these wavelengths and their bandwidth correctly. For NG-EPON, two types of algorithms manage bandwidth and wavelength scheduling, namely offline and online. The online algorithms are generally more efficient at keeping the delay of the network below the desired threshold. On the other hand, offline algorithms can employ power-efficient mechanisms with lower complexity. We use the online algorithms for business users (or those requiring advanced services like tactile Internet, etc.), for whom delay is the most critical network performance parameter. On the other hand, we use offline algorithms to minimize power consumption for residential users, for whom delay is less necessary. In this dissertation, we first propose an online algorithm and later propose three offline algorithms.

Several online algorithms exist that propose schemes to manage wavelength and bandwidth scheduling. However, these algorithms lack efficient wavelength utilization and switching. We propose a novel online bin-packing based dynamic bandwidth and wavelength allocation (DBWA) algorithm for Super-PON, namely updated best fit bin-packing (UBF-BP). This algorithm limits the wavelength switching per cycle and uses the modified version of the best fit bin-packing (BF-BP) technique for optimal wavelength allocation. Simulation results show that the proposed DBWA algorithm has low complexity and overcomes the inefficiencies of wavelength utilization and switching. This results in lower network delay (approx. 50% less) and higher channel utilization (approx. 5% more) than the state-of-the-art DBWA. Furthermore, to verify the correctness of the proposed algorithm, we propose an analytical model and validate these simulation results with the analytical results.

As mentioned before, Super-PON employs many transceivers that also increase the power consumption of the network. Therefore, to reduce the carbon footprint of Super-PON, we propose power-efficient offline DBWA algorithms, namely, first fit bin-packing SMA (BP-SMA), best fit bin-packing SMA (BF-SMA), and updated BF-SMA (UBF-SMA). The proposed algorithms use SMA for bandwidth scheduling and different bin-packing techniques for wavelength allocation. In bin-packing, the number of available wavelengths and their efficient allocation is based on the network load. To restrict the number of available wavelengths, we can switch off the non-essential transceivers at the OLT, which also helps in maximizing the wavelength utilization and power efficiency. The simulation results show that compared to the state-of-the-art DBWA algorithms, the proposed algorithms improve the power efficiency (approx. 9% more) and reduce the average delay (approx. 50% less) of a Super-PON system. Furthermore, we use Jain's fairness index to validate the fairness of the proposed DBWA algorithms.



## सार

हाई-डेफिनिशन मल्टी-मीडिया एप्लिकेशन, मोबाइल बैकहॉलिंग और विषय-समृद्ध क्लाउड सेवाओं के ग्राहकों में वृद्धि के साथ, एक्सेस नेटवर्क की डेटा दर की आवश्यकता तेजी से बढ़ रही है। निष्क्रिय ऑप्टिकल नेटवर्क (पीओएन) अपने उच्च डेटा दर समर्थन और किफायती प्रकृति के कारण एक प्रमुख समाधान बन रहे हैं। इस समय, कई प्रकार के पीओएन हैं - टाइम डिवीजन मल्टीप्लेक्स (टीडीएम) पीओएन (जैसे ईथरनेट पीओएन (ईपीओएन), गिगाबिट पीओएन (जीपीओएन)), वेवलेंथ डिवीजन मल्टीप्लेक्स (डब्ल्यूडीएम) पीओएन, और टाइम एंड वेवलेंथ डिवीजन मल्टीप्लेक्स (टीडब्ल्यूडीएम) पीओएन। न केवल परिचालन व्यय को कम करने के लिए बल्कि कार्बन फुटप्रिंट के लिए भी ऊर्जा दक्षता इन पीओएन का एक अनिवार्य गुण है। इस शोध प्रबंध में, हम ऊर्जा दक्षता को सबसे प्रमुख विशेषता के रूप में रखते हैं और देरी और पैकेट क्षति दर जैसे अन्य निष्पादन मापदंडों के लिए सबसे अधिक शक्ति-कुशल पीओएन का अनुकूलन करते हैं।

इस प्रकार, शोध प्रबंध में पहला कार्य सबसे अधिक ऊर्जा-कुशल पीओएन समाधान की खोज करना है, जो वर्तमान में उपलब्ध ऊर्जा-कुशल तंत्र का मूल्यांकन करके पूरा किया जाता है। पीओएन समाधान की ऊर्जा दक्षता को कई तरीकों से कम किया जा सकता है, उदाहरण के लिए, इष्टतम पीओएन आयाम, स्लीप मोड, और अगली पीढ़ी के ऊर्जा-कुशल पीओएन उम्मीदवारों की रचना करना, जैसे बिट-इंटरलीव्ड पीओएन (बीआई-पीओएन), तरंगदैर्घ्य विभाजन टीडब्ल्यूडीएम-पीओएन, और तरंगदैर्घ्य-स्विचड टीडब्ल्यूडीएम-पीओएन। इनमें से कुछ प्रयासों को संयुक्त भी किया जा सकता है। इस प्रकार एक स्वाभाविक प्रश्न उठता है कि इन विभिन्न तंत्रों की ऊर्जा बचत कितनी है, और यदि इन प्रयासों को मिला दिया जाए तो क्या कुछ सहक्रियात्मक लाभ होंगे?

इस शोध प्रबंध में, हम इष्टतम पीओएन आयाम, स्लीप मोड, और अगली पीढ़ी के पीओएन उम्मीदवारों जैसे बीआई-पीओएन, वेवलेंथ स्प्लिट और वेवलेंथ स्विचड टीडब्ल्यूडीएम-पीओएन की ऊर्जा-बचत क्षमता के मूल्यांकन के लिए विश्लेषणात्मक मॉडल प्रस्तावित करते हैं। इष्टतम पीओएन आयाम के लिए, हम उपयोगकर्ताओं को सेवा के एक वादा किए गए ग्रेड पर विचार करते हैं। इसके अतिरिक्त, स्लीप मोड कार्यक्षमता का पता लगाने के लिए, हम अत्याधुनिक गतिशील बैंडविड्थ आवंटन (डीबीए) एल्गोरिदम जैसे स्लीप मोड अवेयर (एसएमए) और हाइब्रिड स्लीप मोड अवेयर (एचएसएमए) पर विचार करते हैं। फिर हम इष्टतम आयाम के साथ संयोजन में स्लीप मोड की ऊर्जा दक्षता का आकलन करने के लिए ऊर्जा मॉडल का प्रस्ताव करते हैं। इसके अलावा, हम इन तंत्रों को अगली पीढ़ी के पीओएन उम्मीदवारों तक विस्तारित करते हैं और ऊर्जा-बचत क्षमता का मूल्यांकन करते हैं। इसके अलावा, हम इन सभी विश्लेषणात्मक मॉडलों को प्रस्तावित मॉडल की सटीकता दिखाने के लिए सिमुलेशन परिणामों के साथ मान्य करते हैं। इन सभी तकनीकों की ऊर्जा खपत की तुलना करने के बाद, हमने पाया कि टीडब्ल्यूडीएम-पीओएन तकनीक का उपयोग करने वाले आर्किटेक्चर सबसे अधिक ऊर्जा-कुशल हैं।

सुपर निष्क्रिय ऑप्टिकल नेटवर्क (सुपर-पीओएन, टीडब्ल्यूडीएम-पीओएन का ईथरनेट समकक्ष), एक प्रमुख अगली पीढ़ी के ईथरनेट पीओएन (एनजी-ईपीओएन) उम्मीदवार, उच्च डेटा दर और कम विलंबता प्रदान करने के लिए परिकल्पित है। ऐसी आवश्यकताओं का समर्थन करने के लिए, सुपर-पीओएन कई तरंगदैर्घ्य को नियोजित करता है। इन तरंगदैर्घ्य का अधिक और कम उपयोग नेटवर्क के प्रदर्शन को प्रभावित करता है। इसलिए, इन तरंगदैर्घ्य और उनके बैंडविड्थ को सही ढंग से प्रबंधित करने की आवश्यकता है। एनजी-ईपीओएन के लिए, दो प्रकार के एल्गोरिदम बैंडविड्थ और तरंगदैर्घ्य शेड्यूलिंग का प्रबंधन करते हैं: ऑफ़लाइन और ऑनलाइन। नेटवर्क की देरी को वांछित सीमा से नीचे रखने में ऑनलाइन एल्गोरिदम आम तौर पर अधिक कुशल होते हैं। दूसरी ओर, ऑफ़लाइन एल्गोरिदम कम जटिलता वाले ऊर्जा-कुशल तंत्र को नियोजित कर सकते हैं। हम व्यावसायिक उपयोगकर्ताओं (या स्पर्शनीय इंटरनेट जैसी उन्नत सेवाओं की आवश्यकता वाले लोगों) के लिए ऑनलाइन एल्गोरिदम का उपयोग करते हैं, जिनके लिए देरी सबसे महत्वपूर्ण नेटवर्क निष्पादन मापदंड है। दूसरी ओर, हम आवासीय उपयोगकर्ताओं के

लिए ऊर्जा की खपत को कम करने के लिए ऑफ़लाइन एल्गोरिदम का उपयोग करते हैं, जिनके लिए देरी कम आवश्यक है। इस शोध प्रबंध में, हम पहले एक ऑनलाइन एल्गोरिथम प्रस्तावित करते हैं और बाद में तीन ऑफ़लाइन एल्गोरिथम प्रस्तावित करते हैं।

कई ऑनलाइन एल्गोरिदम मौजूद हैं जो तरंगदैर्घ्य और बैंडविड्थ शेड्यूलिंग को प्रबंधित करने के लिए योजनाओं का प्रस्ताव करते हैं। हालांकि, इन एल्गोरिदम में कुशल तरंगदैर्घ्य उपयोग और स्विचिंग का अभाव है। हम सुपर-पीओएन के लिए एक नई ऑनलाइन बिन-पैकिंग आधारित गतिशील बैंडविड्थ और तरंगदैर्घ्य आवंटन (डीबीडब्ल्यूए) एल्गोरिदम का प्रस्ताव करते हैं, जिसका नाम अद्यतन सर्वोत्तम फिट बिन-पैकिंग (यूबीएफ-बीपी) है। यह एल्गोरिथम प्रति चक्र तरंगदैर्घ्य स्विचिंग को सीमित करता है और इष्टतम तरंगदैर्घ्य आवंटन के लिए सर्वोत्तम फिट बिन-पैकिंग (बीएफ-बीपी) तकनीक के संशोधित संस्करण का उपयोग करता है। सिमुलेशन परिणाम बताते हैं कि प्रस्तावित डीबीडब्ल्यूए एल्गोरिथम में कम जटिलता है और तरंगदैर्घ्य उपयोग और स्विचिंग की अक्षमताओं को दूर करता है। इसके परिणामस्वरूप अत्याधुनिक डीबीडब्ल्यूए की तुलना में कम नेटवर्क विलंब (लगभग 50% कम) और उच्च चैनल उपयोग (लगभग 5% अधिक) होता है। इसके अलावा, प्रस्तावित एल्गोरिथम की शुद्धता को सत्यापित करने के लिए, हम एक विश्लेषणात्मक मॉडल का प्रस्ताव करते हैं और विश्लेषणात्मक परिणामों के साथ इन सिमुलेशन परिणामों को मान्य करते हैं।

जैसा कि पहले उल्लेख किया गया है, सुपर-पीओएन कई ट्रांसीवरों को नियोजित करता है जो नेटवर्क की ऊर्जा खपत को भी बढ़ाते हैं। इसलिए, सुपर-पीओएन के कार्बन फुटप्रिंट को कम करने के लिए, हम ऊर्जा-कुशल ऑफ़लाइन डीबीडब्ल्यूए एल्गोरिदम का प्रस्ताव करते हैं: पहले फिट बिन-पैकिंग एसएमए (बीपीएसएमए), बेस्ट फिट बिन-पैकिंग एसएमए (बीएफ-एसएमए), और अपडेटेड बीएफ-एसएमए। (यूबीएफ-एसएमए)। प्रस्तावित एल्गोरिदम बैंडविड्थ शेड्यूलिंग के लिए एसएमए और तरंगदैर्घ्य आवंटन के लिए विभिन्न बिन-पैकिंग तकनीकों का उपयोग करते हैं। बिन-पैकिंग में, उपलब्ध तरंगदैर्घ्य की संख्या और उनका कुशल आवंटन नेटवर्क लोड पर आधारित होता है। उपलब्ध तरंगदैर्घ्य की संख्या को सीमित करने के लिए, हम ओएलटी पर गैर-आवश्यक ट्रांसीवर को बंद कर सकते हैं, जो तरंगदैर्घ्य उपयोग और ऊर्जा दक्षता को अधिकतम करने में भी मदद करता है। सिमुलेशन परिणाम बताते हैं कि अत्याधुनिक डीबीडब्ल्यूए एल्गोरिदम की तुलना में, प्रस्तावित एल्गोरिदम ऊर्जा दक्षता (लगभग 9% अधिक) में सुधार करते हैं और सुपर-पीओएन सिस्टम की औसत देरी (लगभग 50% कम) को कम करते हैं। इसके अलावा, हम प्रस्तावित डीबीडब्ल्यूए एल्गोरिदम की निष्पक्षता को मान्य करने के लिए जैन के निष्पक्षता सूचकांक का उपयोग करते हैं।

# Table of Contents

<b>Certificate</b>	<b>i</b>
<b>Acknowledgements</b>	<b>ii</b>
<b>Abstract</b>	<b>iv</b>
<b>List of Figures</b>	<b>xi</b>
<b>List of Tables</b>	<b>xviii</b>
<b>List of Abbreviations</b>	<b>xix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Passive optical network (PON) . . . . .	2
1.1.1 EPON and GPON . . . . .	2
1.1.2 10 G-EPON and XG-PON . . . . .	3
1.1.3 WDM-PON . . . . .	4
1.1.4 Super-PON and TWDM-PON . . . . .	5

1.2	Resources management in PONs . . . . .	9
1.2.1	Bandwidth management . . . . .	9
1.2.2	Wavelengths management . . . . .	20
1.2.3	Bandwidth and wavelengths management . . . . .	22
1.3	Power saving in PONs . . . . .	23
1.3.1	Power saving potentials at the ONUs . . . . .	24
1.3.2	Power saving potentials at the OLT . . . . .	27
1.3.3	Bit interleaving and caching . . . . .	29
1.4	Research objectives and scope of work . . . . .	30
1.5	Organization of the dissertation . . . . .	34
<b>2</b>	<b>Evaluating Power Saving Techniques in Passive Optical Access Networks</b>	<b>36</b>
2.1	Power consumption model . . . . .	38
2.1.1	Customer premises power consumption . . . . .	39
2.1.2	Central office (CO) power consumption . . . . .	41
2.1.3	Average power per user . . . . .	42
2.2	PON design with optimal dimensioning . . . . .	43
2.3	Sleep mode functionality . . . . .	46
2.3.1	Introduction to the sleep mode enabling DBA . . . . .	46
2.3.2	Sleep time calculations . . . . .	47

2.3.3	Power consumption in PON with optimal dimensioning and sleep mode	50
2.3.4	Performance evaluation . . . . .	51
2.4	Bit interleaving PON (Bi-PON) . . . . .	56
2.5	Two remote nodes based TWDM-PON . . . . .	59
2.5.1	Wavelength split TWDM-PON . . . . .	59
2.5.2	Wavelength switched TWDM-PON . . . . .	61
2.5.3	Performance evaluation . . . . .	62
2.6	Summary . . . . .	65
<b>3</b>	<b>Bin-packing Based Online Dynamic Bandwidth and Wavelength Allocation Algorithm in Super-PON</b>	<b>66</b>
3.1	Super-PON . . . . .	69
3.2	Proposed DBWA algorithm for Super-PON . . . . .	70
3.2.1	Best fit bin-packing . . . . .	71
3.2.2	UBF-BP algorithm . . . . .	71
3.2.3	Grant sizing schemes . . . . .	79
3.3	Delay analysis considering Pareto distributed sources . . . . .	80
3.3.1	Delay model for UBF-BP algorithm . . . . .	81
3.4	Results and discussions . . . . .	85
3.4.1	EFT-OS (State-of-the-art DBWA) . . . . .	85

3.4.2	OMNeT++ implementation of Super-PON . . . . .	86
3.4.3	Performance analysis . . . . .	87
3.4.4	Complexity analysis . . . . .	96
3.5	Summary . . . . .	97
<b>4</b>	<b>Bin-Packing Based Offline Dynamic Bandwidth and Wavelength Allocation Algorithms for Power Efficiency in Super-PON</b>	<b>98</b>
4.1	Super-PON . . . . .	101
4.2	Proposed power-efficient DBWA algorithm . . . . .	101
4.2.1	BP-SMA . . . . .	104
4.2.2	BF-SMA . . . . .	106
4.2.3	UBF-SMA . . . . .	110
4.2.4	Grant sizing methods . . . . .	113
4.2.5	Power calculations . . . . .	114
4.3	Results and discussion . . . . .	114
4.3.1	State-of-the-art algorithms . . . . .	114
4.3.2	Performance analysis . . . . .	115
4.3.3	Complexity analysis . . . . .	128
4.4	Summary . . . . .	128
<b>5</b>	<b>Conclusions and Future Work</b>	<b>129</b>

5.1	Summary of contributions . . . . .	129
5.2	Scope of future work . . . . .	131
	<b>Bibliography</b>	<b>132</b>
	<b>List of Publications</b>	<b>149</b>
	<b>Technical Biography of Author</b>	<b>151</b>



# List of Figures

1.1	PON architecture. . . . .	2
1.2	EPON and GPON architecture. . . . .	3
1.3	Wavelength-split WDM-PON architecture. . . . .	5
1.4	Wavelength select WDM-PON architecture. . . . .	6
1.5	Wavelength split TWDM-PON architecture. . . . .	7
1.6	Wavelength select TWDM-PON architecture. . . . .	8
1.7	MPCP control message exchange. . . . .	11
1.8	Timing diagram for poll and stop polling strategy. . . . .	13
1.9	Timing diagram for interleaved polling strategy. . . . .	14
1.10	Timing diagram for interleaved polling and stop strategy. . . . .	15
1.11	Various parameters of quality of service (QoS). . . . .	19
1.12	Simple ONU construction. . . . .	25
2.1	Illustration of simplified street length model. . . . .	38

2.2	Passive optical access network architecture ( $S$ denotes the split ratio of the remote node). . . . .	39
2.3	Number of users ( $N_A$ ) served vs. violation of promised availability for average user data rate ( $B_m$ ) of 75 Mbps, 100 Mbps, 200 Mbps, and 300 Mbps (theoretical). . . . .	45
2.4	Timing diagram considering sleep mode. . . . .	48
2.5	Theoretical and simulated sleep time per cycle variation considering GPON. . . . .	50
2.6	Percentage of power consumption w.r.t. the maximum power consumed in SMA and HSMA for theoretical and simulation cases (Theoretical maximum power consumption for SMA is 10.23 W, and for HSMA is 9.34 W). . . . .	53
2.7	Percentage of power savings w.r.t. no sleep mode case in SMA and HSMA for theoretical and simulation cases. . . . .	53
2.8	Power consumption of PON considering optimal dimensioning scenario (theoretical). . . . .	54
2.9	Percentage of power savings in sleep mode for PON with optimal dimensioning. . . . .	55
2.10	Percentage of power savings in sleep mode for PON with optimal dimensioning considering asymmetric load and symmetric load. . . . .	56
2.11	(a) Bi-PON ONU construction (b) XG-PON ONU construction. . . . .	57
2.12	Percentage of power consumption w.r.t. the maximum power consumed in Bi-PON for theoretical and simulation cases. . . . .	58
2.13	Theoretical power consumption in XG-PON, Bi-PON, and Bi-PON with sleep mode shown using vertical left axis and theoretical power savings w.r.t. XG-PON shown using vertical right axis and dashed line. . . . .	58

2.14	(a) Wavelength split TWDM-PON architecture (b) Wavelength switched TWDM-PON architecture. . . . .	60
2.15	Variation of split ratio w.r.t. average user data rate $B_m$ for different two remote nodes based TWDM-PONs (theoretical). . . . .	63
2.16	Power consumption of wavelength switched, wavelength split, and wavelength select TWDM-PONs for theoretical and simulation cases. . . . .	63
2.17	Theoretical power consumption in wavelength split architecture with sleep mode shown using the left vertical axis and theoretical power savings are shown using the right vertical axis and the dashed lines. . . . .	64
2.18	Theoretical power consumption per user for different optical access technologies using sleep mode at the average user data rate of 100 Mbps and 600 Mbps. 65	
3.1	Super-PON architecture (Abbreviations in figure: PD - Photodiodes, AWG - Arrayed waveguide grating, DFB - Distributed feedback laser, OA - Optical amplifiers, TF - Tunable optical filter). . . . .	69
3.2	Timing diagram explaining space available on a wavelength for the UBF-BP algorithm. . . . .	73
3.3	Flowchart of the proposed UBF-BP algorithm ( $w$ is the current wavelength of the ONU, and $m$ is the wavelength with the maximum available capacity). 77	
3.4	SIPACT algorithm timing diagram. . . . .	79
3.5	Delay vs. network load for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s, and symmetric network load (simulation). . . . .	88
3.6	Worst-case delay vs. network load for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s, and symmetric network load (simulation). . . . .	90

3.7	Packet loss rate vs. network load for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s, and symmetric network load (simulation). . . . .	90
3.8	Theoretical and simulation case delay vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 4 Gb/s, reach of 25 km, maximum ONU data rate of 100 Mb/s, and symmetric network load. . . . .	91
3.9	Delay vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 10 Gb/s, reach of 25 km, maximum ONU data rate of 200 Mb/s, and symmetric network load (simulation). . . . .	92
3.10	Packet loss rate vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 10 Gb/s, reach of 25 km, maximum ONU data rate of 200 Mb/s, and symmetric network load (simulation). . . . .	92
3.11	Theoretical and simulation case delay vs. network load for the UBF-BP algorithm for different tuning times (TT) with a downstream line rate of 10 Gb/s, reach 25 km, maximum ONU data rate of 200 Mb/s considering the gated grant sizing scheme, and symmetric network load. . . . .	93
3.12	Theoretical and simulation case delay vs. network load for the UBF-BP algorithm using the gated scheme and different reach (L) with a downstream line rate of 10 Gb/s, tuning time of 1 ms, maximum ONU data rate of 200 Mb/s, and symmetric network load. . . . .	94
3.13	Delay shown using vertical left axis and fairness index shown using right vertical axis and dashed line for the UBF-BP algorithm with a downstream line rate of 10 Gb/s, reach of 25 km, tuning time of 100 $\mu$ s, maximum ONU data rate of 200 Mb/s, and asymmetric network load (simulation). . . . .	95

3.14	Delay shown using vertical left axis and fairness index shown using right vertical axis and dashed line for the UBF-BP algorithm with a downstream line rate of 10 Gb/s, reach of 25 km, tuning time of 1 ms, maximum ONU data rate of 200 Mb/s, and asymmetric network load (simulation). . . . .	95
3.15	Packet loss rate shown using vertical left axis and fairness index shown using right vertical axis and dashed line for the UBF-BP algorithm considering different tuning times (TT) with a downstream line rate of 10 Gb/s, reach of 25 km, maximum ONU data rate of 200 Mb/s, and asymmetric network load (simulation). . . . .	96
4.1	Typical Super-PON architecture (Abbreviations in the figure: AWG - Arrayed waveguide grating, WDM - Wavelength division multiplexing, OA - Optical amplifiers). . . . .	102
4.2	Sleep mode aware algorithm timing diagram. . . . .	104
4.3	First-fit algorithm example . . . . .	105
4.4	An example of the BF-SMA algorithm. . . . .	110
4.5	Flowchart of the proposed UBF-SMA algorithm ( $m$ is the wavelength with the maximum available capacity). . . . .	111
4.6	An example of the UBF-SMA algorithm. . . . .	112
4.7	Upstream delay shown using vertical left axis and packet loss rate shown using vertical right axis and the dashed line considering symmetric network load for gated grant sizing scheme. . . . .	117
4.8	Upstream delay shown using vertical left axis and packet loss rate shown using vertical right axis and the dashed line considering symmetric network load for limited grant sizing scheme. . . . .	117

4.9	Upstream delay shown using vertical left axis and packet loss rate shown using vertical right axis and the dashed line considering symmetric network load for UDC grant sizing scheme. . . . .	118
4.10	Percentage of power savings considering symmetric network load for gated grant sizing scheme. . . . .	119
4.11	Percentage of power savings considering symmetric network load for limited grant sizing scheme. . . . .	119
4.12	Percentage of power savings considering symmetric network load for UDC grant sizing scheme. . . . .	120
4.13	Upstream delay vs. packet loss rate considering symmetric network load for gated grant sizing scheme. . . . .	121
4.14	Upstream delay vs. packet loss rate considering symmetric network load for limited grant sizing scheme. . . . .	121
4.15	Upstream delay vs. packet loss rate considering symmetric network load for UDC grant sizing scheme. . . . .	122
4.16	Upstream delay shown using vertical left axis and fairness index shown using vertical right axis and dashed line for UBF-SMA gated scheme and asymmetric load with decreasing ONUs arrangement. . . . .	122
4.17	Upstream delay shown using vertical left axis and fairness index shown using vertical right axis and dashed line for UBF-SMA gated scheme and asymmetric load with increasing ONUs arrangement. . . . .	123
4.18	Packet loss rate vs. network load for UBF-SMA gated scheme and asymmetric load. . . . .	124
4.19	Upstream delay vs. packet loss rate for UBF-SMA gated scheme and asymmetric load. . . . .	125

4.20	Upstream delay shown using vertical left axis and fairness index shown using vertical right axis and dashed line for UBF-SMA limited scheme and asymmetric load with decreasing ONUs arrangement. . . . .	125
4.21	Upstream delay shown using vertical left axis and fairness index shown using vertical right axis and dashed line for UBF-SMA limited scheme and asymmetric load with increasing ONUs arrangement. . . . .	126
4.22	Packet loss rate vs. network load for UBF-SMA limited scheme and asymmetric load. . . . .	127
4.23	Upstream delay vs. packet loss rate for UBF-SMA limited scheme and asymmetric load. . . . .	127



# List of Tables

1.1	Summary of various PON technologies . . . . .	8
2.1	Notations used in this chapter . . . . .	40
2.2	Power consumption parameters . . . . .	40
3.1	Notations used in this chapter . . . . .	70
4.1	Notations used in this chapter . . . . .	102
4.2	Power consumption parameters [96] . . . . .	115



# List of acronyms

<b>AWG</b>	Arrayed waveguide grating
<b>BER</b>	Bit error rate
<b>BF-BP</b>	Best fit bin-packing
<b>BF-SMA</b>	Best fit bin-packing sleep mode aware
<b>Bi-PON</b>	Bit-interleaved passive optical network
<b>BP-SMA</b>	Bin packing sleep mode aware
<b>CCS</b>	Coordinated cyclic sleep
<b>CDR</b>	Clock and data recovery
<b>CO</b>	Central office
<b>CoS</b>	Class of service
<b>CS</b>	Combine/split
<b>CSMA/CD</b>	Carrier sense multiple access with collision detection
<b>DBA</b>	Dynamic bandwidth allocation
<b>DBWA</b>	Dynamic bandwidth and wavelength allocation
<b>DFB</b>	Distributed feedback laser
<b>DS</b>	Downstream
<b>DSL</b>	Digital subscriber loop
<b>EFT</b>	Early finish last transmission time
<b>EPF</b>	Earliest packet first
<b>EPON</b>	Ethernet passive optical network
<b>FTTH</b>	Fiber-to-the-home
<b>FTTx</b>	Fiber-to-the-everything
<b>GoS</b>	Grade of service
<b>GPON</b>	Gigabit passive optical network

<b>HSMA</b>	Hybrid sleep mode aware
<b>ICT</b>	Information and communications technologies
<b>IEEE</b>	Institute of electrical and electronics engineers
<b>ITU-T</b>	International telecommunication union-telecommunication
<b>JTWS</b>	Joint time and wavelength scheduling
<b>LLID</b>	Logical link identifier
<b>LQF</b>	Longest queue first
<b>LS</b>	Limited surplus
<b>M2P</b>	Multipoint-to-point
<b>MAC</b>	Media access control
<b>MPCP</b>	Multipoint control protocol
<b>MUX/DEMUX</b>	Multiplexer/Demultiplexer
<b>NG-EPON</b>	Next-generation Ethernet passive optical network
<b>NG-PON</b>	Next-generation passive optical network
<b>OA</b>	Optical amplifier
<b>OAN</b>	Optical access network
<b>ODN</b>	Optical distribution network
<b>OLT</b>	Optical line terminal
<b>ONU</b>	Optical network unit
<b>OPEX</b>	Operational expenditure
<b>P2M</b>	Point-to-multipoint
<b>PD</b>	Photodiode
<b>PON</b>	Passive optical network
<b>PS</b>	Power splitter
<b>QoS</b>	Quality of service
<b>RTT</b>	Round trip time
<b>SBA</b>	Static bandwidth allocation
<b>SIEPON</b>	Service interoperability in Ethernet passive optical network
<b>SLA</b>	Service level agreement
<b>SLIC</b>	Subscriber line interface chip
<b>SMA</b>	Sleep mode aware
<b>STWS</b>	Separate time and wavelength scheduling
<b>TC</b>	Transmission convergence

<b>TDM</b>	Time division multiplexing
<b>TDMA</b>	Time division multiple access
<b>TF</b>	Tunable filter
<b>TSA</b>	Time slot allotment
<b>TWDM-PON</b>	Time and wavelength division multiplexed passive optical network
<b>UBF-SMA</b>	Updated best fit bin-packing sleep mode aware
<b>UDC</b>	Upstream and downstream centric
<b>UNI</b>	User network interface
<b>US</b>	Upstream
<b>USR</b>	Unused slot remainder
<b>VCSEL</b>	Vertical cavity surface emitting lasers
<b>VOIP</b>	Voice over IP
<b>WDM</b>	Wavelength division multiplexing
<b>WMA</b>	Wavelength minimization and assignment
<b>WSS</b>	Wavelength selective switch

