Optimal Provisioning and Deployment Cost Evaluation of Array Waveguide Grating WDM Passive Optical Networks

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Abstract

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Pan Luo

With the increase of interests in passive optical network (PON) networks, numerous studies have been done in this area, including the multicast and multicast routing and wavelength assignment (MC-RWA) problem. However, the mathematical models for MC-RWA problem to build a solid foundation for solving large network provisioning instances are still missing. Under the assumption of a given topology and static traffic, we propose mathematical optimization models for pure Array Waveguide Grating (AWG)-intermediate node Wavelength-Division Multiplexing (WDM) PONs to solve the MC-RWA and MC-GRWA (with grooming) problems on both tree and light mesh topologies. With these models, we are able to find the optimal provisioning solution for a given topology and a given traffic set. We implement a simulation system based on those models and analyze the network performances under three different traffic scenarios on different tree topologies. We also examine the deployment cost for pure AWG and pure splitter PON networks, taking into account the attenuation factor, in order to demonstrate the advantage of AWGs over splitters in terms of deployment cost.

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And gratefulness to God, who made all this possible.

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Acronyms

APON Asynchronous Transfer Mode PON

AWG Array Waveguide Grating

BPON Broadband PON

CATV cable television

CO Central Office

CPON Composite PON

CSMA/CD Carrier Sense Multiple Access With Collision Detection

DC decreasing coarseness

DSL digital subscriber line

EFM Ethernet in the First Mile

EPON Ethernet PON

FTTB fiber to the building

FTTC fiber to the curb

FTTH fiber to the home

FSR free spectral range

GEM Generic Encapsulation Method

GoS grade of service

GPON Gigabit PON

HDTV high definition television

IC increasing coarseness

LCOS Liquid Crystal on Silicon

LLID Logical Link Identifier

MC-RWA multicast routing and wavelength assignment

MC-GRWA multicast routing and wavelength assignment with grooming

NIC network interface card

ONU Optical Network Unit

OLT Optical Line Terminal

PON passive optical network

PLC planar lightwave circuit

PSC passive star coupler

QoS Quality of Service

RN remote node

RPR resilient packet ring

SOA semiconductor optical amplifier

TDM Time-Division Multiplexing

TDMA Time division multiple access

VCSOA vertical cavity semiconductor optical amplifier

VDSL	very high speed digital subscriber lines
VoD	video on demand
WDM	Wavelength-Division Multiplexing

Chapter 1

Introduction

With the increase of bandwidth demands such as video on demand (VoD), high definition television (HDTV), video conference, on-line gaming, etc., more and more end users are eager to upgrade to a faster connection (larger bandwidth). Nowadays, with digital subscriber line (DSL) technology, an end user can only get a connection up to several mbps, and with very high speed digital subscriber lines (VDSL), one can get a faster (26 Mbit/s in a symmetric access, up to 52 Mbit/s down and 12 Mbit/s up in an asymmetric access) connection with a range of approximately 300 meters. Cable television (CATV) is another technology that enables higher speed connection. However, on the user local network side, 100 Mbit/s Ethernet card is the standard network interface card (NIC) on user's desktop and laptop computers. Some high end computers are also equipped with 1000 Mbit/s Ethernet cards. With the development of wireless technology, 54 Mbit/s or 108 Mbit/s wireless G/N connections can now be easily and cheaply deployed by users in office or at home. With high speed local networks and mass bandwidth applications, the bottleneck on the access network becomes more and more visible. It is possible that the conventional access network infrastructures will not be able to satisfy the user's increasing requirements for bandwidth in the near future.

Fibers are widely used in core networks and metropolitan networks. Research has been done to bring fiber to the last-mile access network. Optical access networks can provide a huge bandwidth to buildings, curbs, and even homes with lower loss and wider coverage. It will well meet the user's different application requirements. Moreover, the major cost of fiber to the home (FTTH) corresponds to the network setup costs such as digging and deploying equipment. The operational costs may be lower than those of a conventional access network, as less active equipment are used in the field. Technologies are ready for fibers to be connected to home, and they will play an important role in the near future.

In an optical access network, all the transmissions are carried on the fibers between an Optical Line Terminal (OLT) and Optical Network Units (ONUs). OLT is connected to the upper level of a network such as a metro network or a long-haul network while ONUs are connected to home networks or end users. Reducing the network deployment cost of an optical access network while serving customers as well as possible is always most important to the service providers. Researchers started to look into passive optical networks (PONs) because they are simpler and easier to deploy, compared to other types of access network. Network operators take advantage of its low management cost and easy maintenance. Passive optical network (PON), as its name implies, is made of passive devices only at intermediate nodes, such as splitters or/and Array Waveguide Gratings (AWGs), which have a simple architecture and require no power supply. A splitter can split the signal to all its output ports regardless of the number of wavelengths in the signal. Moreover, different wavelengths in the same signal can go to different output ports when going through an AWG which has static wavelength routing ability. The advantage of an AWG over a splitter is that an AWG has far less insertion loss than a splitter, especially when the number of output ports is large (more than 16). However, it may require more wavelengths when serving different ONUs under the same branch of an AWG even for a single multicast request (refer to Section 2.3.2 for more details). Employing passive devices can reduce the network cost effectively, compared to active devices.

There is a lack of literature in research that solves the multicast and wavelength assignment problem for Wavelength-Division Multiplexing (WDM) PON network with mathematical optimization models, although there are already several studies with mathematical models which have been proposed for WDM networks in [SMG05] [ZP05]. Therefore, we study and develop the mathematical optimization models for pure AWG based intermediate node WDM PON networks in order to evaluate the network performance under different network parameters, such as the number of ONUs and the number of requests. In our study, we only consider single OLT architectures for WDM PON networks with or without the Time-Division Multiplexing (TDM) technology. We further study and compare the network cost for two different extreme cases: Pure splitter and pure AWG based intermediate node WDM PON networks, taking into account the attenuation to examine the advantages of AWGs and splitters in terms of infrastructure cost.

The goal of our project is to optimize the provisioning of a pure AWG-intermediate node PON in order to maximize the revenue, e.g., to maximize the number of granted requests or the number of served ONUs. Optimization mathematical models for pure AWG-intermediate node PONs are developed in order to explore the characteristics of AWGs in different topologies and traffic patterns (e.g., mix of unicast and multicast requests). We consider two types of access network topologies: tree and light mesh. The bandwidth of most requests is less than the transport capacity of a wavelength in the access network. In order to increase the bandwidth utilization, the TDM feature is added to the optimization model based on the WDM PON model. Accordingly, an

AWG-based multi-topology hybrid TDM-WDM PON optimization model is built.

By exploring the network cost with the consideration of attenuation, we find the advantage of AWGs over splitters. Furthermore, we consider some realistic traffic instances and obtain the optimal provisioning solutions. To explore the network performance under different traffic scenarios, we compare the results with only AWGs and only splitters at intermediate nodes. Based on this last study, further studies may take the advantage of splitters and AWGs in order to find the best combination of splitters and AWGs at intermediate nodes for a given network topology and request set in order to achieve the best revenue.

The contributions of the thesis are:

1. Development of mathematical optimization models for multicast routing and wavelength assignment (MC-RWA) and multicast routing and wavelength assignment with grooming (MC-GRWA) problems with two different objectives on both tree and light mesh topologies.
2. Building an optimization system, which solves the above problems, in order to provide the optimal provisioning solution for given topologies and traffic instances.
3. Investigation of the grade of service (GoS) in three scenarios, which are defined according to the common traffic patterns in rural, suburban and urban areas with different traffic demands.
4. Evaluation and comparison of the infrastructure cost between pure AWG-intermediate node PON network and pure splitters-intermediate node PON network, taking into account the attenuation factor.

The thesis is organized in the following order. In Chapter 2, we review the technologies used in optical access networks, especially for WDM-PON and AWGs. In Chapter 3, we review the current development of PON networks, different proposed PON architectures and cost analysis for access networks. In Chapter 4, we investigate two problems: MC-RWA and MC-GRWA. We develop mathematical optimization models to solve those problems with two different objectives on both tree and light mesh topologies. In Chapter 5, we discuss the algorithms to do the wavelength assignment for MC-RWA and MC-GRWA problems as well as the algorithms for calculating the grade of service and bandwidth utilization. Then through two examples, we explain how the models work. In Chapter 6, we develop a model for network cost calculation and then obtain the infrastructure cost for both AWGs and splitters. Comparing the results, we show the advantage of AWGs over splitters in terms of network cost. In Chapter 7, we generate both tree and light mesh topologies with different number of ONUs and several traffic instances for the developed system based on mathematical optimization models. Then we obtain the optimal solutions and compare them in terms of grade of service (GoS). In Chapter 8, we conclude and propose possible future studies.

Chapter 2

Technologies of Optical Access Networks

2.1 Passive Optical Networks

A passive optical network (PON) is an optical fiber network carrying laser signals from central office to the end users. Different from an active optical network, a PON employs non-active devices between a central office and end users for transmitting optical signals. The fibers between network nodes and the central office are connected by means of passive devices (not electrically powered) such as optical splitters, combiners or Array Waveguide Grating (AWG). A splitter can split the optical signal from one fiber into several fibers, a combiner can combine several fibers into one fiber and an AWG can be used as a splitter or combiner with static routing properties.

Transport capacities in a PON network are usually asymmetrical due to the characteristics of the applications and do not follow physical constraints. For instance, the Internet browsing usually requires more downstream bandwidth than upstream bandwidth. A standard PON could deliver up to 622 Mbit/s for downstream and up to 155 Mbit/s for upstream, taking into account the bandwidth requirements of the current applications on the uplink and downlink directions. Assuming that splitters are used, up to 32 ONUs near the end users can be served within 20 km from OLT to Optical Network Unit (ONU) due to the attenuation.

In this chapter, we will provide an overview of PON networks and their typical architectures, as well as details for the passive devices (such as splitters and AWGs) used in a PON network. Descriptions of the multicast traffic and the wavelength assignment are also included in the chapter.

2.2 PON networks

APON, BPON

Studies on Asynchronous Transfer Mode PON (APON) for the broadband access network started with the full service access network (FSAN) group in 1995. The APON, as its name implies, carries the ATM cells in the optical access network. Broadband PON (BPON) is also based on ATM and is an enhanced version of APON. Its transmission is enhanced by using the Wavelength-Division Multiplexing (WDM) technique on a single fiber. The dynamic and higher upstream bandwidth allocation and survivability features are also specified in the standard [ITU98]. The bit rate for the downstream and upstream of APON and BPON can be symmetric or asymmetric with downstream bit rate at 155.52 Mbit/s, 622.08 Mbit/s or 1244.16 Mbit/s and upstream bit rate at 155.52 Mbit/s or 622.08 Mbit/s. For downstream, 1480 nm-1580 nm wavelength band is divided into time slots to carry 53 octets ATM cells or PLOAM (physical layer operation, administration and maintenance) cells from OLT to ONUs. Each PLOAM cell is attached between every 27 ATM cells to carry the physical layer network information and the grants for upstream access, which is the permission to use a defined interval of time for upstream transmission. Because they share the same wavelength for upstream transmission, the ONUs are assigned grants to allow fair access to the media. For the upstream direction, 53 octets ATM cell plus 3 octets overhead is transmitted in the wavelength band of 1260-1360 nm. For the 155.52 Mbit/s system, PLOAM cells from downstream contain 53 upstream grants for the upstream frame and 212 grants for the 662.08 Mbit/s case. The overhead between two successive cells is 3 bytes, in which a minimum of 4 bits are used to provide space between cells to avoid collision. The rest of the bits are used for the preamble and the delimiter for synchronization. APON and BPON have a maximum fiber length of 20km between OLT and ONUs with a maximum split ratio of 32 due to the path loss and ONUs addressing limits.

The APON/BPON has two limitations. Firstly, it can only provide up to 1244.16 Mbit/s of bandwidth for downstream and 662.08 Mbit/s for upstream. If 32 ONUs share a single OLT connection, each ONU can only get 4.86 Mbit/s for 155.52 Mbit/s systems, 19.44 Mbit/s for 622.08 Mbit/s systems and 38.88 Mbit/s for 1244.16 Mbit/s systems. It is similar for the upstream. The more ONUs the OLT serves, the less bandwidth they get. When more users subscribe to the network, a service provider will have difficulties to provide enough bandwidth for new users. Secondly, it employs ATM as media access control mechanism, which has a higher overhead/payload ratio than Ethernet for the packet size. To serve an IP (Internet Protocol) traffic network, it also needs to perform IP packet segmentation.

EPON

Ethernet PON (EPON) based on Ethernet technology was approved by IEEE in 2004. As part of the Ethernet in the First Mile (EFM) project, it is designed to carry variable-length IEEE 802.3 Ethernet packets (up to 1518 bytes) on the fiber with a high speed (1.25 Gbit/s), compared to fixed-length cells in APON and BPON. 1000BASE-PX10 EPON and 1000BASE-PX20 EPON provide 1.25 Gbit/s speed on one single-mode fiber with 1:16 fiber split ratio. The maximum fiber length between OLT and ONUs for 1000BASE-PX10 is 10 km and for 1000BASE-PX20 20 km. ATM is designed for the data traffic, which can use small data cells and needs small jitter such as voice data or video conference, whereas Ethernet variable-length packets are efficient for the IP traffic. Ethernet-based LANs are widely deployed in buildings, offices, universities and homes. Since the optical access networks are connected to the end users, it is a good choice to use Ethernet protocol in the access network [IEE04].

In EPON, downstream traffic from OLT to ONUs is broadcast through passive optical splitters. The data are encapsulated into an IEEE 802.3 packet which contains a header, payloads and frame check sequences (FCSs). When an ONU registers on the network, it is assigned to a Logical Link Identifier (LLID) and it will extract the packet with the same LLID. In the upstream, the case is comparatively complex for the passive device, which is unable to support scheduling or buffering functions. Traditional media access control mechanisms, e.g., Carrier Sense Multiple Access With Collision Detection (CSMA/CD) used in Ethernet, are not suitable for EPON, because it is difficult for ONUs to detect whether or not there is a collision at the combiner. To address this problem, a Time division multiple access (TDMA) mechanism is adopted in the EPON: Each ONU is assigned one or several time slots per OLT. When it has time slots, it encapsulates one or more packets into one IEEE 802.3 packet and transfer it to OLT. Otherwise, it will buffer the packet and wait until next time slot arrives so that the packets will not collide at the combiner. If there is no packet to transmit, an idle signal will be put into the time slot [IEE04]. As in other systems, TDMA mechanism could be either a static scheme or a dynamic scheme. With the static scheme, the bandwidths shared between ONUs are pre-configured and fixed at run-time. With the dynamic scheme, OLT can manage the bandwidth usage according to the network traffic and control user needs by sending control packets to the ONUs to change their time slot allocation. The centralized control is good for bandwidth efficiency and network management, but it adds complexity to the network design. Various bandwidth allocation schemes have been studied recently [IEE04].

EPON has also a limitation of bandwidth. Although it has higher bit rate than APON/BPON does, it is still not enough for the increasing number of users and needs of bandwidth from end users.

GPON

Gigabit PON (GPON) was introduced in ITU-T G.984 in 2003. It extends a single fiber bandwidth capacity to 2.5 Gbit/s for downstream and 1.25 Gbit/s for upstream and uses a new Generic Encapsulation Method (GEM) transport layer, which can host non-native transport protocols and allows very efficient packet transmission. Therefore, it can encapsulate only ATM cells, or only Ethernet packets, or in the mix mode. With frame segmentation, GPON allows an Ethernet frame fragmented among GEM cells for higher Quality of Service (QoS) for delay-sensitive traffic such as voice and video communications [ITU03]. With some variation and extension, GPON can reach to 100km [TT05] or 135km [DHH+06].

Although the GPON can provide higher bandwidth than APON/BPON and EPON can, it is not very scalable. Since the PONs discussed before only use a single fiber channel, the maximum bandwidth is limited to the capacity of fiber. The maximum number of splitting ratio is limited to 64 by the attenuation in the splitters and absence of amplifiers, thus the network's scalability is limited. We need a new technology to help to scale the PON capacity.

2.3 WDM PON

Although APONs, EPONs and GPONs are able to provide wide bandwidth, the bandwidth requirements from the end users have grown more than 100 times and are still growing rapidly. Peer to peer (P2P) file sharing (e.g., BitTorrent) and movie downloads become very popular nowadays. More and more video clips are put on the web (YouTube, etc.). The advertisements on the webpages are using more and more videos instead of simply texts and images. Based on the rate of growth for the computer usage and the network loads, we can easily foresee that the need for bandwidth will keep growing. A number of emerging bandwidth-intensive technologies and software (such as 3D on-line gaming, HDTV VoD, personal video broadcasting or so-called triple-play) are maturing. We need to find a technology to significantly increase bandwidth, and provide good scalability and cost effectiveness. Wavelength-Division Multiplexing (WDM) PON is a promising technology that becomes more and more attractive to the industry. It can upgrade existing PONs without changing the physical infrastructure. A lot of research has been done in this area recently. Some hybrid PON networks with WDM technology are also proposed to take the advantage of different PONs [MRM06].

2.3.1 Generalization

WDM PON employs Wavelength-Division Multiplexing (WDM) as an additional wavelength dimension so that different wavelength channels can be transmitted on a single fiber simultaneously in either the upstream or downstream directions or both. A WDM PON Access Network consists of a set of fibers connecting OLT and ONUs through passive routing or splitting devices. OLT is located at the Central Office (CO) and connects an optical access network with the Metro Network or Wide Area

Network. Optical Network Unit (ONU) is located on the other side of the optical access network. It may be connected to the buildings (FTTB), road curbs (FTTC) or homes (FTTH). With wavelength division multiplexing enabled, OLT can communicate with ONUs, using different wavelength channels at the maximum bit rate of a channel.

2.3.2 Passive equipment

Light splitter

A light splitter is a passive all-optical device that can split a light signal from an incoming link to two or more (only powers of 2, up to 32, *i.e.*, 1:4, 1:8, 1:16, or 1:32 splitters exist) output signals on different outgoing links without any additional power supply. It is an important building block for the optical multicast since it is a simple and cheap device that makes one signal become multiple signals by means of broadcasting. That is the basic structure of multicasting. Through loss is the amount of attenuation the signal receives as it passes from input to output. The power of the incoming signal is also split into $1/n$ equally to every outgoing link for an ideal splitter. In practice, a typical two-way splitter has a through loss of about 3 or 3.5 dB from the input to each output. Four-and eight-way splitters are also common, with typical through losses of 6-7 and 9-11 dB respectively. If a $1 : x$ splitter is installed at a given node with x outgoing fibers, then all wavelengths, on any of these x outgoing fibers, are split and suffer from the same through loss. There are also $2 : 2$ splitters; they can split two incoming requests on two outgoing fibers into two messages, both on two outgoing fibers. A node that is equipped with a light splitter and is able to split and forward the input signal to all outgoing ports is a multicast-capable (MC) node. A node without splitting ability is called multicast-incapable (MI) node.

Light splitters are used in TDM-PONs (APON/BPON, EPON, GPON), which

Table 1: Splitting Ratio and Insertion Loss for AWG and Splitter

Devices	Splitting Ratio						
	1:2	1:4	1:8	1:16	1:32	1:64	2:2
AWG	4-5	4-5	4-5	4-5	4-5	4-5	4-5
Splitter	3-3.5	6-7	9-11	12-13	15	-	-

usually employ single wavelengths among all the subscribers. Due to attenuation and splitting loss, the number of the ONUs is limited to 32 for a maximum fiber length of 20 km from OLT to ONU and 64 for a maximum of 10 km.

AWG

An Array Waveguide Grating (AWG) is a passive device used in WDM-PON because of its wavelength property. An AWG is a fixed routing device to multiplex or demultiplex a large number of wavelengths with relatively low loss. It routes the incoming signals to the different output ports according to the wavelengths of the incoming signals.

The structure of the AWG is very simple. It is usually a planar lightwave circuit (PLC). The input signal on the fiber enters from the input port of the AWG and carries multiple wavelength channels, to go through the input slab waveguides to the arrayed grating waveguides. The grating is made of several single-mode fibers. Each fiber has a different length with an increment ΔL. The signals are diffracted at the input coupler and propagate through the grating waveguides. Since different wavelengths propagating through the different lengths of waveguides have different phase shifts, they will focus on the different points of output slab. Output slab fibers are placed at different focus points to lead the wavelength signals to different output ports of AWG, where different wavelength channels can be separated and transmitted downstream.

Array Waveguide Grating (AWG) is different from splitter because it does not

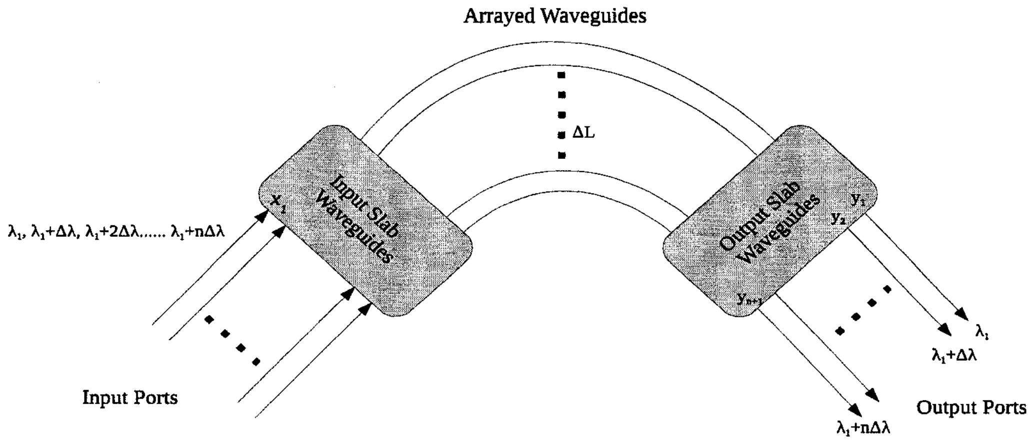


Figure 1: Arrayed Waveguide Grating

split the signals equally to every output port. However, it is able to split the signal according to wavelength and route them to different output ports. If an input channel, consisting of wavelengths λ_1, $\lambda_1+\ \Delta\lambda$, $\lambda_1+2\Delta\lambda ... \lambda_1+n\Delta\lambda$ that are shifted by $\Delta\lambda$, which is the shift space of the AWG and depends on physical properties of the AWG, goes to the input port x_1, the signals will propagate through the waveguides and be routed to the different outputs y_x, as shown in Figure 1.

Another useful feature of an AWG is its periodic wavelength property, which provides AWG with potential extending capability [Muk06]. Different wavelengths with an interval of free spectral range (FSR) can be routed by AWG to the same output port. As shown in Figure 1, λ_1 + FSR will be routed to the same output port y_1 as λ_1.

An AWG can be a remote node (RN) in the WDM PON as a multiplexer/demultiplexer, an add-drop multiplexer or a passive wavelength router. It routes a wavelength channel to a specific port. By utilizing the periodic wavelength property (*i.e.*, FSR), an AWG can be used as a multiplexer and demultiplexer simultaneously, as long as the downstream wavelengths and upstream wavelengths are assigned with a shift of FSR. It has a relatively low insertion loss of about 4-5dB, which does not depend on the number of wavelengths (compared to a 1:N optical splitter). However, AWG is a temperature sensitive device, as the waveguides are made of silica, which is a temperature sensitive material. When the temperature changes, the length of the waveguides change, which causes center wavelength drifts of about 0.011 nm/°C [BPC$^+$05]. The remote node is usually deployed in an outdoor environment, where the temperature may vary from -40°C to 80°C. This makes AWG difficult to be deployed in field for WDM PON unless extra devices such as Peltier effect devices or heaters are provided to help the AWG maintain a constant temperature. Those devices require power supply and are not suitable for passive access networks. To solve this problem, an athermal AWG module has been designed by Hasegawa and Nara in 2004 [HN04] to overcome the temperature sensitive shortcoming of AWG. In their design, the output slab is cut into two pieces and connected with a compensating plate made of copper that expands or shrinks when the temperature changes. The position of the slab remains the same. When the temperature changes, the length of the copper plate changes, causing the small piece to slide in order to move the focus points of the output slab waveguides into the right position, as shown in Figure 2. Through the design of the circuit pattern, it is possible to build a 100-GHz 48-channel athermal AWG module that has an insertion loss of less than 2.8 dB. For all channels, temperature dependence is less than ±0.015 nm for center wavelength and ±0.1 dB for insertion loss.

2.3.3 WDM-PON Architecture

Architectures for WDM-PONs have been proposed in mid-1990s. Some variations have been studied in the recent years.

The traditional WDM-PON structure is shown in Figure 3. OLT on the CO side

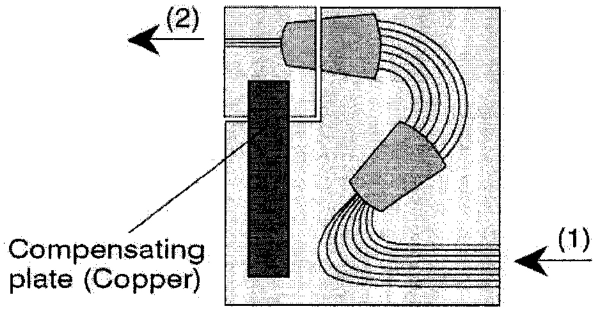


Figure 2: Athermal AWG Design [HN04]

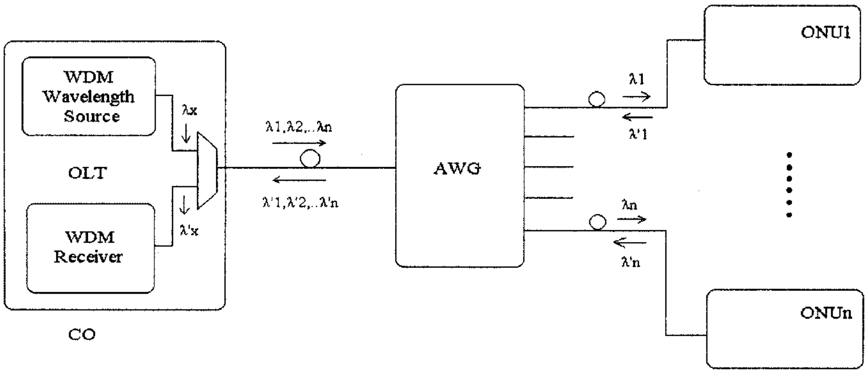


Figure 3: WDM PON Architecture

consists of a WDM transmitter and a WDM receiver. Either a multi-wavelength source (MFL, DFB LD array or Chirped-Pulse WDM) or a wavelength-selection-free source (Spectrum-Sliced Source or Injection-Locked Laser) may be used in the OLT transmitter as they both can emit multiple wavelengths simultaneously for several WDM channels. A receiver for both OLT and ONU may consist of a photo-detector and electronics for recovering the signals. A demux device may be needed to separate the WDM signals on the OLT side. The transmitter on the ONU side may have a wavelength-specified source or wavelength-shared source to transmit the signal back to OLT. In the middle, WDM-PON employs remote nodes (Array Waveguide Gratings) to route the signal downstream from OLT to different ONUs according to the wavelengths. The AWG can also act as a passive combiner for upstream. Each ONU equipped with a wavelength specified source sends different wavelength traffic to upstream. The OLT is connected to each ONU, separated only by wavelength channels. There is no time slot allocation or sharing of channel bandwidth. Each channel is used to transmit signals at any bit rate (up to full bit rate of the channel speed). This module can be considered as a logical point-to-point architecture. Because different services can use different set of wavelengths for different requirements, WDM-PON is well-suited for service separation. Low latency services can be assigned to a set of wavelengths that have a higher bandwidth, and be routed at high priority to guarantee losslessness and delay-free performance. Service providers may charge higher prices for such performance. The AWG based WDM PONs can also support different service providers on the same physical infrastructure. Each provider can have its own virtual topology by being assigned separate channels. The network operator can easily change the network capacity by adding or removing the wavelength channels on the link, and can also reroute the traffic for link failure recovery and network congestion control [Koo06].

In order to use a different wavelength upstream, different light sources must be deployed to different ONUs to generate different wavelengths. It significantly increases the cost of installation and maintenance on the ONU side. To avoid the drawback of upstream WDM PON, Composite PON (CPON) was proposed in 1998 [FHJ+98]. It combines a light splitter/combiner with a WDM router in the remote nodes, where the WDM router is used to distribute downstream traffic and the light splitter/combiner is used for combining upstream traffic in the remote node. The identical wavelength specified source with the same wavelength emitting can be used in the transmitters on the ONU side. However, the upstream bandwidth is limited to a single wavelength channel, which is not good for the scalability and needs symmetrical communication.

Several other improved architectures were proposed to overcome the limitation of scalability as well as the bandwidth utilization. One is the multistage AWG-based WDM-PON architecture [MMPS00]. Utilizing the period wavelength property motioned above in Section 2.3.2, multiple AWGs are cascaded in two or more stages so that the reuse of a given wavelength for more than one subscriber is possible. The scalability of the WDM PON is also increased by increasing the number of AWGs at each stage.

The Stanford University access dynamic wavelength division multiplexing (SUCCESS DWDM) PON is another extension that is based on a topology of a collector ring and distribution stars connecting CO and the users [AKG+04]. It offers an environment for TDM PONs and new DWDM PONs to coexist and also provides a migration path for the current-generation optical access networks from TDM to DWDM. ONUs employ uncooled components to minimize the system cost. AWGs are used to double the number of ONUs supported by the network. The OLT uses tunable lasers and tunable filters to decrease total number of transceivers and to generate optical carriers, onto which ONUs can modulate their upstream traffic. The Stanford simulation demonstrates the feasibility of this architecture with efficient transmission over 22.5-km-long path on a line rate of 1.25 Gbit/s as well as good scalability (more than 60 DWDM ONUs and 100 CWDM ONUs). In spite of the good performance of the system, the complexity of the network illustrates a drawback of the system: the cost of ONU and network deployment and maintenance will be higher than that in other architectures.

2.3.4 Multicast Routing and Wavelength Assignment

Optical multicast is an attractive feature of light-trees and it improves performance by sharing the network resources (e.g., wavelength). The multicast session is similar to broadcast session but with some specific destinations. It can be useful for transporting high-bandwidth applications such as high-definition TV (HDTV) [Rou03].

In the WDM-PON, sometimes the multicast sessions are known beforehand and the multicast traffic will keep the same pattern for a relatively long time. It is worth taking some time to do better optimization off-line even if the algorithm is complex. This is the static MC-RWA scenario. In this scenario, the objective is to find as many lightrees for multicast sessions as possible and minimize the cost. In the dynamic MC-RWA scenario, the traffic routing can be changed according to the network traffic or network management [LLW06]. Although the dynamic MC-RWA scenario is more flexible for the network design, it also increases the network deployment, management and maintenance cost by adding active devices to the network. We prefer passive devices such as light splitters and AWGs than active devices (*i.e.*, amplifier, wavelength converter), because passive devices can be deployed underground several kilometers around from a city without needing any power supply, which is required by active devices. In addition, passive devices are cheaper and incur lower operation, administration and maintenance cost. The network should be kept as simple as possible. In order to maximize bandwidth utilization, TDM technology is employed to group together different requests that have the same source or destination(s). The MC-RWA problem with TDM technology is called MC-GRWA problem.

In the MC-RWA problem, with the absence of wavelength converters (which are active devices), light-paths should use a unique wavelength between the OLT and an ONU [XR04]. It is impossible to convert the wavelength once the signal is sent out from the OLT. This is the wavelength continuity constraint. There is only one exception for ONU to ONU requests, which will pass through the OLT. With the wavelength equipment in OLT, the signal can be converted from one wavelength to another. If two requests with the same wavelength are sent on the same link, the signal will be corrupted. Therefore, it is impossible to have two multicast sessions using the same wavelength if they have a shared link. This is the distinct wavelength constraint [HCT02].

In the MC-GRWA problem, TDM is employed to increase bandwidth utilization. Although our assumption is that each ONU is equipped with only one receiver and can receive only one wavelength, we can still bind several requests on the same wavelength with TDM technology. The sum of the bandwidth requirements for all bound requests should be less than or equal to the transport capacity of a wavelength. The ONU can accept several requests at the same time as long as the bandwidth constraint and the same constraints (wavelength continuity and distinct wavelength constraints) in MC-RWA problem are satisfied. Therefore, two or more requests may share the same wavelength when they have the same source or destination(s). If so, a wavelength that satisfies all the constraints for each request should be found. Otherwise, one or more requests have to be rejected.

Our goal is to develop optimization models for both the MC-RWA and the MC-GRWA problems with only AWG equipment at intermediate node for PON network to explore how to minimize the network cost for a given topology as well as to maximize the number of granted requests or the number of served ONUs according to different requirements from service providers. We explore two different objectives for each problem. One is to maximize the number of granted requests and the other is to maximize the number of served ONUs. In the second objective, we allow partial requests to be granted. Keeping in mind the above objective, we develop a system based on the mathematical optimization models to find the best request provisioning for a given topology. Given the different sizes of networks and the sizes of request sets, we will be able to compare the grade of service in terms of the number of requests and the bandwidth utilization to explore the impact of different sizes of requests on the PON network. By comparing the result with Shaikh's study [Sha08] on splitters, we examine the differences between splitter and AWG equipment at the intermediate nodes for PON network. In addition, we explore the network cost in terms of infrastructure cost. Taking into account the attenuation for the network deployment, we compared the cost for both splitter and AWG case that serve the same area and the same number of users. Further research will be conducted to explore different combinations of splitters and AWGs in a network and determine whether deploy a splitter or an AWG in a given node in a given network topology is the best solution to maximize the revenue with minimal resources.

Chapter 3

Literature Review

3.1 PON Network Design

With the increase of bandwidth requirements in access networks, many studies have been conducted in the PON network area over the recent years. PON networks with either single or multiple OLT architectures have been proposed. Most of the studies are done with a single OLT, which connects to the upper level network (e.g., metro network) and serves all ONUs. A study on a multiple OLT architecture is also included in this chapter. These studies focus on not only increasing the throughput of PON networks but also on the possibility of improving a PON network design in order to extend its scalability and flexibility.

3.1.1 Single OLT Generalization

There are several existing topologies in an access network: tree, ring, bus or mesh. Double ring or double tree topology may be also deployed in a PON network for reliability. To limit the scope, we only consider tree topology and light mesh topology (defined in Section 4.7) with a single OLT in this thesis.

Besides the topology, the attenuation and power budget are important constraints when considering the design of PON networks, because of the absence of optical-power amplifiers. According to ITU-T recommendation G.983.1, there are two classes of access line interfaces defined as class B and class C. The mean launch power from OLT should be from -2dBm to +4dBm for both class B and class C for 622 Mbit/s downstream transmission, while the minimum sensitivity for the receiver on the ONU side should be between -25dBm and -33dBm for class B and class C respectively. For 622 Mbit/s upstream transmission, the mean launch power from ONU should be from -1dBm to +4dBm for both class B and class C, while the receiver minimum sensitivity in the OLT should be -27dBm for class B and -32dBm for class C. The maximum distance between an OLT and the ONUs should be 20km with an attenuation range from 10dB to 25dB for class B and from 15dB to 30dB for class C. The power budget of a PON is affected by the following factors: The splitting loss on a splitter (depending on the splitting ratio), transmission loss (that is about 0.2dB/km on a 1.55μm wavelength fiber for the long distance fiber link, which may be several kilometers), and the loss from connectors and splices (that is around 3dB). The signal loss should be within the attenuation range so that the receiver can detect the signal and recover it correctly. As a result, the maximum number of ONUs that an OLT can support is limited to 16 for class B and 32 for class C. Those requirements have been made a priori independently of the equipment (AWG or splitter) [ITU98].

3.1.2 Single OLT with Splitter Architecture

Splitter is a wavelength independent device and is usually used in the PON networks that do not employ WDM technology, e.g., EPON. A group [ZH03] has designed a scalable optical access network with variable optical splitters, which are active devices based on Liquid Crystal on Silicon (LCOS) technology. The variable optical power splitter is able to control the distribution of the input signal power between output ports dynamically, where the traditional passive optical splitters usually split the input optical signal power equally or by a fixed ratio between output ports. For any output port of variable optical power splitter, the output signal power varies from 0 to the maximum input power. The variable optical power splitter has 4dB insertion loss. They propose an architecture for an optical access network with variable optical splitters to increase the scalability and flexibility of the traditional optical networks that use passive splitters.

In their experiments, the authors of [ZH03] assume the topology of the optical access network is a tree structure with two stages of branching devices. The first stage, which is closer to OLT, employs a 1:2N variable optical splitter, where N is the number of splitters in the second stage. The second stage employs 2:M passive optical splitters, where M is the number of ONUs under the second level passive optical splitters. All passive optical splitters split the input signal power equally. The distance between the OLT and the ONUs is 20km in the worst case (maximum path loss). They also assume that the launch power from OLT has a maximum value of +4dBm. The OLT is equipped with an optical-power amplifier (maximum 17dBm) to boost the output power. In their testing system, where $N = 5$, the number of subscribers is able to change dynamically only at one of the output ports of the variable power splitter, while the other 4 ports have a fixed number of 32 subscribers. In their results, their system can support about 650 ONUs per OLT when the maximum output power of 17dBm is provided. Since the output power in the variable power splitters can be changed from 0 to maximum input power, the number of subscribers under this output port can be changed dynamically. Thus the network scalability is provided with more flexibility. Another advantage is that the number of output ports of the variable power splitter can be changed and the optical power can be changed between the output ports. This can be used to protect the network from a link failure without increasing the power budget of the system. When the primary link fails, the variable power splitter can switch the output power to the supplementary output port.

The drawback of this proposed system is that the variable optical splitter is an active device, which means it needs a power supply and more maintenance than a pure passive device. The optical-power amplifier in the OLT increases the total system cost.

3.1.3 Single OLT with AWG Architecture

In order to increase the throughput, WDM technology is used in PON networks. The splitters are replaced with AWGs because of its wavelength routing and lower loss characteristics. In [MMPS00], Maier *et al.* discuss the properties of AWGs and examine two types of AWGs, the increasing coarseness (IC) and decreasing coarseness (DC) AWGs. Multistage IC WDM-PONs can be easily extended, which requires only adding new AWGs to the last stage, connecting them with new subscribers and adding suitable wavelengths for the transmission. In contrast, to extend DC WDM-PONs, the entire network has to be changed. Thus IC AWGs are more suitable for the multistage WDM-PON. They propose WDM-PON architectures based on cascading multiple AWG stages in order to reuse the wavelengths for more than one subscriber. Each stage has a number of AWGs with the same characteristics (such as size and coarseness) interconnected by fiber links with upper and lower stages. Thus the topology of the network is a tree structure as shown in Figure 4. The cost of the IC WDM-PON architecture is measured in terms of the cost of AWGs and the cost of cable and installation (assuming that all the fibers going to the same AWG stage are hosted in one single cable and there is no reuse on the cable). Given a number of subscribers (ONUs) and the maximum number of wavelengths, the challenge is to find the optimal design of the network topology, including the number of stages, the number of AWGs in each stage, the size of AWGs and the number of used inputs and the coarseness of the AWGs with the minimum cost.

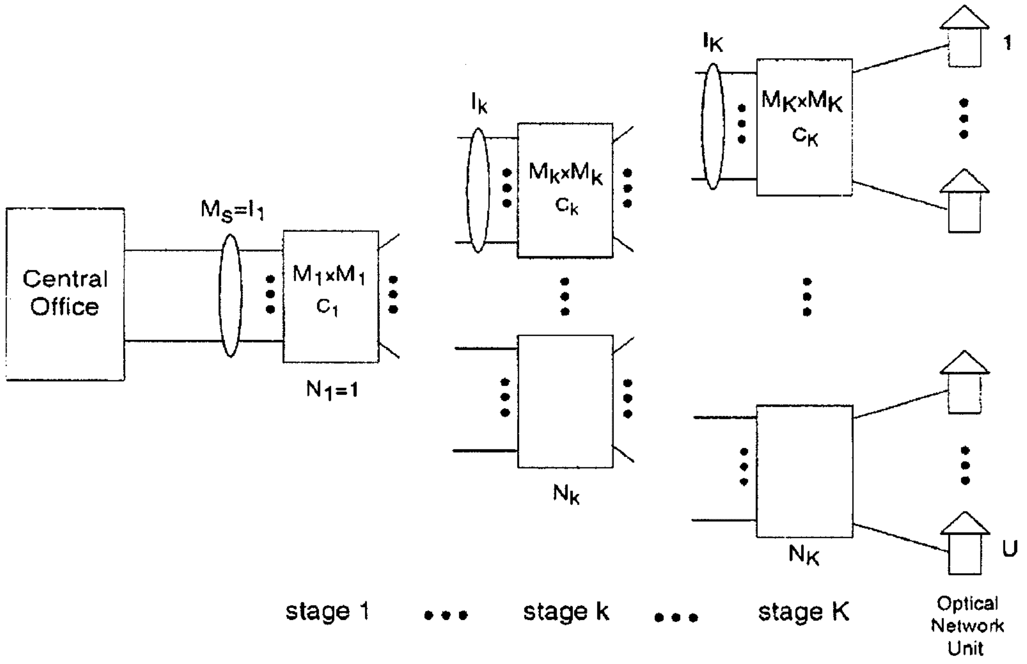


Figure 4: Architecture of Multistage WDM PON [MMPS00]

In their experiments, an exhaustive search algorithm is used to find out the optimal parameters. This is possible because the search space is relatively small. They assume that the launch power from OLT is the maximum value of 0dBm per wavelength. The size of AWGs is between 4 and 64. With the satisfaction of constraints (such as power budget), the algorithm recursively generates all the possibilities and calculates the total cost of each possibility. They consider WDM-PON architectures with various numbers of subscribers (128, 512 and 1024) and different values for the maximum number of multiplexed wavelengths (16, 32 and 64). In their research, they analyze the case of 128 subscribers and 16 wavelengths. Several scenarios are studied. They also propose a model based on a matrix representation of the AWG routing function and the network connectivity.

The architecture proposed by [MMPS00] also provides scalability and a higher number of users. To extend the network, a network operator only needs to add more AWGs at the remote nodes. However, the limitation of the architecture is that the number of stages is limited to 5 due to the insertion loss of AWGs and power budget of a passive optical network with a single OLT.

Migrating from an existing TDM PON to a WDM PON may require a large number of network component replacement. A smooth transition is required by network operators. In [AKG$^+$04], a hybrid WDM/TDM optical access network architecture (SUCCESS) is proposed to provide a method to allow existing TDM PONs to migrate to WDM PONs as shown in Figure 5 so as to protect the network investment. The SUCCESS architecture consists of a collector ring and several distribution star networks. As in the above architecture, central office and remote nodes are connected by a single-fiber collector ring, which can provide protection and restoration capabilities. In the distribution networks, ONUs are attached to the remote nodes, which define the center of a CWDM TDM-based star topology or DWDM WDM-based star topology (see Figure 5). The remote nodes employ passive power splitters or AWGs. Splitters are used on one wavelength for broadcasting the downstream signals for the ONUs and AWGs used for routing the dedicated wavelengths to each ONU. Three-remote node structures are proposed. One structure consists of a N×N AWG and two band splitters, which are three-port passive devices made of a thin-film filter that performs add/drop functionality [AKG$^+$04]. The remote node will route the unique wavelength to each ONU. Another design is composed of a N×N passive power splitter, a cascade of a CWDM add/drop thin-film filter and a channel add/drop thin-film filter. Downstream signals are broadcast to all ONUs through the splitter while upstream signals are collected by the power splitter. The third design is a semi-passive design to provide protection and restoration. Based on the three-remote node structures, a 2×2 optical switch, a photo diode and an electrical controller are added. The photo diode is used to detect the signal loss. The switch controlled by the electrical controller is able to provide protection from the broken fiber, while the ONU employs a semiconductor optical amplifier (SOA) as a modulator and preamplifier or the vertical cavity semiconductor optical amplifier (VCSOA). In OLT, tunable lasers are employed and receivers are shared by all ONUs to reduce the system cost.

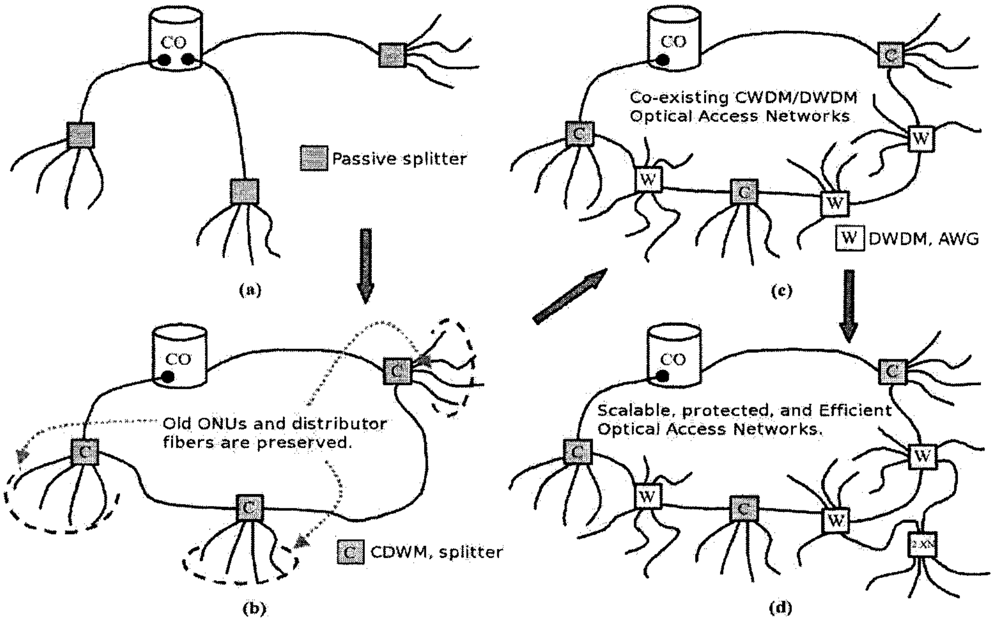


Figure 5: Network migration scenario under SUCCESS architecture [AKG+04]

With this design of WDM/TDM architecture, the system can achieve the scalability of more than 60 DWDM ONUs or more than 100 CWDM ONUs with a line rate of 1.25 Gbit/s on the ring and total transmission distance of 22.5 km. It also has the capability of providing protection and restoration with the collector ring topology and semi-passive remote nodes. The SUCCESS architecture provides economical migration paths from current-generation TDM PONs to future WDM-based optical access networks. However, this design employs the semi-passive component, which needs power supply to operate in the remote node. This will increase system cost and maintenance.

3.1.4 Multiple OLT Architecture

A multiple OLT architecture is considered in [MHM07] to increase the scalability over the single OLT. It has a higher-level design of the access network and part of the metro network; it also integrates all-optical WDM PON with Ethernet. Ethernet-based PONs are TDM single wavelength channel systems using one single wavelength for downstream transmission and one single wavelength for upstream transmission. In the proposed system called STARGATE, shown in Figure 6, central offices and other ring nodes are stringed by a dual-fiber bidirectional ring. Central offices are also interconnected by an N×N passive star coupler and an N×N athermal AWG. Other ring nodes may connect to the Internet or server farms. There are two pairs of links in the distribution network. One link is from the central office (CO) to remote nodes, which are passive couplers connecting all ONUs in this sub-network. The other link from the AWG in the metro network is connected to the P2P or P2MP link for downstream signaling and is coupled with the first link through a WDM coupler for upstream signaling. This second link is called optical bypassing. Deploying AWGs enables wavelength reuse at each AWG port.

In their simulation, they set up 4 central offices interconnected by a 4×4 AWG and a 4×4 passive star coupler (PSC). There are 12 resilient packet ring (RPR) nodes. Each WDM EPON has 32 ONUs, resulting in 128 ONUs in the whole simulation network. The number of wavelengths is 5 for PSC and 4 for AWG. The distance between the ONU and the OLT is 20 km and the RPR ring is 100 km in length.

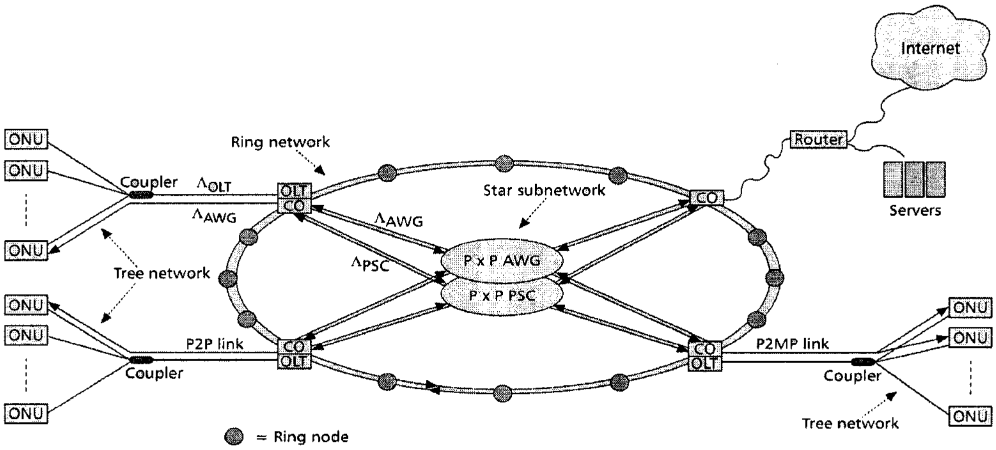


Figure 6: STARGATE system architecture with Multiple OLTs [MHM07]

The line rate is 1 Gbit/s for both the distribution network and the ring network and 10 Gbit/s for the star sub-network. The traffic distribution is 50 percent of 40-byte packets, 30 percent of 552-byte packets, and 20 percent of 1500-byte packets. Two types of ONUs are compared in the simulation: one has a single transmitter that can only transform the wavelengths into those that are used by the OLT. Another is able to transform the wavelengths to those that are used by both the OLT and AWGs. The result shows that the more second type ONUs are used (meaning more ONUs have access to optical bypassing wavelengths), the better the system performs in terms of throughput-delay.

The STARGATE system architecture integrates the WDM PON technology with Ethernet, thus provides a cost effective design and good performance. However, scalability is still a problem for STARGATE, because it can only support a maximum of 32 ONUs per central office.

3.2 Deployment Cost of PON Network

The network cost can be analyzed in many ways under different standards. For access network, the key part is to build a suitable network cost model to estimate the total cost of the network infrastructures, i.e., device cost, housing cost, trench cost and cable cost. In [WZ03], Weldon *et al.* propose a network cost model to calculate the trench and cable lengths in order to estimate their cost. To capture the issues in real street topologies, they assume all homes are distributed on a regular grid with uniform density and each remote node serves a square area in the grid. All the cables follow the grid and share the same trenches as much as possible. Based on the model, they evaluate the cost of five different access networks: VDSL-26, VDSL-52, active optical network, passive optical network and future passive optical network under different take rates, which are defined as the percentage of users who subscribe the services. The authors found that when the take rate is low, the infrastructure costs become significant. According to their comparison, VDSL is the most economical solution at lower bandwidth requirement and it is predicted that Ethernet PON will be the future solution for high bandwidth access network.

However, the paper was written in 2003 and its prediction may be out of date. WDM is also a promising technology and provides high bandwidth for PON networks.

Based on the model in [WZ03], Tran *et al.* [TCT05] studied the cost and reliability for Ethernet PON and WDM PON. They consider two different types of network protection models as suggested in [ITU98]. The first type uses a spare fiber for the feeder network, which is located between OLT and remote nodes. In the second type, all the network components are doubled, including OLT, remote nodes, ONUs and fibers. Taking into account the network protection, they propose the same network topology with different technologies (APON, EPON and WDM PON) and analyze the network cost for both unprotected and protected case. They also evaluate the reliability for each proposed network and derive a parameter called figure of merit to capture the trade-off between network cost and reliability. They found that EPON architecture has a lower network cost than WPON at a low take rate. When the take rate is higher than 60%, WPON shows the lowest cost per subscriber per Mbit/s. Taking the reliability into account, they found that WPON with the second type of protection is the best option for high reliability and relatively low cost access network architecture.

A similar network deployment model is studied in [SBFP04]. Sananes *et al.* evaluated the parameters for different types of architectures based on passive optical networks, including number of users, bandwidths, multiplexing techniques, distances, installation, flexibility, scalability and upgrade ability and costs. Then they simulate five different architectures of FTTH to be employed in a generalized city with a given number of users and compare the deployment cost for those architectures. They found WDM PON is the most cost effective and may be the key technologies for service providers and enterprises wanting to upgrade their networks.

Chapter 4

Mathematical Models

4.1 Notations and Assumptions

In this chapter, we investigate two problems (MC-RWA and MC-GRWA) with two different objectives on two topologies: tree and light mesh. We develop mathematical optimization models to solve those problems.

Notations

Consider an optical access network represented by undirected graph $G = (V, L)$, where $V = \{OLT, ONU_1, ONU_2, ..., ONU_n\}$ is the set of nodes and $L = \{\ell_1, \ell_2, ..., \ell_m\}$ represents the set of links, where ℓ is the physical fiber link between two nodes in the network. Let $\omega(v)$ be the set of fiber links connected to node v. $\omega(OLT)$ represents the set of fiber links connected to the OLT. Let $\mathcal{O} = \{ONU_1, ONU_2, ..., ONU_n\}$ denote the overall set of ONUs. Given $\ell \in \omega(OLT)$, $\mathcal{O}^\ell$ is the subset of ONUs, which can be reached by OLT through link ℓ. The total transport capacity of one wavelength is denoted by B_ℓ. The set of available wavelengths is denoted by $\Lambda = \{\lambda_1, \lambda_2, ..., \lambda_W\}$ and $W = |\Lambda|$ is the total number of wavelengths. We assume that there are enough wavelengths to serve all ONUs on each link $\ell \in \omega(OLT)$ for both upstream and downstream transmission. The transport capacity required in any request does not exceed the capacity of a single wavelength. We assume that all links have the same transport capacity.

The network traffic is defined by $T = \{T_{sD}\}$, in which, for a given request $r = (s_r, D_r)$, $s_r \in \mathcal{O} \cup OLT$ is the source of the request, $D_r \subseteq \mathcal{O} \cup OLT$ is the set of destinations of the request and T_{sD} denotes the traffic (the number of requests) from source node s_r to destination node set D. Let R be the overall request set, in which each request r has a source node s_r and a set of destination nodes D_r. The request can be sent either from or between the OLT to ONU(s) or originate from ONU to ONU(s). We use R^{CORE} to represent the set of requests originated from the OLT (the former case) and R^{ACCESS} to represent the set of requests originated from ONU (the latter case). Therefore $R = R^{CORE} \cup R^{ACCESS}$.

Two problems with different objectives are studied: the MC-RWA and MC-GRWA problems. In this thesis, we use MC-RWA and MC-GRWA to denote the problems with objective of maximizing the number of granted requests and MC-RWA_P and MC-GRWA_P denote the problems with objective of maximizing the weighted number of served ONUs, where P stands for partial granted requests. The MC-RWA problem can be formally stated as follows: Given a graph G corresponding to a WDM-PON network and a set of requests R, find the suitable light-paths (for unicast requests) and light-trees (for multicast requests) that offer a good compromise between minimizing network cost and maximizing the total number The locations of the intermediate nodes are given. The MC-GRWA is based on the MC-RWA problem with TDMA support (which is employed to transfer multiple requests in the same wavelength in order to increase the bandwidth utilization).

However, it is possible that the service provider may be interested in serving as many customers as possible rather than granting the requests in order to get better revenue. Keeping in mind the goal of maximizing the number of served ONUs, we consider the MC-RWA_P and MC-GRWA_P problems as follows: The assumptions and notations are the same with MC-RWA and MC-GRWA problems described above except that the objective is now to maximize the number of served ONUs instead of granted requests. Due to the change in the objective, partially granted requests are allowed, which means selected ONUs can be served for an arbitrary request.

We only consider the bandwidth constraints (for MC-GRWA problems) and the number of wavelength constraints (for the problems on light mesh topology) on the OLT-link level where is the bottleneck of the network. If those constraints are satisfied, the constraints for the links after them are all satisfied.

In summary, we study two problems (MC-RWA and MC-GRWA) on two different topologies (tree and light mesh), which are defined in Section 4.2 and 4.7, with two different objectives: to maximize the total number of granted requests and to maximize the total number of served ONUs.

Equipment

In this chapter, we consider pure AWG PON networks, which means that each intermediate node is equipped with an AWG. The physical links are employed with bidirectional wavelengths, which means that the upstream and downstream transmissions are carried out in the same fiber. In order to reduce the network cost, we assume that each ONU is equipped with only one receiver and one transmitter. Therefore, each ONU can only receive one wavelength and send another wavelength. Those wavelengths are the dedicated channels between the OLT and ONUs. Because of the wavelength routing characteristics of an AWG (refer to Section 2.3.2), the transmissions are considered as point-to-point connections. Also, if a request is from an ONU to another ONU(s), the request must go through the OLT, which has the ability to convert the incoming wavelength to the wavelengths required by destination ONUs. In other words, if a request is passing through the OLT, it can be assigned to two wavelengths, one for upstream signaling one for downstream signaling.

Cost Functions

The cost functions can be defined in different standards for different requirements. How to define the cost functions is still an open question. However, in this chapter, we propose some cost functions according to the profits and network resources, which correspond to the models we build in order to explore the different requirements for requests.

The costs in the models are denoted as C_r and C_{ri}, where C_r is the cost of request r for the fully granted request scenarios and C_{ri} is the cost of request r to ONU_i for the partially granted request scenarios. Because the different scenarios have different cost functions, they will be discussed separately. In each cost function, p_r is the revenue of the request r and assumed to be given along with the request set data. It can be the price that the user pays to the service provider or the profit that the network operator earns if the request r is served. b_r denotes the bandwidth that the request r will use if it is granted. It is always less than or equal to the transport capacity of a wavelength. w_r is the maximum number of used wavelengths for request r on all outgoing links of the OLT, i.e., $\ell \in \omega(OLT)$.

$$w_r = \max\{w_{r\ell} : \ell \in \omega(OLT)\}\,, \tag{1}$$

where $w_{r\ell}$ is the number of wavelengths on each link $\ell \in \omega(OLT)$. It can be calculated as the number of destination ONUs plus 1 if the source ONU is on link ℓ, or plus 0 if not. The last variable n_r is the total number of ONUs served by request r.

The cost function depends on whether granting a partial request is allowed and whether TDMA is employed. If partially granting requests is not allowed, the whole request is either granted or rejected, i.e., all destination ONUs are served or none of them. The cost is calculated as a function of the whole request. Otherwise, any ONU can be either served or not served in the request. The cost should be calculable for each ONU and for each request. Here are four proposals:

Scenario 1: Requests are fully granted if granted, no TDMA

$$C_r = \frac{p_r}{w_r n_r}. \tag{2}$$

Scenario 2: Requests are fully granted if granted, TDMA is used

$$C_r = \frac{p_r}{w_r n_r b_r}. \tag{3}$$

The pricing parameter p_r is a positive factor for the cost functions. Because wavelengths correspond to limited resources for the whole network, it is considered as a parameter in the cost functions for each request. Requests requiring fewer wavelengths are preferred because there are more wavelengths left for other requests. For the same reason, for a given total number of ONUs served by a request, if other parameters are kept the same, a request that serves two ONUs is more valuable than a request that serves twenty ONUs. The rest of the ONUs can be served in other requests so that more requests can be granted. If a request uses 2 wavelengths and serves 8 ONUs, while another request uses 4 wavelengths and serves 4 ONUs, the products of w_r and n_r are the same. Therefore, those two requests have the same chance to be granted. If TDMA is employed in the network, the bandwidth factor b_r is considered as the requests can be combined together on a wavelength. If other conditions are the same, the more bandwidth the request consumes, the less probability to be granted the request has. The requests that require less bandwidth are preferred.

In the following scenarios, the notations are the same as above except the cost is calculated based on each ONU rather than at the request level.

Scenario 3: Requests can be partially granted, no TDMA

$$C_{ri} = \frac{p_r}{n_r}. \tag{4}$$

The wavelength parameter is removed because (1) the cost is calculated based on ONU and (2) the request can be partially granted (which means that any number of ONUs can be granted in a multicast request). The bandwidth variable is ignored in the 4 because without TDMA each request uses a whole wavelength to transmit the request so that there is no bandwidth factor to be considered.

Scenario 4: Requests can be partially granted, TDMA is used

$$C_{ri} = \frac{p_r}{n_r b_r}. \tag{5}$$

The bandwidth variable b_r is added because TDMA is employed to share the bandwidth of a wavelength. Priority is given to the ONUs, for whom the request requires less bandwidth.

Grade of Service and Throughput

The results are shown in terms of grade of service, which is a important parameter for a network operator to measure the throughput of a network.

The GoS for MC-RWA and MC-GRWA problems is calculated as:

$$P_{GoS} = \frac{n_R^g}{n_R}, \tag{6}$$

where n_R^g is the number of granted requests and n_R is the total number of requests.

For MC-RWA and MC-GRWA problems with maximizing the number of served ONUs, if we only calculate the number of requests, the result will not be accurate because of partially granted requests. Therefore, the base unit of calculation is based on destination ONUs instead of requests:

$$P_{GoS} = \frac{n_O^g}{n_O}, \tag{7}$$

where n_O^g is the number of served destination ONUs and n_O is the total number of destination ONUs for all requests.

The throughput shows another view of the network performance. It is evaluated using the following parameters:

$$P_{throughput} = \frac{b_R^g}{b_R}, \tag{8}$$

where b_R^g is the total bandwidth of all granted requests and b_R is the total bandwidth required for all requests, including the requests that are not granted.

For the MC-RWA_P and the MC-GRWA_P problems to maximize the number of served ONUs, the throughput is calculated as:

$$P_{throughput} = \frac{b_O^g}{b_O}, \tag{9}$$

where b_O^g is the total bandwidth required by all served destination ONUs and b_O is the total bandwidth required by all destination ONUs for all requests.

4.2 Models on tree topology

Tree topology (also known as hierarchical topology) is the most common topology in PON networks, as the OLT is the "root" (the top level of the hierarchy) and ONUs are the "leaves". The remote nodes, which are assumed to be equipped with AWGs in this thesis, sit in intermediate levels of the tree, as shown in Figure 7. In a tree topology, the light path between the OLT and an ONU is unique. For both upstream and downstream, the traffic for the same ONU will follow a unique path. It can be observed that, in the mathematical models, we only need to care about the links which are adjacent to the OLT due to the unicity of a lightpath linking the OLT and a given ONU. In addition, it can be shown that the solution can be done in two steps, firstly the routing, secondly the wavelength assignment, without impairing searching the optimal solution. (refer to Chapter 5)

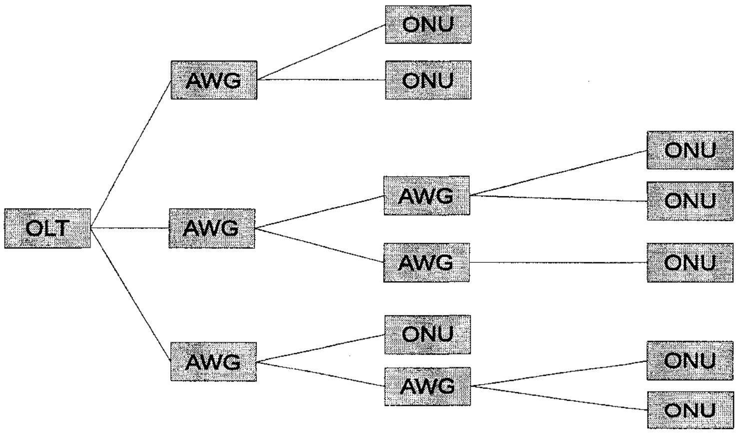


Figure 7: Tree Topology

4.3 MC-RWA with maximizing the number of granted requests

We consider that the tree topology is given. Each granted request will be assigned a λ, while the route is unique for every request $r \in R$ in the tree topology. Since the topology is given, we assume that the signal is strong enough to be captured by the receivers of ONUs and all ONUs can be reached from OLT, which means that the attenuation constraint is always satisfied. For request granting, if in a multicast request one destination cannot be served, the whole request has to be rejected. For the wavelength assignment, we assume that we have enough wavelengths to serve all ONUs on each link so that we can always assign wavelengths to a request for both upstream and downstream. Therefore, we will do the wavelength assignment with an exact greedy algorithm after solving the routing problem, see Chapter 5 for the details.

- Parameters: $\mathcal{O}^\ell$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$.
- Variables: Decision vector x, where each component x_r satisfies

$$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R\,.$$

- Objective: Maximize the income

$$\max \sum_{r \in R} c_r x_r\,, \tag{10}$$

where c_r is the revenue defined by the cost function.

- Constraints: We assume that no request requires the bandwidth for more than one wavelength and there is no TDMA in this case. Each request has a full wavelength for transmission.

  Considering the wavelength constraints for ONU, each ONU can read only one wavelength:

  $$\sum_{r \in R : ONU_i \in D_r} x_r \leq 1, \qquad ONU_i \in \mathcal{O}. \tag{11}$$

  Each ONU can send messages on only one wavelength:

  $$\sum_{r \in R^{ACCESS} : ONU_i = s_r} x_r \leq 1, \qquad ONU_i \in \mathcal{O}. \tag{12}$$

  In order to grant an ONU-to-ONU request, both downstream and upstream requests must be granted. However, in this model, each ONU is assigned two wavelengths for incoming and outgoing requests. Constraints (11) and (12) correspond to the fact that only one request can be sent per wavelength. Constraints (11) implies that if ONU_i is the destination of all downstream requests, only one request can be granted if and only if the second constraint is satisfied. Constraints (12) expresses that the upstream part of the request must be granted. If a request r is granted, both constraints should be satisfied.

4.4 MC-GRWA with maximizing the number of granted requests

In order to maximize the bandwidth usage, some requests with the same source or destination can be combined and transmitted on the same wavelength. TDMA is employed to achieve this. In this case, we need to consider that the total bandwidth required by the requests sharing the same wavelength should not exceed the wavelength transport capacity.

- Parameters: $\mathcal{O}^{\ell}$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$. B_{ℓ} is the transport capacity of a wavelength.
- Variables: Decision vector x where each component satisfies.

$$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R\,.$$

- Objective: Maximize the income

$$\max \sum_{r \in R} c_r x_r\,, \tag{13}$$

  where c_r is the revenue defined by the cost function.

- Constraints:

  With TDMA, we need to consider the bandwidth constraints for the requests sharing the same wavelength. They should not exceed the bandwidth of a single wavelength. b_r denotes the bandwidth required by request r:

$$\sum_{r \in R: ONU_i \in D_r} b_r x_r \leq B_{\ell} \qquad ONU_i \in \mathcal{O}\,. \tag{14}$$

  For upstream signals:

$$\sum_{r \in R: ONU_i = s_r} b_r x_r \leq B_{\ell} \qquad ONU_i \in \mathcal{O}\,. \tag{15}$$

  These two constraints (14) and (15) ensure that the required bandwidth for all requests, which are sent from (to) an ONU will not exceed the transport capacity of one wavelength. Both constraints also imply that each ONU can read only one wavelength and send messages on only one wavelength.

4.5 MC-RWA with maximizing the number of served ONUs (MC-RWA_P)

Service providers may be interested in serving as many customers as possible, which means maximizing the number of served ONUs. In this case, we consider partially granted requests, which means that if all the destinations of a request cannot be served, we do not simply reject the request, but serve the ONUs that can be served. Therefore, part of the request is granted.

We consider the MC-RWA_P problem:

- Parameters: $\mathcal{O}^\ell$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$
- Variables: Decision vector x, where each component x_r satisfies

  $$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted, possibly only partially} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R\,.$$

  Decision vector x, where each component x_{ri} satisfies

  $$x_{ri} = \begin{cases} 1 & \text{if request } r \text{ is granted for } ONU_i \\ 0 & \text{if request } r \text{ is not granted for } ONU_i \end{cases} \qquad r \in R, i \in \mathcal{O}\,.$$

- Objective: Maximize the number of served ONUs

$$\max \sum_{r \in R} \sum_{i:ONU_i \in Dr} c_{ri} x_{ri} \,, \tag{16}$$

where c_{ri} is the revenue defined by the cost function.

- Constraints: We assume that no request requires the bandwidth for more than one wavelength and that there is no TDMA in this case. Each request has a full wavelength for transmission. Therefore, we do not need to consider the bandwidth constraint.

  For upstream signals, constraints are the same as for the basic MC-RWA problem. Each ONU can send messages on only one wavelength:

  $$\sum_{r \in R^{ACCESS}:ONU_i = S_r} x_r \leq 1, \qquad ONU_i \in \mathcal{O}\,. \tag{17}$$

  For downstream, each ONU can read only one wavelength, but the destinations of the request can now be served separately:

  $$\sum_{r \in R:ONU_i \in D_r} x_{ri} \leq 1, \qquad ONU_i \in \mathcal{O}\,. \tag{18}$$

  In order to grant the request, at least one ONU in the destinations of request r must be accepted:

  $$x_r \leq \sum_{i:ONU_i \in D_r} x_{ri}, \qquad r \in R\,. \tag{19}$$

  The request r must be granted in order to grant the core and downstream requests:

  $$x_r \geq x_{ri}, \qquad i : ONU_i \in D_r\,, r \in R\,. \tag{20}$$

  We assume that each request has only one source node, either OLT or ONU. For the upstream constraint of all access request, if a request r is granted, the source s_r must be granted. Contrariwise, if the source s_r is granted, the request r should be granted.

$$x_r = x_{rs_r}, \qquad r \in R^{ACCESS}. \tag{21}$$

4.6 MC-GRWA with maximizing the number of served ONUs (MC-GRWA_P)

In the MC-GRWA problem, the requests with the same source or destination can be combined in order to increase the bandwidth utilization. Therefore, we need to consider the transport capacity constraint.

- Parameters: $\mathcal{O}^\ell$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$. B_ℓ is the transport capacity for a wavelength.
- Variables: Decision vector x, where each component x_r satisfies

$$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R.$$

Decision vector x, where each component x_{ri} satisfies

$$x_{ri} = \begin{cases} 1 & \text{if request } r \text{ is granted for } ONU_i \\ 0 & \text{if request } r \text{ is not granted for } ONU_i \end{cases} \qquad r \in R, i \in \mathcal{O}.$$

- Objective: Maximize the served ONUs.

$$\max \sum_{r \in R} \sum_{i \in Dr} c_{ri} x_{ri}\,, \tag{22}$$

where c_{ri} is the revenue defined by the cost function.

- Constraints:

  For upstream signals, constraints are the same as for the MC-GRWA:

$$\sum_{r \in R^{ACCESS}: ONU_i = s_r} b_r x_r \leq B_\ell \qquad ONU_i \in \mathcal{O}\,. \tag{23}$$

  For downstream signals, all the traffic to the same ONU share the bandwidth of one wavelength. Those constraints are to guarantee enough bandwidth for each destination ONU.

$$\sum_{r \in R: ONU_i \in D_r} b_r x_{ri} \leq B_\ell, \qquad ONU_i \in \mathcal{O}\,. \tag{24}$$

  In order to grant the request r, at least one ONU in the destinations of request r must be accepted:

$$x_r \leq \sum_{i: ONU_i \in D_r} x_{ri} \qquad r \in R\,. \tag{25}$$

  The request r must be granted in order to grant the core and downstream requests:

$$x_r \geq x_{ri} \qquad i : ONU_i \in D_r, r \in R\,. \tag{26}$$

  We assume that each request have only one source node, either OLT or ONU. For the upstream constraints of all access requests, if a request r is granted, the source s_r must be granted. Contrariwise, if the source s_r is granted, the request r should be granted.

$$x_r = x_{rs_r} \qquad r \in R^{ACCESS}\,. \tag{27}$$

4.7 Models on light mesh topology

Now let us consider the MC-RWA on a WDM-PON light mesh topology. First, we will describe what we mean by a light mesh topology. "Mesh" means that there are some loops in the network and "light" means that only the end node branches are merged. Therefore, in this thesis, the light mesh topology is defined as a modified tree topology, where some leaf nodes can be reached using two distinct routes from the OLT, as shown in Figure 8. We call it tree converted light mesh topology in this thesis. There may be more than one light path from the OLT to an ONU and the traffic for upstream and downstream may not follow the same path. For the combiner in the merged branch ONU, AWGs are used. For the link protection and resiliency in case of link failure, network operators may be interested in the light mesh topology. We assume that all downstream traffic will end at ONU and will not be sent to another link of a merged branch ONU. Therefore, the message will not travel in a loop on the network. It can be observed that, in the mathematical models, we only need to care about the links which are adjacent to the OLT due to the unicity of a lightpath linking the OLT and a given ONU. In addition, it can be shown that the solution can be done in two steps, firstly the routing, secondly the wavelength assignment, without impairing searching the optimal solution. (refer to Chapter 5)

In the tree topology, we ignore the constraint of maximum link capacity. We assume that the network topology is given and any ONU can be reached by the OLT, which means all the ONUs can be reached by the OLT at the same time, if there are no request constraints. There is only one route for each ONU and it needs a unique wavelength to communicate with the OLT. Different branches from the OLT can share the same wavelength. Therefore, the maximum number of wavelengths

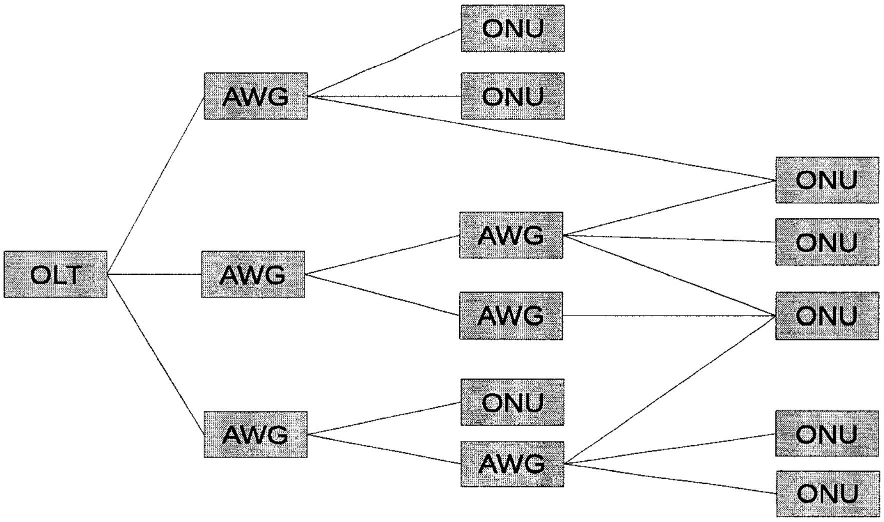


Figure 8: Light Mesh Topology

needed in the tree topology is

$$2 \times \max\{n_1, n_2, ...n_m\}\ , \tag{28}$$

where n is the number of ONUs on branch m and m is the number of level one branches ℓ where $\ell \in \omega(OLT)$.

However, when the topology is light mesh, the above conclusion may be incorrect. One ONU may be reached by two different links ℓ_i or ℓ_j, which means there may be several routes between the OLT and the ONU. Therefore, in this case, we consider the constraint of maximum link capacity W, which is how many wavelengths a link can carry. Since there may be several paths from the OLT to the ONU, we are also interested in how the wavelengths are assigned in the light mesh network, e.g. on which link from the OLT the request will be sent to the ONU (In the tree topology, the request will be sent to the link where ONU is). Other assumptions are the same with those in tree topology.

Comparing the tree topology and its converted light mesh topology, where both topologies have the same number of AWGs and ONUs, it is impossible to increase the grade of service for pure AWG-based PON network. Because we assume that there are enough wavelengths to reach all ONUs and each ONU can receive only one wavelength and send on only one wavelength. Only one link connected to ONU is used at a given time. The reason that a request is rejected is that there is not enough transport capacity to bind all requests that will be received by a given ONU. One or more requests have to be rejected. The infrastructure cost is also increased in light mesh topology, because more fibers are used and trenching distances are longer (refer to Chapter 6 for cost calculation). However, the trenching and fiber costs are far less than other costs, e.g., device cost. Because of the physical characteristics of AWG, the insertion loss does not depend on the number of output ports (refer to Section 2.3.2). Using the light mesh topology, which means more output ports required for an AWG than the tree topology, will not introduce more attenuation on devices, but maybe on fibers, which may be considered by taking margins when calculating the attenuation. If a ONU requires more reliability, the light mesh topology is preferred.

4.8 MC-RWA with maximizing the number of granted requests on light mesh topology

- Parameters: $\mathcal{O}^\ell$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$ where $\mathcal{O}^\ell \cap \mathcal{O}^{\ell'} \neq \emptyset$ for some ℓ and $\ell' \in \omega(OLT)$, $\ell \neq \ell'$.
- Variables: Decision vector x, where each component x_r satisfies

$$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R\,.$$

Another two vectors $x_{rD}^{\ell i}$ and $x_{rU}^{\ell i}$ satisfy

$$x_{rD}^{\ell i} = \begin{cases} 1 & \text{if request } r \text{ is sent on link } \ell \text{ to} \\ & \text{downstream direction for } ONU_i \\ 0 & \text{otherwise.} \end{cases} \qquad r \in R, \ell \in \omega(OLT)\,,$$

and

$$x_{rU}^{\ell i} = \begin{cases} 1 & \text{if request } r \text{ is sent on link } \ell \text{ to} \\ & \text{upstream direction for } ONU_i \\ 0 & \text{otherwise.} \end{cases} \qquad r \in R, \ell \in \omega(OLT)\,.$$

- Objective: Maximize the income

$$\max \sum_{r \in R} c_r x_r\,, \tag{29}$$

where c_r is the revenue defined by cost function.

- Constraints:

In this case, we assume that no request requires a bandwidth greater than that of one wavelength and that there is no TDMA. Each request has a full wavelength bandwidth for transmission. Therefore, we do not need to consider the bandwidth constraint for each request. However, we do need to consider the wavelength constraint for the links. If an ONU can be reached by both links ℓ and $\ell' \in \omega(OLT)$ and ℓ is already assigned the maximum number of wavelengths W, the request can still be granted through link ℓ' to reach the ONU.

The constraints on the number of wavelengths:

$$\sum_{r\in R: D_r \cap \mathcal{O}^\ell \neq \emptyset} x_{rD}^{\ell i} + \sum_{r\in R^{ACCESS}: s_r \in \mathcal{O}^l} x_{rU}^{\ell i} \leq W, \qquad \ell \in \omega(OLT)\,. \tag{30}$$

Considering the wavelength constraints for an ONU, each ONU can read only one wavelength:

$$\sum_{r\in R: ONU_i \in D_r} x_r \leq 1, \qquad ONU_i \in \mathcal{O}\,. \tag{31}$$

Each ONU can send on only one wavelength:

$$\sum_{r\in R^{ACCESS}: ONU_i = s_r} x_r \leq 1, \qquad ONU_i \in \mathcal{O}\,. \tag{32}$$

In order to grant an ONU-to-ONU request, both downstream (on each level one links) and upstream requests must be granted. If the request is granted, each ONU in the request should also be granted. These two constraints also ensure that each ONU in the granted request only uses one link for upstream or downstream transmission, if there are multiple paths available:

$$x_r = \sum_{\ell: ONU_i \in \mathcal{O}^\ell} x_{rU}^{\ell i}, \qquad r \in R^{ACCESS}, ONU_i = s^r\,, \tag{33}$$

$$x_r = \sum_{\ell: ONU_i \in \mathcal{O}^\ell} x_{rD}^{\ell i}, \qquad r \in R, ONU_i \in D^r\,. \tag{34}$$

4.9 MC-GRWA with maximizing the number of granted requests on light mesh topology

- Parameters: $\mathcal{O}^\ell$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$ where $\mathcal{O}^\ell \cap \mathcal{O}^\ell \neq \emptyset$ for some ℓ and $\ell' \in \omega(OLT)$, $\ell \neq \ell'$. B_ℓ is the transport capacity for a wavelength.

- Variables: Decision vector x, where each component x_r satisfies

$$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R\,.$$

The other two vectors $x^{\ell i}_{rD}$ and $x^{\ell i}_{rU}$ satisfy

$$x^{\ell i}_{rD} = \begin{cases} 1 & \begin{array}{l}\text{if request } r \text{ is sent on link } \ell \text{ to} \\ \text{downstream direction for } ONU_i\end{array} \\ 0 & \text{otherwise} \end{cases} \qquad r \in R, \ell \in \omega(OLT)\,,$$

and

$$x^{\ell i}_{rU} = \begin{cases} 1 & \begin{array}{l}\text{if request } r \text{ is sent on link } \ell \text{ to} \\ \text{upstream direction for } ONU_i\end{array} \\ 0 & \text{otherwise} \end{cases} \qquad r \in R, \ell \in \omega(OLT)\,.$$

- Objective: Maximize the income

$$\max \sum_{r \in R} c_r x_r \,, \tag{35}$$

where c_r is the revenue defined by the cost function.

- Constraints: We assume that no request requires the bandwidth for more than one wavelength and that there is no TDMA in this case. Each request has a full wavelength bandwidth for transmission. Therefore, we do not need to consider the bandwidth constraints.

The constraints on the number of wavelengths:

$$\sum_{i:ONU_i \in D_r \cap \mathcal{O}^\ell \neq \emptyset} \max_{r \in R} x_{rD}^{\ell i} + \sum_{i:ONU_i = s_r} \max_{r \in R^{ACCESS}} x_{rU}^{\ell i} \leq W, \qquad \ell \in \omega(OLT)\,. \quad (36)$$

In order to eliminate the max functions in constraint (36), we convert the max functions into the following linear inequations:

Let $\max_{r \in R} x_{rD}^{\ell i}$ be y^D and $\max_{r \in R^{ACCESS}} x_{rU}^{\ell i}$ be y^U, which are binary variables, then we have:

$$y^D \geq x_{rD}^{\ell i}, \qquad r \in R\,, \quad (37)$$

$$\sum_{r \in R} x_{rD}^{\ell i} \geq y^D\,. \quad (38)$$

If any $x_{rD}^{\ell i}$ is 1, the value of y^D is forced to be 1 by constraint (37). When all $x_{rD}^{\ell i}$ are 0, the constraint (38) forces y^D to 0. Therefore, the max functions are converted into inequalities.

For upstream transmission:

$$y^U \geq x_{rU}^{\ell i}, \qquad r \in R^{ACCESS}\,, \quad (39)$$

$$\sum_{r \in R} x_{rU}^{\ell i} \geq y^U\,. \quad (40)$$

Considering the wavelength constraints for an ONU, each ONU can read only one wavelength:

$$\sum_{r \in R:ONU_i \in D_r} b_r x_r \leq B_\ell, \qquad ONU_i \in \mathcal{O}\,. \quad (41)$$

Each ONU can send on only one wavelength:

$$\sum_{r \in R^{ACCESS}:ONU_i = s_r} b_r x_r \leq B_\ell, \qquad ONU_i \in \mathcal{O}\,. \quad (42)$$

In order to grant an ONU-to-ONU request, both downstream (on each level one links) and upstream must be granted. If the request is granted, each ONU in the request should also be granted. These two constraints also ensure that each ONU in the granted request only uses one link for upstream or downstream transmission, if there are multiple paths available:

$$x_r = \sum_{\ell : ONU_i \in \mathcal{O}^\ell} x_{rU}^{\ell i}, \qquad r \in R^{ACCESS}, ONU_i = s_r\,, \tag{43}$$

$$x_r = \sum_{\ell : ONU_i \in \mathcal{O}^\ell} x_{rD}^{\ell i}, \qquad r \in R, ONU_i \in D_r\,, \tag{44}$$

4.10 MC-RWA with maximizing the number of served ONUs on light mesh topology (MC-RWA_P)

- Parameters: $\mathcal{O}^\ell$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$ where $\mathcal{O}^\ell \cap \mathcal{O}^\ell \neq \emptyset$ for some ℓ and $\ell' \in \omega(OLT)$, $\ell \neq \ell'$.
- Variables: Decision vector x, where each component x_r satisfies

$$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R\,.$$

Decision vectors for each ONU:

$$x_{rU}^{\ell,i} = \begin{cases} 1 & \text{if request } r \text{ is sent from } ONU_i \text{ on link} \\ & \ell \text{ to upstream direction} \\ 0 & \text{otherwise} \end{cases} \qquad r \in R, \ell \in \omega(OLT),$$

and

$$x_{rU}^{\ell i} = \begin{cases} 1 & \text{if request } r \text{ is sent to } ONU_i \text{ on link} \\ & \ell \text{ to downstream direction} \\ 0 & \text{otherwise} \end{cases} \qquad r \in R, \ell \in \omega(OLT),$$

- Objective: Maximize the income

$$\max \sum_{r \in R} \sum_{i: ONU_i \in D_r} \sum_{\ell \in \omega(OLT)} c_{ri} x_{rD}^{\ell i}\,, \tag{45}$$

where c_{ri} is the revenue defined by the cost function.

- Constraints:

The constraints on the number of wavelengths:

$$\sum_{r \in R: D_r \cap \mathcal{O}^{\ell} \neq \emptyset} x_{rD}^{\ell i} + \sum_{r \in R^{ACCESS}: s_r \in \mathcal{O}^{\ell}} x_{rU}^{\ell i} \leq W, \qquad \ell \in \omega(OLT)\,. \tag{46}$$

Considering the wavelength constraints for the ONU, each ONU can read only one wavelength:

$$\sum_{r \in R: ONU_i \in D_r} x_r \leq 1, \qquad ONU_i \in \mathcal{O}\,. \tag{47}$$

Each ONU can send on only one wavelength:

$$\sum_{r \in R^{ACCESS}: ONU_i = s_r} x_r \leq 1, \qquad ONU_i \in \mathcal{O}\,. \tag{48}$$

In order to grant an ONU-to-ONU request, both downstream (on each level one links) and upstream must be granted. If the request is granted, at least one ONU in the request should also be granted. These two constraints also ensure that each ONU in the granted request only uses one link for upstream or downstream transmission, if there are multiple paths available:

$$x_r = \sum_{\ell : ONU_i \in \mathcal{O}^\ell} x_{rU}^{\ell i}, \qquad r \in R^{ACCESS}, i : ONU_i = s_r \, , \tag{49}$$

$$x_r \leq \sum_{i : ONU_i \in D_r} \sum_{\ell : ONU_i \in \mathcal{O}^\ell} x_{rD}^{\ell i}, \qquad r \in R \, . \tag{50}$$

Ensure the request is granted, if a destination ONU of a request is granted.

$$x_r \geq \sum_{\ell : ONU_i \in \mathcal{O}^\ell} x_{rD}^{\ell i}, \qquad r \in R, i : ONU_i \in D_r \, . \tag{51}$$

4.11 MC-GRWA with maximizing the number of served ONUs on light mesh topology (MC-GRWA_P)

- Parameters: $\mathcal{O}^\ell$ denotes the set of ONUs that can be reached by link $\ell \in \omega(OLT)$ where $\mathcal{O}^\ell \cap \mathcal{O}^\ell \neq \emptyset$ for some ℓ and $\ell' \in \omega(OLT)$, $\ell \neq \ell'$. B_ℓ is the transport capacity for a wavelength.
- Variables: Decision vector x, where each component x_r satisfies

$$x_r = \begin{cases} 1 & \text{if request } r \text{ is granted} \\ 0 & \text{if request } r \text{ is not granted} \end{cases} \qquad r \in R \, .$$

Decision vectors for each ONU:

$$x_{rU}^{\ell i} = \begin{cases} 1 & \text{if request } r \text{ is sent from } ONU_i \text{ on link} \\ & \ell \text{ to upstream direction} \\ 0 & \text{otherwise} \end{cases} \qquad r \in R, \ell \in \omega(OLT) \, ,$$

and

$$x_{rU}^{\ell i} = \begin{cases} 1 & \begin{array}{l}\text{if request } r \text{ is sent to } ONU_i \text{ on link} \\ \ell \text{ to downstream direction}\end{array} \\ 0 & \text{otherwise} \end{cases} \qquad r \in R, \ell \in \omega(OLT)\,.$$

- Objective: Maximize the income

$$\max \sum_{r\in R} \sum_{i:ONU_i \in D_r} \sum_{\ell \in \omega(OLT)} c_r x_{rD}^{\ell i}\,, \tag{52}$$

where c_r is the revenue defined by the cost function.

- Constraints:

The constraints on the number of wavelengths:

$$\sum_{i:ONU_i \in D_r \cap O^\ell \neq \emptyset} \max_{r\in R} x_{rD}^{\ell i} + \sum_{i:ONU_i = s_r} \max_{r\in R^{ACCESS}} x_{rU}^{\ell i} \leq W, \qquad \ell \in \omega(OLT)\,. \tag{53}$$

In order to eliminate the max functions in constraint (53), we convert the max functions into the following inequations:

Let $\max_{r\in R} x_{rD}^{\ell i}$ be y^D and $\max_{r\in R^{ACCESS}} x_{rU}^{\ell i}$ be y^U, which are binary variables, then we have:

$$y^D \geq x_{rD}^{\ell i}, \qquad r \in R\,, \tag{54}$$

and

$$\sum_{r\in R} x_{rD}^{\ell i} \geq y^D\,. \tag{55}$$

If any $x_{rD}^{\ell i}$ is 1, the value of y^D is forced to be 1 by constraint (54). When all $x_{rD}^{\ell i}$ are 0, the constraint (55) forces y^D to 0. Therefore, the max functions are converted into inequations.

For upstream transmission:

$$y \geq x_{rU}^{\ell i}, \qquad r \in R^{ACCESS}, \tag{56}$$

and

$$\sum_{r \in R} x_{rU}^{\ell i} \geq y\,. \tag{57}$$

Considering the wavelength constraints for the ONU, each ONU can read only one wavelength. Requests with the same destinations can be grouped into one wavelength. The total bandwidth used by all grouped requests should not exceed the bandwidth of a wavelength:

$$\sum_{r \in R : ONU_i \in D_r} b_r x_r \leq B_\ell, \qquad ONU_i \in \mathcal{O}\,. \tag{58}$$

Each ONU can send on only one wavelength. Requests with the same source can be grouped into one wavelength. The total bandwidth should not exceed the bandwidth of a wavelength:

$$\sum_{r \in R^{ACCESS} : ONU_i = s_r} b_r x_r \leq B_\ell, \qquad ONU_i \in \mathcal{O}\,. \tag{59}$$

In order to grant an ONU-to-ONU request, both downstream (on each level one links) and upstream must be granted. If the request is granted, at least one ONU in the request should also be granted. These two constraints also ensure that each ONU in the granted request only uses one link for upstream or downstream transmission, if there are multiple paths available:

$$x_r = \sum_{\ell : ONU_i \in \mathcal{O}^\ell} x_{rU}^{\ell i}, \qquad r \in R^{ACCESS}, i : ONU_i = s_r\,, \tag{60}$$

$$x_r \leq \sum_{i:ONU_i \in D_r} \sum_{\ell:ONU_i \in \mathcal{O}^\ell} x_{r^D}^{\ell i}, \qquad r \in R. \tag{61}$$

Ensure the request is granted, if a destination ONU of a request is granted.

$$x_r \geq \sum_{\ell:ONU_i \in \mathcal{O}^\ell} x_{r^D}^{\ell i}, \qquad r \in R, i : ONU_i \in D_r. \tag{62}$$

Chapter 5

Algorithms

Integer linear-programming-based models and algorithms are very important for solving network planning problems. The MC-RWA and MC-GRWA problems can be considered as integer linear optimization problems and thus can be solved by using ILOG CPLEX Concert Technology with C++ interface. According to the model, we feed all the problem information including variables, constraints and objective to ILOG CPLEX. After optimization, the result will be returned for further processing. With the CPLEX output, we can then calculate the GoS and the throughput, which are defined in Section 4.1.

5.1 Wavelength Assignment

As mentioned in Section 2.3.2, with the FSR property, an AWG routes every R wavelengths to the same port. Each FSR provides one wavelength for communication between a given AWG input port and an arbitrary output port. In a tree or light mesh network topology, we cascade several levels of AWGs carefully so that each ONU can be reached by the OLT. In order to send messages from the OLT to the ONUs, the

OLT selects a suitable wavelength to reach the destinations.

Each ONU can receive only one wavelength and send only one wavelength as equations (11) and (12) stated. However, the same wavelength can be shared between each link $\ell \in \omega(OLT)$. The OLT is able to convert one wavelength to another. If the request is originated from ONU, the upstream wavelength and downstream wavelength can be different. This is because all requests either originate from the OLT or pass through the OLT, which can perform the wavelength conversions.

5.1.1 MC-RWA Problem

Maximizing the Number of Granted Requests

For the MC-RWA problem with the objective of maximizing the number of granted requests, because requests do not share wavelengths, the number of wavelengths needed on link ℓ is $W_\ell = W_\ell^D + W_\ell^U$, where $W_\ell^D = \sum\limits_{r \in R, D_r \cap O^\ell \neq \emptyset} x_r$ for downstream requests and $W_\ell^U = \sum\limits_{r \in R, s_r \cap O^\ell} x_r$ for upstream requests. Equation (11) and Equation (12) ensure that any ONU can only read one wavelength and send one wavelength where the wavelength continuous constraints are satisfied.

If the topology is a tree, there is only one lightpath from OLT to ONU_i. The OLT can always select a proper wavelength to reach ONU_i. Because the same wavelength can be used on different links $\ell \in \omega(OLT)$, the number of used wavelengths in this network for request set R is $\max\{W_\ell | \ell \in \omega(OLT)\}$, where W_ℓ is the number of used wavelength on link ℓ. As there is no wavelength shared between requests and each ONU can read and send only one wavelength, W_ℓ is the sum of the total number of ONUs, which are in the destinations of granted requests, and the total number of upstream requests granted on link ℓ. The decision on which link the request should be sent on, depends on where the destination ONUs are. If two destination ONUs of a request are on links ℓ and ℓ' respectively, there will be two wavelengths sent on both links ℓ and ℓ' for this request. The assignment for each link ℓ is independent because of the sharing of wavelengths on each link $\ell \in \omega(OLT)$. On each link ℓ, wavelengths $(\lambda_1, ..., \lambda_j)$ are assigned to all j granted downstream requests, i.e., request r_j is assigned to wavelength λ_j for downstream. Also the next k wavelengths $(\lambda_{j+1}, ..., \lambda_{j+k})$ are assigned for granted upstream requests on link ℓ. As such, $j + k \leq W$.

If the topology is a light mesh, there may be more than one lightpath from the OLT to ONU_i on different links. The wavelength assignment algorithm has to know through which link the request is granted so that it can assign the wavelength to that link. The models in Section 4.7 have been modified to calculate on which link the wavelength is used. Therefore, the system will give this information for the result to wavelength assignment algorithm. The algorithm takes the link information into account and assigns the wavelengths. The number of used wavelengths for a request set R is still $\max\{W_\ell | \ell \in \omega(OLT)\}$, where W_ℓ is the sum of the total number of ONUs that are in the destinations of granted requests and the total number of upstream requests granted on link ℓ. The decision of which link the request should be sent on does not only depend on where the destination ONUs are, but also depends on the request-link pairing information calculated through a 0-1 linear programming program. If both links ℓ and ℓ' can reach an ONU, the wavelength will be assigned according to the results from optimal solution of the models, which will indicate which link will be used for the destination ONU of the request in order to satisfy the number of wavelengths constraints and bandwidth constraints. If the number of used wavelengths on link ℓ equals the maximum number of available wavelengths W and link ℓ' does not, the program will grant the request on link ℓ' and wavelength assignment algorithm will assign a wavelength for the request on link ℓ'. The assignment of each link ℓ is independent because of the sharing of wavelengths on each link $\ell \in \omega(OLT)$.

According to the request-link pairing information, the wavelengths will be assigned for each request on the links. The method is the same as that for tree topology.

Maximizing the Number of Served ONUs

For the objective of maximizing the number of served ONUs, we allow requests to be partially granted. We basically use the same wavelength assignment algorithm for both partially granted requests (maximizing the number of served ONUs) and non-partially granted requests (maximizing the number of granted requests) scenarios. Before the wavelengths are assigned by the algorithm for the partially granted request scenarios, we remove the non-served ONUs from the requests. Therefore, the new granted request set $\{r_g | r_g \in R_g\}$ is generated by the wavelength assignment algorithm. Each request r_g has a counterpart request r where $r \in R$, but with only served ONUs in the destinations. The new request set R_g is a set with granted requests which only served ONUs destinations. The wavelength assignment algorithm handles the request set R_g in the same way as before. The same cases apply for both tree and light mesh topology.

5.1.2 MC-GRWA Problem

For the MC-GRWA problem, we can combine those requests that share the same destinations. We may not be able to use fewer wavelengths for the same network topology and requests set in MC-GRWA problem as we could in MC-RWA problem. However, we may be able to grant more requests to increase revenue.

On link ℓ, if granted requests have the same source ONU_{s_r}, one wavelength will be assigned to the upstream part of requests, and the traffic will be combined in this wavelength and sent to OLT. For the downstream requests, if two or more different granted requests have the same destination, they will be combined in the OLT and sent to the destination ONU in one newly assigned wavelength. The number of assigned wavelengths for upstream requests on link ℓ is the number of source ONUs (W_ℓ^U) that send the granted requests on link ℓ. The number of assigned wavelengths for downstream requests on link ℓ is the number of destination ONUs (W_ℓ^D) that receive the granted requests on link ℓ. Therefore, the total number of wavelengths used in the network is:

$$\max\{W_\ell | \ell \in \omega(O)\} \tag{63}$$

Maximizing the Number of Granted Requests

If the topology is that of a tree, the lightpath from the OLT to an ONU is unique. The algorithm is almost the same as one for MC-RWA problem. The difference is that before assigning the wavelengths to a request, the algorithm will check all the other granted requests that have the same source ONU. If other requests are found, a wavelength will be assigned to those requests that have the same source ONU. The same happens for the destination ONUs. Equations (14) and (15) ensure that the total bandwidth used for all requests on the wavelength will not exceed the bandwidth that one wavelength can carry. They also imply that each ONU can read only one wavelength and receive on one wavelength.

If the topology is a light mesh, the algorithm will read the request-link pairing information from the result of a linear programming program. According to the information, the wavelength assignment algorithm will know which links the requests should be sent on. Then, instead of searching the links for the destination ONUs, the algorithm uses this information to assign the wavelength. The other parts of the algorithm are the same as that for tree topology.

Maximizing the Number of Served ONUs

Same as in MC-RWA problem, partially granted requests are allowed. The results from the integer linear programming program will be processed to remove the rejected requests and rejected destination ONUs. The algorithm will look for the requests that have the same source ONU to assign the wavelength. Before the requests are combined, the link on which the requests are sent on should be determined. For the tree topology, the wavelength assignment algorithm takes the source or destination ONU and searches upstream to the OLT so that the algorithm can find a unique path from the OLT to the ONU. The link will be the first outgoing link from the OLT. For the light mesh topology, the request-link information will be obtained from the linear programming program. The wavelength assignment algorithm will use it directly to determine which link the combined requests will be sent on. The rest of the algorithm is the same as that in MC-RWA problem.

5.2 Implementation

Input Data

The sources of the input data are network topology description file and request description file. The network topology description file contains a matrix that is used to describe the network topology. Each row/column represents a node in the network. The nodes include an OLT, ONUs and AWGs. Row/column 0 is reserved for OLT. If there is a link between node x and node y, a number is marked at the intersection of row x and column y (as well as row y and column x). Otherwise a number 0 at the intersection indicates no link between node x and y. Because of the symmetry of the topology matrix (bidirectional links), only half of the matrix is used. If the topology is light mesh, there will be some ONU columns with more than one non-zero values, which means that more than one intermediate nodes are connected with that ONU.

The request description file has several lines, each of which is made up of several numbers separated by a space. The length of each line may vary because of the number of destinations. The first number is the revenue of the request. The second number is the bandwidth requirement of the request. The third number is the source node of the request (which can be either 0 (OLT) or any ONU number). The rest of the numbers are the destination ONUs of the request (which can be any of the ONU numbers).

Node numbering is defined as follows: the number for each node (OLT, AWG or ONU) is a non-negative integer. OLT is always numbered as 0. The intermediate nodes (AWGs) are numbered from 1 to the total number of the intermediate nodes n_{AWG} (starting from closest to OLT). Then the ONUs are numbered from n_i to the total number of nodes n.

A sample of the data files for the topology is shown in Figure 9 and Figure 11. Note that it is a light mesh topology description file because the last column has two non-zero values, which means that ONU connects to AWG_1 and AWG_2.

```
0 1 1 0 0 0 0
1 0 0 1 1 0 1
1 0 0 0 0 1 1
0 1 0 0 0 0 0
0 1 0 0 0 0 0
0 0 1 0 0 0 0
0 1 1 0 0 0 0
```

Figure 9: Input Data File for Network Topology

As shown in Figure 9, there are 2 AWGs (numbered as 1 and 2) and 4 ONUs

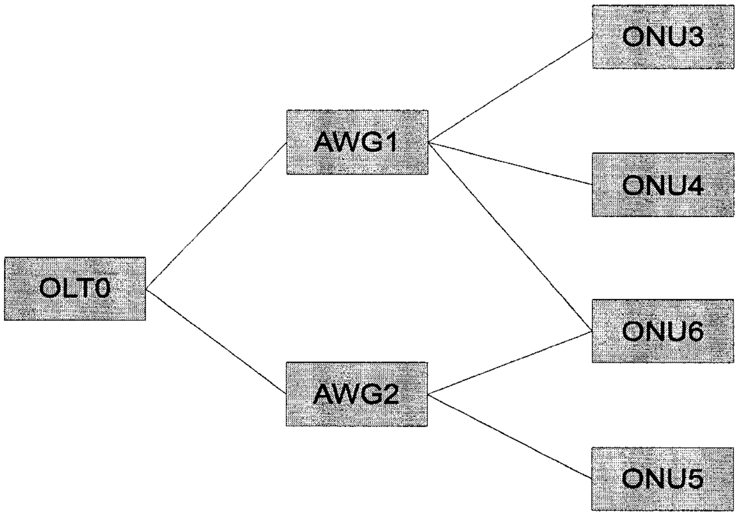


Figure 10: The Graph of Network Topology

```
1 3 2 0 3 4
3 4 2 3 4 5
1 4 1 3 6
1 2 1 5 3 6
```

Figure 11: Input Data File for Request Set

(numbered from 3 to 6) in a light mesh topology. In Figure 11, there is a request set of four requests applied to the network. The first request from the OLT (0) to ONU_3 and ONU_4 gives a revenue of 2 units and requires the transport capacity of 1 unit for upstream transmission and 3 units for downstream transmission. The second request is an ONU to ONU request from ONU_3 to ONU_4 and ONU_5 with a revenue of 2 units. It requires the transport capacity of 3 units for upstream transmission and 4 units for downstream transmission. The rest of the data can be explained in the same fashion.

Simulation System

The system first initializes the environment and the configuration files. The configuration file contains some system wide parameters and switches such as the bandwidth capacity for the wavelength and the wavelength capacity per link. Those options can also be overridden through the command line. Then the system will read the topology files and request files according to the command line parameters. The input data can be read from default files, specified files or in a batch-processed fashion (i.e. reading from a file that lists all the input topology-request data files)

The system creates the network model by reading one topology file and one request set file each time. After creating the model, the system builds the mathematical models for each problem according to the equations in Chapter 4. The ILOG CPLEX Concert Technology with C++ interface will be used to build the models and do the optimizations. To build the CPLEX model object, variables are created first for constraints and objectives. For each equation in the model, a set of constraints will be created and added to the model object. There is a cost function builder, which will help to calculate the cost for each request or each ONU according to the equations in Section 4.1. The system will use the cost function builder and variables to build the objective function, which will be added to the CPLEX model object as well. Finally, the model object will be solved by CPLEX.

The raw results will be stored in the CPLEX object after the problem is solved and will show whether the solution is optimal, if the solution is optimal what the optimal value is, and which requests could be granted or which ONUs could be served. According to the results, the system will drop those requests or ONUs that are not granted or served and make a new request set, which includes all granted requests and ONUs. The new set will be passed to the wavelength assignment algorithm to assign a wavelength for each request. Then the raw results and wavelength assignments will be used by a utilization calculation module, which will calculate the grade of service (GoS) and throughput.

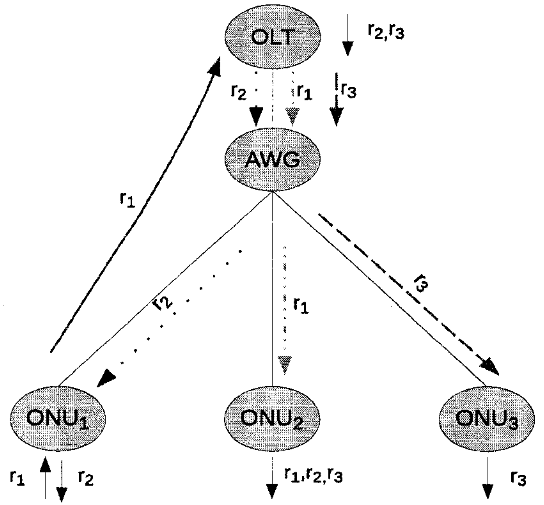
The system has been implemented under Linux. The source codes are managed in Subversion version control system and can be provided upon request. ILOG CPLEX Concert Technology C++ libraries are required for linear programming module of the system.

Examples

We have two examples to illustrate the models of Chapter 4. We assume that in both examples we have 1 unit of bandwidth for each wavelength and enough wavelengths (32) for all requests.

Tree Topology

The first example is for tree topology with three requests, which are shown in Figure 12. The requests are shown in black arrows. The solutions for MC-RWA_P problem are shown in color arrows. Each color arrow is an assigned wavelength for a request.



Request r_1: 1 -> 2 with 0.5 bandwidth and 6 profits
Request r_2: 0 -> 1,2 with 0.4 bandwidth and 2 profit
Request r_3: 0 -> 2,3 with 0.6 bandwidth and 4 profits

Figure 12: Example 1 - Tree Topology with Three Requests

An integer linear programming solution is given in Table 2. The left part of the table shows which requests are granted and the maximum profit for each problem. The right part of table shows the requests such that all their ONUs (for downstream) are served.

Table 2: Solutions for Example 1

Problems	r_1	r_2	r_3	Profit	ONU_1	ONU_2	ONU_3
MC-RWA	G	R	R	6	-	-	-
MC-GRWA	G	G	R	8	-	-	-
MC-RWA_P	G	P	P	9	r_2	r_1	r_3
MC-GRWA_P	G	G	P	10	r_2	r_1,r_2	r_3

G stands for granted, P for partial granted and R for rejected.

We assume that the profits are based on serving the whole request. If in partially granted request scenario, the profits for each ONU is the total profits divided by the number of ONUs.

For MC-RWA problem, only r_1 is granted and is assigned two wavelengths λ_1 and λ_2 for upstream and downstream respectively. The reason for that r_2 and r_3 are rejected is that each ONU can only receive one wavelength and send on one wavelength. The profit for granting r_1 is the same (6 profits) as that for granting both r_2 and r_3. However, granting r_1 requires less network resources (such as wavelength).

For MC-GRWA problem, both r_1 and r_2 are granted and three wavelengths are assigned, λ_1 for the upstream of r_1, and λ_2 and λ_3 for downstream for both r_1 and r_2. r_1 and r_2 have the same destination ONU_2 and the total bandwidth is 0.9. Therefore, the downstream of them are bound together with one wavelength. r_3 is rejected, because the total bandwidth of r_1 and r_3 (they have the same source ONU) are more than 1 unit of bandwidth and cannot be groomed within one wavelength. If we grant r_2 and r_3 rather than r_1 and r_2, more resources are required.

For MC-RWA_P problem, r_1 is fully granted and r_2 and r_3 are partially granted because of the wavelength constraint. By granting all three requests, we have three ONUs served. Destination ONU_2 in both request 2 and in request 3 is rejected, because ONU_2 can only read on one wavelength, which comes from the highest profit request r_1. Four wavelengths are assigned, one for upstream of r_1 and three for downstreams of r_1 (ONU_2), r_2 (ONU_1) and r_3 (ONU_3).

For MC-GRWA_P problem, r_1 and r_2 are fully granted and r_3 is partially granted. The traffic for ONU_2 are groomed into one wavelength from r_1 and r_2. The traffic of r_3 for ONU_2 is not groomed, because r_3 requires more than 0.5 unit bandwidth. There is not enough transport capacity for ONU_2 of r_3. A wavelength is assigned to upstream of r_3 (ONU_1). Three other wavelength are assigned to downstreams of the three requests. The profit is 10, which is the maximum profit of the four problems.

Light Mesh Topology

For the light mesh topology, we consider a simple case to show how the wavelength constraint works. The other constraints are similar to those in tree topology.

We examine the light topology with two requests, which are shown in Figure 13. The requests are shown in black arrows. The solutions are shown in color arrows. Each color arrow is an assigned wavelength for a request.

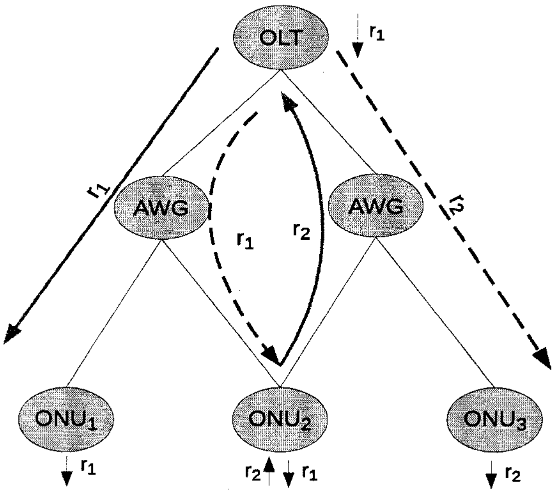


Figure 13: Example 2 - Light Mesh Topology with Two Requests

Table 3: One Possible Solution for Example 2

Requests		ONU_1	ONU_2	ONU_3
r_1	Upstream	-	-	-
	Downstream	1	1	-
r_2	Upstream	-	2	-
	Downstream	-	-	2

1 stands for the request using $link_1$, *2 for* $link_2$.

The system gives one possible optimal solution (Table 3 with both of the requests granted. Because of the wavelength constraint, each OLT link can carry maximum 2 wavelengths. Therefore, the upstream and downstream transmissions for ONU_2 have to be on different links.

Chapter 6

Network Cost

Network cost is one of the most important factors for network designer or operator taking into account when designing or building a network. With the increase of research on optical networks and the development of technologies, cheap optical components have been made available over the recent years. High bandwidth connection or fiber to home becomes affordable to users [SBP05]. In this chapter, we discuss the PON network costs, taking into account the request provisioning as well as the network attenuation. We compare the different topologies for AWG case and splitter case with the same goal: serving the same area of homes (the same number of homes and the same home distribution). We explore the network costs in both AWG case and splitter case with the limitation of attenuation.

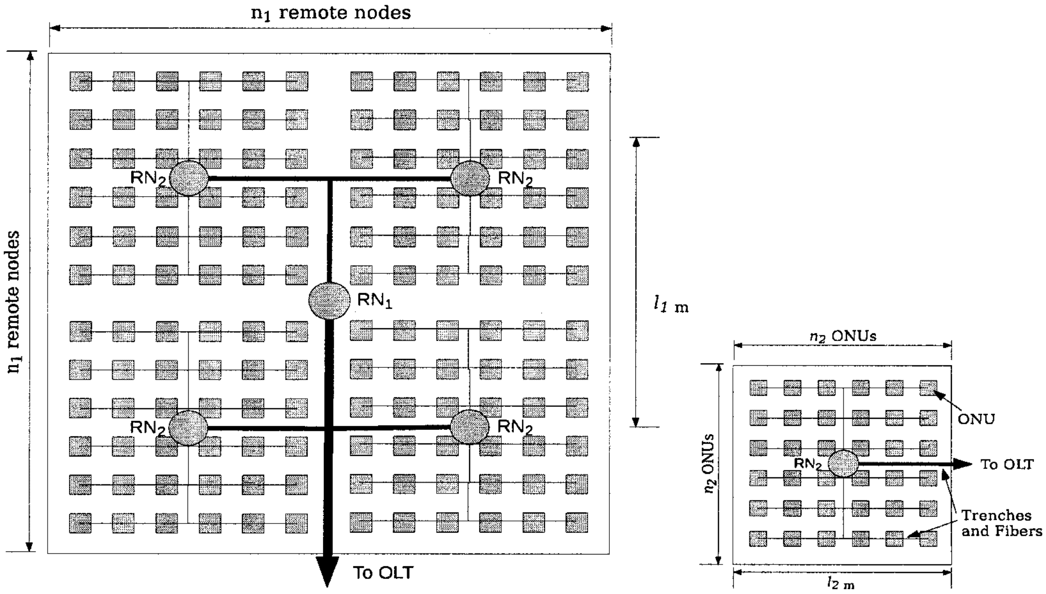
One of the advantages of an AWG over a splitter is its corresponding network cost, considering the attenuation. A topology with an AWG at every remote node requires that each ONU under the same OLT link has a unique wavelength to communicate with OLT. The required number of wavelengths is the number of ONUs on the same OLT link. Even if the ONUs on the same OLT link are destinations of the same multicast request, OLT has to send it separately on different wavelengths. However, if splitters are installed at remote nodes, the above case will be different as splitters split the signals in a broadcast manner. In the extreme case, where all the ONUs on a OLT link are accepting the same request, only one wavelength is required to serve all of the ONUs. If one has a solution for pure splitter case, the solution can always be converted for the pure AWG case by increasing the number of wavelengths as long as there are enough wavelengths. Likewise, if one has a solution for pure AWG case, the solution can always be converted for the pure splitter case by using the same number of wavelengths or less. Without considering the attenuation and network cost, under the same network topology, the splitter case always requires less or equal number of wavelengths than the AWG case. Therefore, there is no advantage for AWG without considering the attenuation and network cost.

6.1 Network Deployment Model

Model

For simplicity, a similar generic network model from [WZ03] is used. In this model, we assume that all ONUs are distributed on a regular grid with the same distance between each other. It is a simple tree topology with several levels. The OLT is located at the root of the tree. (We only consider single OLT scenario. Multiple OLTs scenario can be treated as repeating the single OLT scenario). The intermediate levels are remote node levels and the last one is ONU level. Each ONU may serve one or more homes. The whole area to be served is divided into $n_1 \times n_1$ small square areas, where 1 stands for the first level. Each small square area can be divided into smaller ones, depending on the level of the topology. Each remote node (AWG or splitter) located in the level next to the last level aggregates $n_n \times n_n$ ONUs in a square area. Each ONU serves a small square area. The upper level remote nodes aggregate $n_{n-1} \times n_{n-1}$

remote nodes. The OLT aggregates $n_1 \times n_1$ remote nodes. To lower the trenching cost, all the cables sharing a common trench as far as possible.



(a) Level 1 (b) Level 2

Figure 14: The Network Deployment Model

As shown in Figure 14, there are three levels in the tree topology. In Figure 14(a), a level one remote node (RN_1) aggregates $n_1 \times n_1$ level two remote nodes (RN_2) and two neighbor remote nodes RN2 are l_1 m away from each other. Similarly, in Figure 14(b). a level two remote node (RN_2) aggregates $n_2 \times n_2$ ONUs. The distance between two neighbor ONUs is l_2.

Attenuation

Taking the attenuation into account, we may serve the same area with different numbers of remote nodes for the splitter case and the AWG case. We assume that the power budget P_b is 20dB. The attenuation table is shown as Table 4.

Table 4: Attenuation

		Splitting Ratio	Attenuation
Fiber loss (dB/km)			0.2
Through loss (dB)	AWG	ALL	3
	Splitter	1:2	3
	Splitter	1:4	6
	Splitter	1:8	9
	Splitter	1:16	12
	Splitter	1:32	15
	Splitter	2:2	3.5
Insertion loss (dB)			0.1-1
Margin (dB)			1

The total signal loss between OLT and ONU is calculated as:

$$P_t = P_{fiber} + P_{insertion\ loss} + P_{margin} \tag{64}$$

where P_{fiber} is the signal loss on the fiber, $P_{insertion\ loss}$ is total insertion loss for all nodes on the link. P_{margin} is a power margin to ensure that the calculation of the total loss are within the power budget range. In order to reach an ONU from OLT, the total signal loss P_t should be less than or equal to the power budget P_b. For each ONU, as the fiber length may be different and the signal may pass through different numbers of remote nodes, the power budget constraint should be satisfied for the maximum signal loss on any light path. Otherwise, some of ONUs cannot be reached by OLT, which is not under the assumption in this thesis and is not considered.

According to Table 4, we calculate the attenuation for both splitter and AWG cases. For splitter case, the topology can support a maximum of 2 levels of splitters (1:16 + 1:4) for 64 ONUs within $10km^2$ or 2 levels of splitters (1:16 + 1:2) for 32 ONUs within $20km^2$. For AWG case, the topology may support up to five levels of

AWGs (any splitting ratio) for more than 64 ONUs within 30 km^2 without considering the constraint of wavelength.

Trenching

For the trenching length, as shown in Figure 14(a), there is a trench between each neighbor along the grid and all trenches aggregate to a trench towards the upper level of remote node. Therefore the total trenching length of an square area for $n \times n$ nodes with ℓm distance between the neighbors is

$$(n-1) \times \ell \times n + (n-1) \times \ell \,. \tag{65}$$

The average trenching length for each node is

$$\ell - \frac{\ell}{n^2} \,. \tag{66}$$

the length of calculation for the higher level of remote nodes is the same.

Cabling

The calculation for the cable length is slightly different from the calculation of trenching length, because the cables can share the same trench, but each node has to use a separate cable to connect to the higher level of node. We assume that the higher level node is located in the middle of the square area. The maximum length of the cable from a node to the higher level node is

$$(n-1) \times \ell \,. \tag{67}$$

The minimum length of cable from a node to the higher level node is ℓ. And the length is decreased by ℓ units. Therefore, the distance for other nodes are sequentially decreased by ℓ units. The average cable length from a node to a higher level node is

$$\frac{n \times \ell}{2}. \tag{68}$$

Take Rate

The take rate is the percentage of ONUs, who subscribe to the services, covered by the WDM-PON access network. It is a measurement parameter for network operators to describe the cost for each subscriber. The network cost per subscriber is given by:

$$\text{Cost per Subscriber} = \frac{\text{Network Cost per ONU}}{\text{Take Rate}} + \text{Installation Cost}\,. \text{ [TCT05]} \tag{69}$$

The network cost is the total cost for all ONUs, including those ONUs that do not subscribe to the service but the cables pass through.

6.2 Network Cost

We assume that the suburban area has 177 homes [TCT05] in a uniform distribution and each ONU serves one home. We serve a $5km^2$ suburban area with 885 homes. Assuming that each OLT port can support 32 ONUs and we use 1:2+1:16-splitter-three-level tree topology and 1:32-splitter-two-level tree topology for splitter case and 1:32-AWG-two-level tree topology for AWG case. The required OLT ports is: $885 \div 32 = 28$ OLT output ports for both cases. Therefore, for splitter-three-level topology, we need 28 1:2 splitters located at the first level of the tree and 28×2 1:16 splitters located at the second level of the tree. For splitter-two-level and AWG case, we need

28 1:32 remote nodes located at the first level of the tree to serve all 885 ONUs.

The calculation of the network cost is done according to the parameter values of Table 5.

Table 5: Component and Installation Costs [TCT05] and [BS03]

		Splitter	AWG
OLT			
Enclosure cost (\$)	Urban	200000	200000
	Suburban	160000	160000
Output port cost (\$)		16000	16000
Remote Node			
Enclosure cost (\$)	Urban	480	480
	Suburban	384	384
Max. no. of inputs		32	32
Device cost (\$)	1:2	200	400
	1:4	400	600
	1:8	600	800
	1:16	800	1000
	1:32	1000	1200
Cable costs (\$/km)		128	128
Splice cost (\$/sub)		32	32
Tab cost (\$/sub)		23	23
Trenching Costs			
OLT to RN (\$/km)	Urban	5600	5600
	Suburban	2800	2800
RN to ONU (\$/km)	Urban	5600	5600
	Suburban	2800	2800
ONU Costs			
Install cost (\$)		144	144
ONU cost (\$)		384	284

For the trenching cost, in splitter-three-level topology case, we divide 885 ONUs into 28 blocks (the number of OLT ports), each block has a 1:2-level-1 splitter. Each block is divided into 16 sub-blocks for 2 1:16-level-2 splitters. Each sub-block has 16 ONUs. Therefore, the parameters for each level are: $n_1 = 5.29, \ell_1 = 0.42km, n_2 = 1.41, \ell_2 = 0.30km, n_3 = 4, \ell_3 = 0.075$. The total trench length from OLT to all ONUs is

$$n_1^2 \times (n_2^2 \times (n_3^2 - 1) \times \ell_3 + (n_2^2 - 1) \times \ell_2) + (n_1^2 - 1) \times \ell_1 = 82.91km\,. \tag{70}$$

In splitter-three-level topology and AWG-two-level topology case, we divide 885 ONUs into 28 blocks (the number of OLT ports), each block has 1 1:32-level-1 AWG or splitter. Each block has 32 ONUs. The parameters for the level are: $n_1 = 5.29, \ell_1 = 0.42km, n_2 = 5.66, \ell_2 = 0.075km$. The total trench length from OLT to all ONUs is

$$n_1^2 \times (n_2 - 1) \times \ell_2 + (n_1 - 1) \times \ell_1 = 76.65km. \tag{71}$$

For the fiber cost, we use RN_1 to denote the first level remote node, and RN_2 for the second level remote node. For splitter-two-level topology case, according to (68), the average length of cable from RN_2 to ONUs (d_3) is 0.15 km; the average length of cable from RN_1 to RN_2 (d_2) is 0.21 km. The average length of cable from OLT to RN_1 (d_1) is 1.12 km. The total length of fiber from the OLT to all ONUs is

$$n_1^2 \times (n_2^2 \times (n_3^2 + d_3 + d_2) + d_1) = 177.83km. \tag{72}$$

For splitter-two-level topology and AWG-two-level topology case, the cable length from RN_1 to ONUs (d_2) is 0.21 km and the average length of cable from OLT to RN_1 (d_1) is 1.12 km. The total length of fiber from the OLT to all ONUs is

$$n_1^2 \times (n_2^2 \times d_2 + d1) = 221.79km. \tag{73}$$

The network cost for both splitter case and AWG case are shown in Table 6, Table 7 and Table 8.

	OLT Housing	OLT Port Cost	Trenching (km)	Fiber		Splitter			ONU Cost	Total
				Cable	Splice+Tab	Housing	1:2	1:16		
cost	$160,000	$16,000	$2,800	$128	$55	$384	$400	$800	$384	
count	1	28	82.91	177.83	885	84	28	56	885	
subtotal				22762.51	48675	32256	11200	44800		
total($)	160,000.00	448,000.00	232,160.46	71,437.51		88,256.00			339,840.00	1,339,693.96
%	11.94%	33.44%	17.33%	5.33%		6.59%			25.37%	100%

Table 6: Network Cost for Splitter Case - Three Levels

	OLT Housing	Output Port Cost	Trenching (km)	Fiber		Splitter		ONU Cost	Total
				Cable	Splice+Tab	Splitter Housing	1:32		
cost	$160,000	$16,000	$2,800	$128	$55	$384	$1,000	$384	
count	1	28	76.65	221.79	885	28	28	885	
subtotal				28389.43	48675	10752	28,000		
total	160,000.00	448,000.00	214,626.88	77,064.43		38,752.00		339,840.00	1,278,283.31
%	12.52%	35.05%	16.79%	6.03%		3.03%		26.59%	100%

Table 7: Network Cost for Splitter Case - Two Levels

	OLT Housing	Output Port Cost	Trenching (km)	Fiber		AWG		ONU Cost	Total
				Cable	Splice+Tab	AWG Housing	1:32		
cost	$160,000	$16,000	$2,800	$128	$55	$384	$1,200	$284	
count	1	28	76.65	221.79	885	28	28	885	
subtotal				28389.43	48675	10752	33,600		
total	160,000.00	448,000.00	214,626.88	77,064.43		44,352.00		251,340.00	1,195,383.31
%	13.38%	37.48%	17.95%	6.45%		3.71%		21.03%	

Table 8: Network Cost for AWG Case

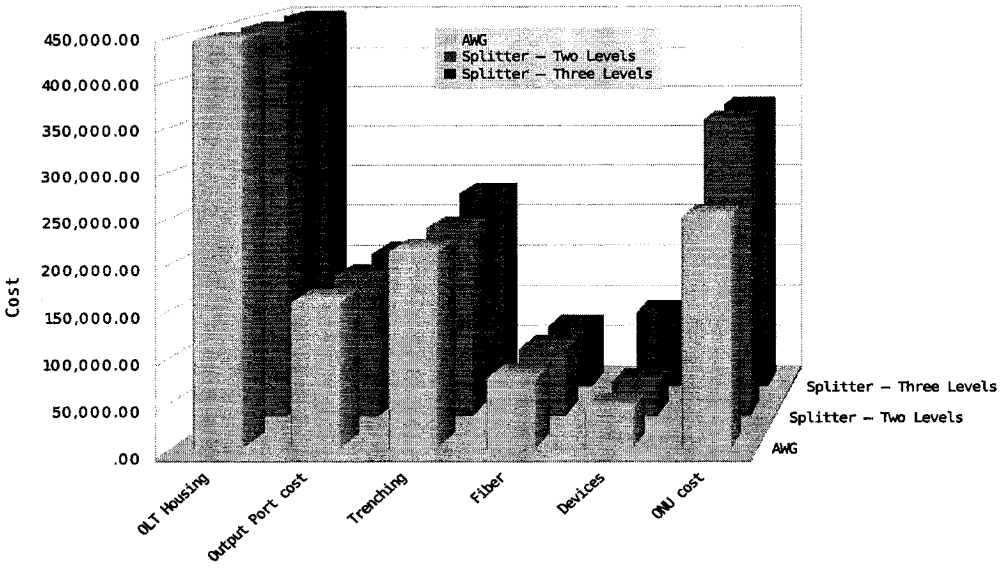


Figure 15: Comparison of the Network Cost for Splitter and AWG

6.3 Comparison

From Table 6, Table 7 and Table 8, we can see that, the total network cost for AWG case is lower than that for the two splitter cases. There are two factors that reduce the network cost: the cost for remote nodes and the cost for ONUs. The remote nodes are reduced from 84 splitters to 28 AWGs or splitters for two levels topology. Although the cost price for AWGs is more expensive than the splitters, the total number of remote nodes reduces so that the total cost for remote nodes reduces. To serve the same number of ONUs, the same number of ONUs are needed for both cases. Comparing splitter-two-level topology and AWG-two-level topology, the one with AWG is still cheaper than the one with splitter. It is because, for the AWG case, the cheaper colorless ONUs, which do not need wavelength filters as in color ONUs, are used. Therefore, the cost for ONU reduces because of the employment of colorless ONU receiver, comparing to color ONU in the splitter case.

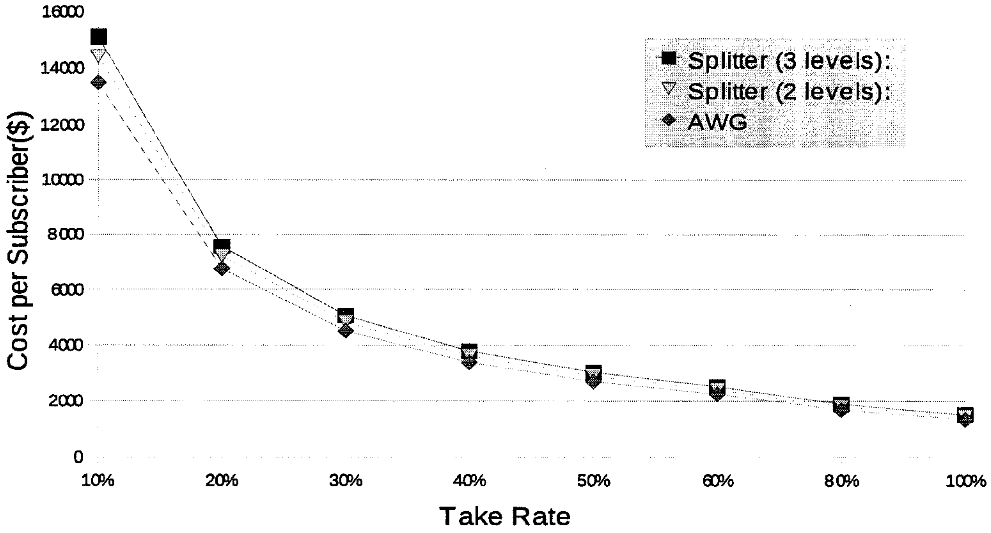


Figure 16: The Cost per Subscriber Under Different Take Rate

The cost per ONU for splitter-three-level topology, splitter-two-level topology and AWG-two-level topology are \$1,513, \$1,444 and \$1,350, respectively. We consider that the installation cost for each ONU is \$144 [TCT05]. Figure 16 shows the cost per subscriber under different take rates. When the take rate is 20%, the cost per subscriber is \$6,753 for the AWG case, comparing to \$7,568 and \$7,221 for the splitter cases. However, at the high take rate of 80%, the cost per subscriber reduces to \$1,688 for the AWG case, comparing to \$1,892 and \$1,805 for the splitter cases. Under the different take rates, the cost per subscriber for the splitter cases is 10% and 6% higher than that for the AWG case. Higher difference value will be shown if more ONUs are served, e.g., in urban area.

Chapter 7

Simulation Results

In this chapter, we present some experimental results aiming firstly at validating the models developed in Chapter 4, and secondly at evaluating the provisioning capacities of an AWG PON network under a given traffic scenario. For the MC-RWA problem, the models are suitable for network operators that only deal with the communication level of the network. Different services provided by service providers are aggregated by the upper level of the network (such as Metropolitan Area Network) and will be distributed after the ONU level (such as gateway routers). The traffic patterns and instances are simple, comparing to MC-GRWA problem. Therefore, in the experiment, we consider only MC-GRWA problem for more complex traffic instances. For MC-GRWA problem, the simulations are done on both tree and light mesh topologies for certain given instances. The parameters are defined as the typical values in a real network (as, e.g., in Table 9).

Table 9: Parameter Values

Parameters	Values
Transport capacity per wavelength	1Gbps
Maximum # of ONUs on an outgoing link	32

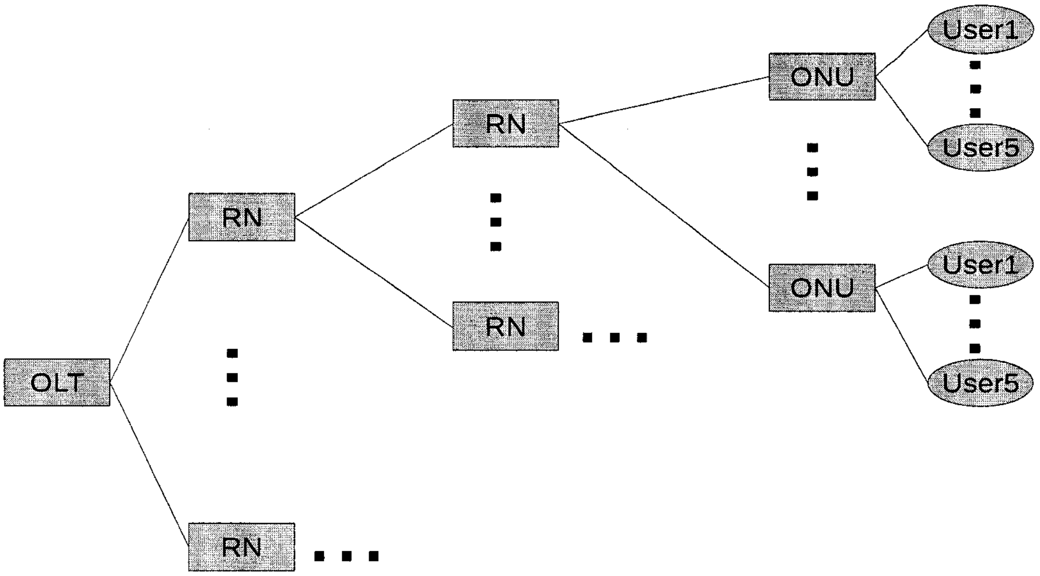


Figure 17: The Network Model

7.1 Network and Traffic Instances

7.1.1 Network Instances

In the simulation, we use three network instances to study the performance for pure AWG-based PON networks on tree topology with 256, 512, 1024 ONUs respectively in Scenario 1 (described later). Each topology is generated randomly with 1 to 2 levels of remote nodes (AWG) and a maximum of 32 ONUs under each OLT link. In Scenario 2 and 3, we use the tree topology with 512 ONUs, which can be supported by the minimal 16 OLT links. There is no limitation for the number of wavelengths because of the given network.

7.1.2 Traffic Instances

There are several typical traffic types on Internet or intranet. The first type is personal communications including telephony, video telephony and instant messaging. The second type is broadcast radio/TV and streaming video/audio on demand. The third type is Internet access including Internet browsing, teleworking, on-line gaming and file sharing. For personal communications, instant messaging consumes very low bandwidth (less than 5 Kb/s), comparing to other method of communication. VOIP phone as a complementary for PSTN system is very popular nowadays. It requires less than 64 Kb/s per channel and provides rich features such as conference calling, call forwarding, automatic redial, caller ID, independent location, low rate long distance call and integration with other services available over the Internet. In the future, it is likely that video phone will replace the VOIP phone to provide more user interaction during the communication. Video phone will require larger bandwidth (around 20 Mb/s) to transmit high-definition video (1280×720 or 1920×1080) in real-time. For the second type, broadcast radio or stream audio needs 256 Kb/s bandwidth to encode a CD-quality channel (44.1 kHz sampling rate at a resolution of 16-bit) or 1 Mb/s to encode a SuperAudio CD-quality channel (2.8224 MHz sampling rate at a resolution of 1-bit). The broadcast TV or streaming video on demand requires 20 Mb/s to transmit HDTV signals (1080p format encoded as MPEG2 or MEPG4) per channel [vVWBH05]. Internet access may require more bandwidth than it does nowadays because more and more flash animation or video content will appear on the web pages and peer-to-peer file sharing is become more and more popular. It is not hard to predict that 100 Mb/s bandwidth will be used for Internet access in the future. For business users, video conference can enable individuals on different sites to have meetings on a short notice in order to reduce travel time and expenses. The bandwidth for each attendant of the conference to establish a high-definition quality video conference is around 20 Mb/s [vW05].

We have all the above services; their required bandwidth and number of destinations are listed in Table 10. Two types of traffic are defined: residential traffic and business traffic. Residential traffic includes the first four services: HDTV, telephony, Internet and on-line gaming. Business traffic includes all services. The network model is shown in Figure 17. We assume that:

- Each ONU may serve maximum 5 users, either residential or business.
- Every user subscribes to telephone and Internet browsing services.
- Each ONU subscribes to several (9) basic HDTV channels, which are the same channels for all users on all ONUs.
- Each user may subscribe to other different services individually.
- User may subscribe to multiple channels for HDTV and stream audio.
- The bandwidth of basic services such as telephone and basic HDTV channels is reserved for all users and removed from total transport capacity.

Traffic Patterns

We define two traffic patterns for simulation according to Table 10: residential traffic and business traffic. We assume that each ONU can support either residential usage or business usage. The residential traffic only includes the first four services in Table 10 and the business traffic includes all services.

For high definition television (HDTV) request, we consider it on both channel basis and a package basis. For package basis, we group 5 channels into a package, which

Table 10: The Service Traffic for Each User

Service	Bandwidth (Mb/s)		Number of Destinations
	Upsteam	Downstream	
HDTV	N/A	100 (per package)	Depending on Scenarios
Telephony (Voice)	1	1	unicast
Internet Browsing	1	20	unicast
On-line gaming	20	20	unicast
Stream Audio	N/A	1	1-5
Video Conference	20	20 × # of attendants	2-6

may represent a given plan or service that TV service providers offer to users. Each high definition television (HDTV) channel consumes around 20 Mbit/s, totaling 100 Mbit/s per package. The second type of requests is telephony, such as VOIP phone, which has symmetrical traffic and consumes around 1 Mbit/s bandwidth. We assume that every user subscribes to these services, consuming 5 Mbit/s bandwidth per ONU in total for both upstream and downstream transmission. The third type of request is Internet browsing, which is asymmetrical traffic. 1 Mbit/s bandwidth for upstream and 20 Mbit/s for downstream are reserved for this kind of requests. The fourth type of request is on-line gaming, which is considered as symmetrical unicast request with 20 Mbit/s for both upstream and downstream transmissions. The fifth type of requests is stream audio, which is multicast request for downstream only. It consumes 1 Mbit/s per request. The last type of requests is video conference. We assume that each video conference has a maximum of 6 attendants. Because the destinations are dynamic and may change from time to time, we consider it as symmetrical traffic and reserve 100 Mbit/s for both upstream and downstream.

Because all users subscribe to 10 basic HDTV channels and telephone services, which are unicast traffic, required bandwidth for those services can be reduced from the total transport capacity B_ℓ. The available transport capacity is $B_a = B_\ell - B^{Broadcast} - B^{Voice} \times n$, where $B^{Broadcast}$ (9 * 20 Mbit/s for downstream only) is the total bandwidth for 10 basic HDTV channels, B^{Voice} (1 Mbit/s for both upstream and downstream) is the bandwidth required for telephone or voice service. n (5) is the number of users served per ONU. Therefore, the available transport capacity is $B_a^U = 995$ Mbit/s for upstream and $B_a^D = 815$ Mbit/s for downstream. Because we want the traffic to be mixed by unicast and multicast, the Internet browsing is not included in the above formula but in the traffic generation.

The weight for each request is defined as follows: each unicast request has 1 unit weight. The weight for multicast request equals to the number of destinations. When a multicast request with 3 destinations is served, the effect is the same as granting three unicast requests. Therefore, the unicast request and multicast request are in a fairly weighted network in terms of the number of ONUs.

Traffic Instance Scenarios

We define three traffic instance scenarios. In the first scenario, we consider pure residential traffic, which may represent the rural areas. We consider two cases: in Scenario 1a, we assume that there are 10 types of packages provided by TV provider. Each package binds 10 channels. Each ONU subscribes to around 2 to 4 packages. In Scenario 1b, we consider channel basis subscription, where there are 100 channels available. Each ONU subscribes to 20 to 40 channels. Therefore, we break down the large bandwidth requirement requests (case 1a) into smaller ones (case 1b). The average number of subscribed channels and the required transport capacity for each ONU in both cases are the same. For both cases, we assume that there are 80% of ONUs subscribed to HDTV services and 10% ONUs subscribe to on-line gaming. The number of ONUs is 256, 512 and 1024 for both cases. This scenario show how the large bandwidth requests impact the network performance under different numbers of ONUs.

In the second scenario, we want to examine the limitation of the network for granting a large amount of requests under two traffic cases. In Scenario 2a, we consider that most of the requests are from residential traffic, which may represent the suburban areas. There are 80% of ONUs that subscribe to HDTV for both residential and business users, 10% ONUs that subscribe to on-line gaming. The number of requests for both HDTV and on-gaming depends on the number of ONUs. For audio stream and video conference, we treat them as request basis, for which we increase the number of those requests to examine the network performance. We assume that each of them has 50% requests. In Scenario 2b, we increase the traffic for business to represent the urban or downtown areas. 60% of ONUs subscribe to HDTV and 5% to on-line gaming. The percentage of the request for video conference increase from 50% to 80% and 20% is left for stream audio, which means that the business traffic increases. We also increase the total number of requests for stream audio and video conference from 50 to 2500 for both cases.

To examine the impact of the HDTV requests on the network performance, we consider the third scenario, which derives from Scenario 2a with some changes of the request parameters. Instead of changing the total number of requests for stream audio and video conference, we fix it as 1500. The calculation of HDTV requests is changed to channel basis as in Scenario 1b and the number of requests for HDTV will not depend on the number of ONUs, but it changes from 1000 to 2500. Each HDTV request has 1 to 5 destinations.

7.2 Results on Provisioning Plans

We generate the traffic randomly according to the description of the parameters in Section 7.1.2. The values obtained in each scenario are averages over 5 experimental

Table 11: Percentage of Services Request for Each Scenarios

Service	Scenario 1		Scenario 2a		Scenario 2b		Scenario 3	
	ONU	Request	ONU	Request	ONU	Request	ONU	Request
HDTV	80%	-	80%	-	60%	-	-	1000-2500
On-line Gaming	10%	-	10%	-	5%	-	5%	-
Stream Audio	-	-	-	50%	-	20%	-	50%
Video Conference	-	-	-	50%	-	80%	-	50%

The bandwidth required by basic TV service and telephony are deduct from the total transport capacity, therefore they are not considered or generated in the requests.

runs in order to eliminate the extreme case caused by randomization. We calculate GoS in terms of request and bandwidth for each scenario.

Table 12: Scenario 1a with different number of ONUs (5 runs)

Number of ONUs		256	512	1024
MC-GRWA	GoS	96.76%	96.85%	96.25%
	Throughput	96.89%	96.92%	96.28%
	Requests (Total/Accepted)	266/257	522/505	1034/995
MC-GRWA_P	GoS	98.90%	98.95%	98.76%
	Throughput	99.35%	99.37%	99.26%
	ONUs (Total/Accepted)	787/778	1560/1544	3137/3098

HDTV requests are defined as packages. There are 10 packages, each of which contains 10 channels. Each ONU subscribes to 2-4 packages

Table 13: Scenario 1b with different number of ONUs (5 runs)

Number of ONUs		256	512	1024
MC-GRWA	GoS	84.72%	82.78%	83.36%
	Throughput	80.17%	79.89%	82.02%
	Requests (Total/Accepted)	356/301	612/506	1124/937
MC-GRWA_P	GoS	98.99%	99.02%	99.12%
	Throughput	96.10%	96.23%	96.68%
	ONUs (Total/Accepted)	6426/6362	12843/12719	25524/25299

HDTV requests are defined as channels. There are 100 channels. Each channel is served in separate requests. Each ONU subscribes to 20-40 channels.

Scenario 1

From Table 12 and 13 we can see that the GoS and throughput only slightly change while increasing the number of ONUs. It is because that all the services (generated requests) depend on the number of ONUs. When the number of ONUs increases, the number of requests and the destinations of requests increase the same time. Comparing the GoS and throughput in MC-GRWA and MC-GRWA_P problems, MC-GRWA_P GoS and throughput is higher than MC-GRWA GoS and throughput, because the MC-GRWA_P case accepts partial granted requests, which means that the system will serve as many ONUs as possible to achieve the maximum revenue. The number of rejected requests (266-257) in the MC-GRWA case and the number of rejected ONUs (787-778) in the column of 256 ONUs in Table 12 are the same. It indicates that all the rejected requests are unicast in the MC-GRWA case. Because the system would reject 10 unicast requests rather than a multicast request with 40 destinations (in the case of total 256 ONUs). However, the revenue is higher in rejecting 10 unicasts case than in 1 multicast case. Therefore, calculating the GoS in terms of request is not always accurate, so we calculate the GoS and throughput in terms of ONU in the MC-GRWA_P case.

Comparing the values of Table 12 and 13, we see that the GoS for MC-GRWA drops from 96% to 83%, but GoS for MC-GRWA_P remains the same. We originally expected an increase of GoS and throughput, when the large requests are broken into smaller ones from Scenario 1a to Scenario 1b. However, we find that the average number of destinations for HDTV requests are the same for both scenarios. The only changes are the change of the bandwidth requirements from 200 Mbit/s to 20 Mbit/s and the change of the number of requests from 10 to 100. The number of rejected requests increase from 10 to 55, which is a large ratio comparing to the increased ratio for the total number of requests.

Table 14: MC-GRWA and MC-GRWA_P problems in Scenario 2a with 512 ONUs

Extra Requests		50	100	500	1000	1500	2000	2500
MC-GRWA	GoS	100.00%	100.00%	99.86%	99.69%	99.23%	98.39%	96.91%
	Throughput	100.00%	100.00%	99.81%	99.56%	98.81%	97.40%	94.63%
	Requests (Total/Accepted)	572/572	622/622	1022/1020	1522/1517	2022/2006	2522/2481	3022/2928
MC-GRWA_P	GoS	100.00%	100.00%	99.93%	99.85%	99.62%	99.34%	98.78%
	Throughput	100.00%	100.00%	99.91%	99.74%	99.28%	98.36%	96.48%
	ONUs (Total/Accepted)	1055/1055	1148/1148	1935/1933	2948/2943	3986/3971	4997/4964	5954/5882

Internet browsing(with 10% on-line gaming) + stream audio (50% extra) + video conference (50% extra) + HDTV (10) Requests. Each ONU subscribes to 2-4 HDTV packages. For stream audio, there are 1-5 destinations.

Table 15: MC-GRWA and MC-GRWA_P problems in Scenario 2b with 512 ONUs

Extra Requests		50	100	500	1000	1500	2000	2500
MC-GRWA	GoS	100.00%	100.00%	99.59%	98.60%	95.80%	92.65%	88.41%
	Throughput	100.00%	100.00%	99.56%	98.44%	95.13%	91.37%	86.03%
	Requests (Total/Accepted)	572/572	622/622	1022/1017	1522/1500	2022/1937	2522/2336	3022/2671
MC-GRWA_P	GoS	100.00%	100.00%	99.79%	99.27%	98.02%	96.40%	94.24%
	Throughput	100.00%	100.00%	99.76%	99.03%	96.75%	93.83%	89.75%
	ONUs (Total/Accepted)	1024/1024	1096/1096	1666/1663	2360/2343	3064/3003	3743/3609	4422/4168

Internet browsing(with 10% on-line gaming) + stream audio (20% extra) + video conference (80% extra) + HDTV (10) Requests Each ONU subscribes to 2-4 HDTV packages. For stream audio, there are 1-5 destinations.

Table 16: MC-GRWA and MC-GRWA_P problems in Scenario 3 with 512 ONUs and 1500 Extra Requests

HDTV Requests		1000	1500	2000	2500
MC-GRWA	GoS	99.84%	99.01%	95.62%	90.23%
	Throughput	99.72%	98.28%	92.25%	83.31%
	Requests (Total/Accepted)	2112/2108	2612/2586	3112/2975	3612/3259
MC-GRWA_P	GoS	99.88%	99.52%	98.09%	93.94%
	Throughput	99.81%	99.00%	95.93%	91.52%
	ONUs (Total/Accepted)	4727/4722	6184/6154	7706/7559	9527/8949

Internet browsing(with 10% on-line gaming) + stream audio (20% extra) + video conference (80% extra) (1500 extra request)
Each HDTV request has 1-5 destinations and includes 1-3 channels. For stream audio, there are 1-5 destinations

Scenario 2

From Table 14, we can see that, when the ratio of high bandwidth requests (video conference) is relatively low (comparing to Scenario 2b), the GoS and throughput are good even at a large amount of traffic. When the ratio is high, the GoS drops fast. If a network operator wants to keep the GoS above 90%, more than 2500 requests may not be allowed in the network environment of Scenario 2b. Comparing Table 14 and 15, the GoS is affected by the number of large bandwidth consumption requests.

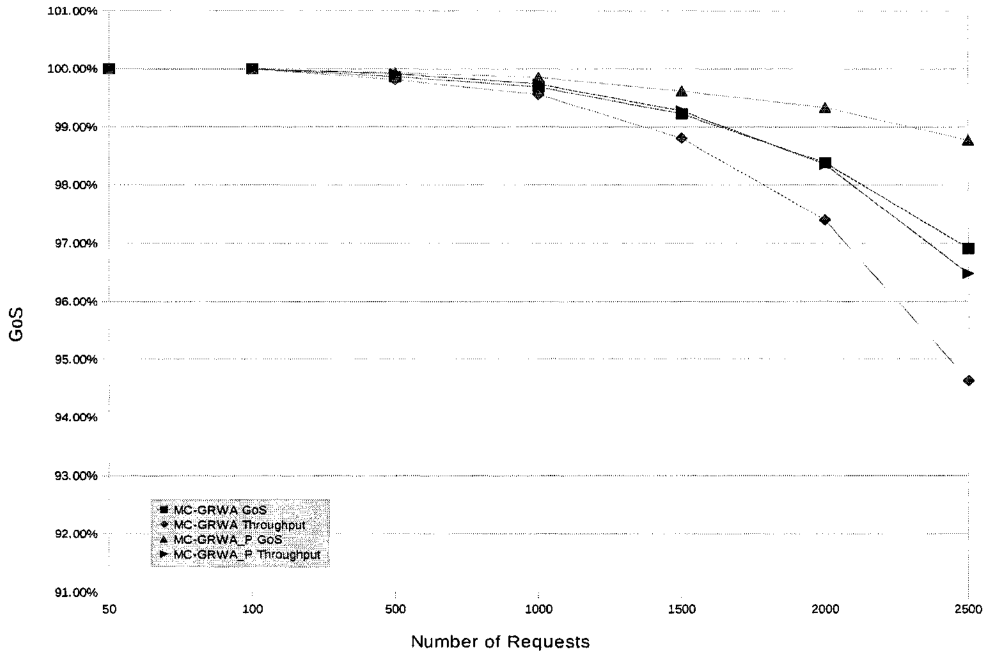


Figure 18: GoS and Throughput in Scenario 2a

Scenario 3

HDTV requests are the multicast requests with large bandwidth requirements. If the number of HDTV requests is large, it will put a lot of pressure on the network. From Table 16 and Figure 20, we can see that if the number of requests is less than 1500,

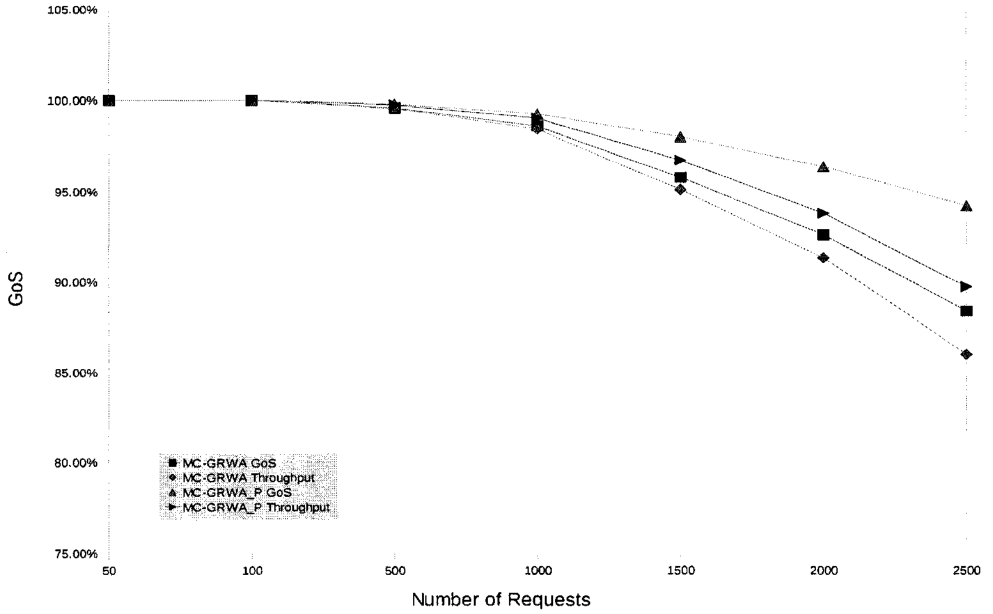


Figure 19: GoS and Throughput in Scenario 2b

almost all requests are granted and the network performance is very good. When the number of HDTV requests increases, the GoS drops rapidly.

Light Mesh Topology

The experiment results for light mesh topology will be the same as for tree topology. Because we assume that each ONU can only receive one signal and send one signal and that there is no limitation on the number of wavelengths. In the pure AWG PON network, each ONU on a given OLT link has a unique wavelength for upstream or downstream transmission. There is no share of wavelength between ONUs on any given OLT link. It is impossible to increase the bandwidth utilization by adding more links to ONU. An ONU has to choose one link to send or receive signals with a optical switch. Therefore, the light mesh topology only brings more reliability to the pure

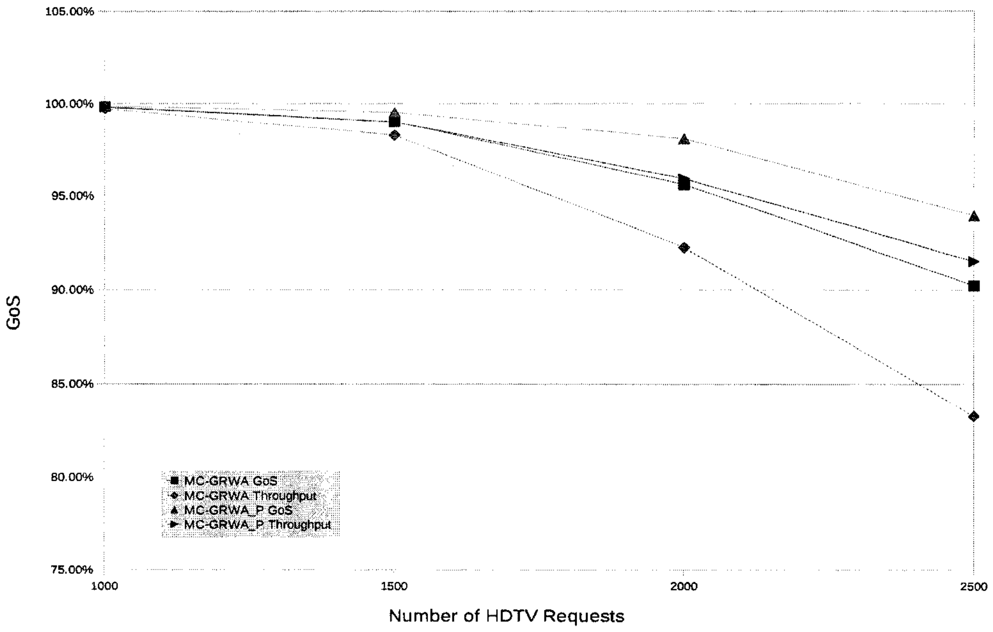


Figure 20: GoS and Throughput in Scenario 3

AWG PON network.

Concluding Remarks

The results for light mesh topology are not included, because the results are the same for tree topology and tree converted light mesh topology (refer to 4.7). We assume each ONU can only receive on one wavelength, which means only one OLT link is used for each ONU on light mesh topology. Therefore, there is no advantage of AWG for multicast on light mesh topology in terms of bandwidth utilization or wavelength utilization.

A comparison of the provisioning of an AWG PON network will be made with a splitter PON network, within the MSc thesis of A. Shaikh [Sha08] to be shortly submitted. We will assume an identical set of requests and users for both cases as well as similar topology costs (see Chapter 6), i.e., meaning that we will use less AWGs than splitters to cover the same set of users. Preliminary results seem to indicate that provisioning schemes are rather similar, although we did not reach the provisioning limit for the AWG PON network while we did (in terms of attenuation) for the splitter PON network.

Chapter 8

Conclusions

In our study, we have surveyed existing passive optical networks and current technologies employed by different PON networks. We examined the physical structure of AWGs as well as its FSR property. We also compared the AWG with splitters in terms of insertion loss (where AWGs provide a relatively low insertion loss of around 4-5dB regardless of the number of outgoing ports) and their characteristics of handling the wavelengths that pass through. We also introduced the TDM-WDM hybrid PON architecture. By employing WDM and TDM technologies on passive optical network, the bandwidth has been increased several times depending on how many wavelengths are employed. The wavelength utilization is also increased by employing TDM technology, which allows several requests to share one wavelength. Then we build mathematical optimization models for two problems (MC-RWA and MC-GRWA) with two objectives (maximizing the number of granted requests and maximizing the number of served ONUs) on two different topologies (tree and light mesh). Our mathematical optimization models provide a solid foundation for the optimization system and wavelength assignment algorithms. We developed a system based on our mathematical optimization models. Given a network topology and a set of requests, we can determine the highest possible revenue for each of the four different scenarios (MC-RWA, MC-GRWA, MC-RWA_P and MC-GRWA_P) on both tree topology and light mesh topology. Our model also provides network operators with valuable reference information, for example, information on the GoS in terms of request and bandwidth. Therefore, a network operator may know which kind of requests should be granted and how many requests should be granted in order to maintain an acceptable GoS.

We also examined the deployment cost of WDM-TDM PON network by case studies on both AWG and splitter. Deploying AWGs as intermediate nodes may not reduce the network resources, such as the number of wavelengths used for the same topology and request set with splitters. However, an AWG has less insertion loss than the splitter does regardless of the size of AWG, which means that we can offer more stages of cascaded intermediate nodes and support more ONUs. For the cost study in Chapter 6, we find that by using AWGs as intermediate nodes, the deployment cost for PON network is cheaper than using splitters. The difference value will be even higher while when the size of the network increases. Using AWG also provides more security than the splitter does because AWG handles wavelengths in a routing manner instead of a broadcasting manner as in the splitter. Each ONU has dedicated wavelengths for downstream and upstream transmissions and all wavelengths or signals are sent to relevant ONUs. Therefore, no one can eavesdrop the transmissions to other ONUs on a compromised ONU.

Furthermore, our study provides a foundation for further research of AWG and splitter combinations that seek to achieve a better balance between performance and cost efficiency. The splitter handles wavelengths in a broadcasting manner, which is good for multicasting because it may reduce the number of wavelengths used. Given a network topology and request set, we can deploy both AWGs and splitters as intermediate nodes. We may then find a solution to maximize the revenue as well as to minimize the number of wavelengths used. Therefore, the best results in terms of revenue and scalability can be obtained in order to serve more ONUs.

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