Protection Architectures for Multi-wavelength Optical Networks

BY

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Abstract

In recent years, with the rapid growth of the Internet, the bandwidth demand for data traffic has ever been exploding. Optical fiber networks based on wavelength-division multiplexing (WDM) technology offer a promising solution to satisfy the bandwidth requirements of the Internet infrastructure. In order to enhance the network management, practical protection network architectures are highly desirable such that in case of any failure in the network physical layer, the affected traffic can be restored timely and thus the data loss can be minimized. However, little work has been done to offer protection capability in conventional passive optical network. This thesis discusses our proposed protection schemes on both optical access networks as well as optical metro networks to realize protection and traffic restoration.

In order to sustain a high growth rate in access network subscribers, multi-wavelength passive optical networks are emerging to deliver broadband interactive services in the mile applications. The stringent requirements on the cost and components' reliability, together with no manual intervention for switching, impose a great challenge to the system operators. In view of this, by adopting appropriate wavelength assignments and incorporating optical switches into the optical network units (ONUs), the affected bidirectional data wavelengths can be re-routed and be delivered to the isolated ONU due to possible fiber cut. In this thesis, we propose two new access network designs with protection capability. The first scheme focuses on the automatic protection capability on a tree-structured access network while the second scheme focuses on another network design on a tree-ring access network. By employing these protection architectures, the affected traffic can be automatically re-routed. By utilizing the periodic spectral properties of the Array-Waveguide-Grating (AWG) and with appropriate wavelength routing techniques, link-based protection can be achieved automatically.

As High-Definition TV will be widely deployed in Europe and China in the next two years, data multi-casting is important for network service provisioning in optical networks. A new scheme is proposed to provide re-configurable data multicasting service to various optical network units in a multi-wavelength access network.

For the sake of completeness, open issues related to the possibility multi-wavelength applications are presented. This gives an account on the challenging problems in security, performance, protection and robustness to design secure survivable networks.

摘要

近年來，隨著互聯網（Internet）的快速發展，資料業務對帶寬的要求也呈爆炸式增長。基於波分複用（WDM）的多波長光纖網路爲滿足互聯網帶寬要求提供了一個有效的解決方案。爲了增強網路的管理能力，網路需要具備有實用的保護結構，從而使得被網路物理層故障所影響的資料可以在很短時間內恢復，降低資料丟失的可能性。但是，在傳統無源光網路的保護方面，到目前爲止，僅有很少的研究工作。本論文提出並討論了用於光接入網和光城域網方面的保護結構，來實現網路保護和業務資料恢復。

爲了保持接入網用戶的高速增長率，多波長無源光網路爲寬帶互動式業務提供了一個有效的解決方案。網路中器件成本和穩定性的嚴格要求，以及自動保護倒換功能，都是系統設計者要面對的巨大挑戰。從這個觀點上來看，通過合理分配波長和在光網路單元（ONU）中採用光開關，受影響的資料業務可以從新路由到由於光纖故障被隔離的光網路單元中。在本論文中，我們提出了兩種新的具備保護能力的接入網路。第一個結構主要討論了在樹狀網路中的自動保護，而第二個結構討論了樹狀-環形混合接入網路的情況。通過採用以上的保護結構，受影響的資料業務可以自動地被重新路由，並且光纖路終端（OLT）將毫不察覺網路中的任何光纖故障。利用陣列波導光柵（AWG）的週期譜特性和合理的波長路由技術，可以實現基於鏈路的自動保護。

隨著未來兩年高解析度電視將在歐洲和中國等國家普及化，在光網路的服務提供方面，資料的多播是一個很重要的問題。我們提出了一種新的用於多波長光接入網路的資料多播結構，爲用戶提供可重置的資料多播業務。這樣就在保持網路設計安全生存性的前提下，對網路安全、性能、保護、強健性提出了挑戰。

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Chapter 1

Introduction

1.1 Background

Understanding our history and identifying 'where we are' are always the first step to study a specific area. Before presenting our framework on the existing network, access and backbone network are reviewed so that the critical issues can be figured out. Backbone network and access network actually play a different role and function in our life. In this section, we are going to review the state-of-the-art and try to figure out some future insights on research and development. The backbone network will first be reviewed in section 1.1.1, while the access network history will be reviewed in section 1.1.2. And the integration problem of both networks will be discussed in section 1.1.3.

1.1.1 Backbone network - Long haul mesh network problem

Broadband services are emerging

As the telecommunications network evolves, more and more people are subscribing to broadband services [1-2].

Network overlay of different services leading to a waste of resource

In order to provide different network services, network providers are continuously laying new fibers and installing new network nodes to provide different types of network services. Unfortunately, the service providers have restricted their networks for their own companies' usage only. Other providers have to build their own infrastructures in order to join the competition. Furthermore, the same company may have a few disconnected networks, which overlay one another to provision fixed-line voice service, lease line service, broadband service and TV service. In this sense, they waste not only the network resources, but also the operation and maintenance cost for different network equipment.

ATM revolution - voice and data grooming

Actually, resources can be utilized in a more efficient sense. The physical layer, the data link layer and the network layer of a network, in fact, are basically the same or similar in various network technologies. A couple of decades ago, asynchronous transfer mode (ATM) technology was used to support voice from telephony transmission and data from IP services over the same ATM transport medium [3-4]. This offers the flexibility to support any type of source data over the same transmission and switching system.

IP convergence and Ethernet technology

The efficiency in the protocol stack is a ciritical aspect. IP seems to have won out among all other options [4-5]. That is what we called IP convergence. By adopting TCP/IP technology, a large scale of metro network can be built to provision all services including data and voice. The introduction of the low-cost Ethernet technology in the medium access layer drives the market to be economically feasible.

IP over WDM

To meet the needs of the growing demands of bandwidth, multi-wavelength technology is employed. In order to speed up the operation of switching, layers such as SONET and ATM are removed where network function are implemented in the physical layer. The NGI ONRAMP consortium in US is focusing on providing high speed optical access to businesses [6]. The aim is to build thousands of regional ONRAMP nodes, each being low cost and easy to provide and manage. These networks are going to be realized using IP over WDM, with no intelligent networking layer (e.g. ATM) in between. A testbed in the Boston area is being implemented to demonstrate these technology choices [6]. Implementing an IP over WDM network introduces new issues in resource management.

Packet switching time and protection time

Packet switching technology is very critical in packet-based networks. Even though many papers focus on how to use wavelengths for traffic engineering, most of them involves complicated heuristic algorithm for switching. The switching time may rise up to more than hundreds of milliseconds. In a metro-environment, the ring networks would be of very large scale. The protection switching at the medium access control

(MAC) layer may takes up to even 1 to 2 seconds for fast restoration. Protection measures at IP layer may even take up to a few minutes or more by using open shortest path first (OSPF) algorithm.

In 2003, the management and control plane of Automatic Switched Optical Network (ASON) [7-8] has been a hot topic in mainland China and worldwide. Vendors and operators are eager to search for a solution that can achieve both the IP convergence and fast switching and protection mechanism as in the traditional SDH ring networks.

Multi-protocol label switching (MPLS) [9-10] and Resilient Packet Ring (RPR) [11-14] are some of the solutions proposed recently but their problems are that both of them still operate in the MAC layer or above, which may suffer from possible speed limit and thus may lead to latency.

Protection in mesh network

Actually, the traditional SONET/SDH can achieve a really fast protection switching due to the fact that an automatic switching [15-16] is almost done in the physical layer. Traffic is redirected to another path without any delay if a link failure is detected. However, those technologies are only limited to ring networks. No physical layer protection switching in mesh is known so far except protection by mere duplication of fiber links.

1.1.2 Access network – Last mile problems

Relation between the evolution of networks and Services

Telecommunications and electronic media have commenced a process of transformation from "narrow-band" towards "broadband". The main driving forces are the emerging broadband services which are further distributed to many households. Different kind of services may impose different requirement to the network design considerations. Therefore, the evolution of a network is related to the evolution of the services.

The first impact on network from service – Greater broadband needs

The new services that are now emerging in the market are mainly: video on demand (VOD), high speed internet, video conferencing, telemedicine, gaming, tele-learning, etc. All of them require a substantial bandwidth in order to offer a good quality of service (QoS). Thus the access networks have to offer more bandwidth to support them and deliver these services with an admissible QoS.

The second impact on network from service – No physical-layer adaptation

Among the broadband services such as video on demand, the data have to be multicasted to many subscribers for service provisioning. Traditionally, multicast is done in transport or even the application layer in the protocol stack. No adaptation or grouping in the lower layers has yet been done due to the complicated operation of multicast services.

Minimize unnecessary protocol layer complication

Even though services are more flexible in higher layer of the protocol stack, some multicast services such as Cable TV and VOD, for which the destinations' light path is routine, can actually be done in a lower layer. It can greatly simplify the complicated protocol. Sometimes, data traffic can be transmitted more effectively over the lower layers of the protocol stack. Unfortunately, multicast scheme in the physical layer is still not available.

Rising needs in survivability solution in passive optical networks

Robustness against failures is another important issue in the service level agreement. Even though multi-wavelength technologies have satisfied the exploding capacity demand in passive optical networks, little work has been done in the protection. Up to now, only simple redundant links are employed alongside with the normal working fiber for protection measures. Automatic switching protection without manual intervention, short recovery time, no additional equipment cost, pose the challenges.

Topology adaptation in different landscape poses a new challenge

As the broadband services are emerging, the access points are expected to reach the subscribers wherever they are. Some towns may be far away from urban area. Lakes or river may separate some villages, which share the same central office geographically. Topology adaptation to different landscape with virtually no additional equipment and design cost seems to be a new challenge when the fiber really comes 'to the home'.

In this thesis, we are going to develop a framework to design an access network in the physical layer in a more systematic manner.

1.1.3 Network integration

Integration problem of access and backbone networks

In order to solve the problems on the access and the backbone networks discussed in the previous two sections, many innovative network designs have been suggested previously. Very often, the network designs are divided crystal clear between the access and the backbone. Central office acts as an interfacing point for both types of network. But the question 'where the central office should be placed to optimize the cost/performance ratio' usually poses a big challenge, especially when new backbone network architecture comes out.

Interface point equipment consideration

It is well known to the telephony companies that incompatibility of products among different vendors is a big problem to intra- or inter-system connection. People try to solve this problem by standardization. But vendors sometimes introduce proprietary protocols to optimize the performance without passing IEEE, ANSI, ETSI to standardize. Bugs or unexpected network behaviour could result. Thus, workers are hired in testing lab for performing compatibility testing. As a result, both cost and time are wasted. Therefore, interface point should be as simple as possible. And, ideally, all interface point shares the same physical structure regardless of layer 2 protocol so that backbone-access integration can be integrated easily.

Scalability of network and Extensibility in 'all direction'

The traditional backbone network is made up of point-to-point link and metro rings. There is no systematic way to extend the existing network to a larger distance. The design cycle for extending existing network always incurs human resources cost and time delay. The standardized ways for a network to extend a network in any new area is an important challenge.

In order to solve all the problems address in the previous two sections, many designs proposed from researcher are not extensible in all direction. But due to the novel design of network node to solve some problems addressed earlier, their asymmetric topology design makes them suffered from extensibility problem.

1.2 Summary of Insights

Here is the summary of requirements that needs to be addressed in the network.

Backbone network requirements

1) One unified network instead of overlaying of few disconnected network for different services
2) Physical resource sharing for voice and data grooming as in ATM
3) High protocol stack efficiency as in elimination of ATM
4) High-capacity as in IP over WDM
5) Fast switching time as in circuit switching
6) Short recovery time for protection
7) Tackle fundamental speed limit in higher protocol layers
8) Mesh network topology instead of rings only

Access network requirements

1) Diversity of services provisioning at ease with network adaptation
2) Support broadband services
3) Data sharing in multicast fashion to support different services
4) Survivability in access network
5) Topology adaptation in different access landscape

Integration of backbone and access network

1) Backbone-access integration point
2) All interface points share the same physical structure due to Interface point equipment problem
3) Backbone network should be scalable to broaden coverage and large distance

A systematic way to address problem is crucial in these long-listed and complicated requirements.

1.3 Contribution of this thesis

This thesis addresses various aspects in optical network protection against vulnerability. In particular, this thesis provides a framework to discuss:

- Group Protection Architecture
- Cone Protection Architecture
- Simple Multicast Network and two-level reconfigurable multicast network scheme

1.4 Structure of the thesis

The organization of the thesis is as follows. In Chapter 2, several traditional protection architectures will be outlined. We review the self-healing ring architectures in metro network. We also review four traditional protection architectures in ATM-PON and in star-ring bus architecture.

In Chapter 3, two Group Protection Architectures in access network based on Group-wise level variation are proposed. They are Simple Group Protection Architecture (SGPA) and Enhanced Group Protection Architecture (EGPA) in our published paper. By assigning a special interconnection in the subscriber side, fast and automatic protection switching without interference to normal traffic is achieved.

In Chapter 4, we are going to propose a hierarchy of access network with a basic building block called Cone. The standard architecture is called Cone Protection Architecture. Based on the special connection method in remote node (RN) and wavelength assignment, different level of variations can actually be achieved.

In Chapter 5, we are going to propose a set of multicast access networks. By using different connection patterns and Duplication theory introduced, data sharing flexibility are addressed. From short wavelength range Simple Multicast Network Architecture (SMNA) to Fully Re-configurable Multicast Architecture (FRMA), the connection pattern theory demonstrates the bright future of extra-ordinary high-speed data sharing architecture with Two-Level re-configurable capability.

We will have the conclusions over the thesis in the last chapter.

Chapter 2

Previous Protection Architectures

2.1 Introduction

Network survivability is a critical issue to achieve a reliable access network. Any kind of network failure due to link breakage or component failure will interrupt the broadband services to the subscribers and definitely translate into enormous loss in data and business. To alleviate the disastrous situation, it is desirable to have fault tolerant network architectures, which can detect the link failure and automatically restore the network traffic via other alternative or backup paths. Currently, little work has been done to offer protection and restoration capability in the optical layer for optical access networks. We believe the use of a new global physical layer protection network framework is indispensable.

In this chapter, we will review a number of conventional protection architectures in optical networks. In section 2.2, we will review some traditional physical-layer protection architectures in traditional metro-area networks. Bi-directional Line-switched Ring (BLSR) / Unidirectional Path-switched Ring (UPSR) protection in metro ring networks will be addressed. In section 2.3, we are going to review some traditional physical-layer protection schemes in access network. Some basic protection methods in APON (Asynchronous Transfer Mode Passive Optical Network) will be reviewed. In section 2.4, we will review two more interesting protection architectures in passive optical network. The variations of the topology and the network node in Star-Ring and Star-Ring-Bus topology give some good insight for the further research.

2.2 Traditional physical protection architectures in metro area

2.2.1 Self healing ring

The network ring incorporates protection mechanisms that automatically detect failures and reroute traffic away from the failed links and nodes onto other routes rapidly. Unidirectional Path-switched Rings and Bi-directional Line-switched Rings are commonly used in the SONET ring networks for protection purpose. Interconnected rings and dual homing are some improved version. We will review those architectures in this section.

2.2.2 Some terminology in ring protection

Path layer protection: It operates on individual paths or connections in the network. It is SONET terminology. It corresponds to Channel Layer (Ch) in SDH.

Line Layer protection: It operates on the entire set of connections at once and generally does not distinguish between different connections that are part of the aggregate signal. It is SONET terminology. It corresponds to Multiplex section (MS) Layer in SDH.

2.2.3 Unidirectional path-switched rings (UPSR) [17]

UPSR can be viewed as 1+1 path protection at path layer. One fiber is used as the working fiber and the other as the protection fiber. Traffic from node A to node B is sent simultaneously on the working fiber in the clockwise direction and on the protection fiber in the counter-clockwise direction. The protection is performed at the path layer for each connection as follows: Node B continuously monitors both the working and protection fiber and selects the better signal between the two for each SONET connection. Under normal operation, suppose node B receives traffic from the working fiber. If there is a link failure, say, of link AB, then B will switch over to the protection fiber and continue to receive the data.

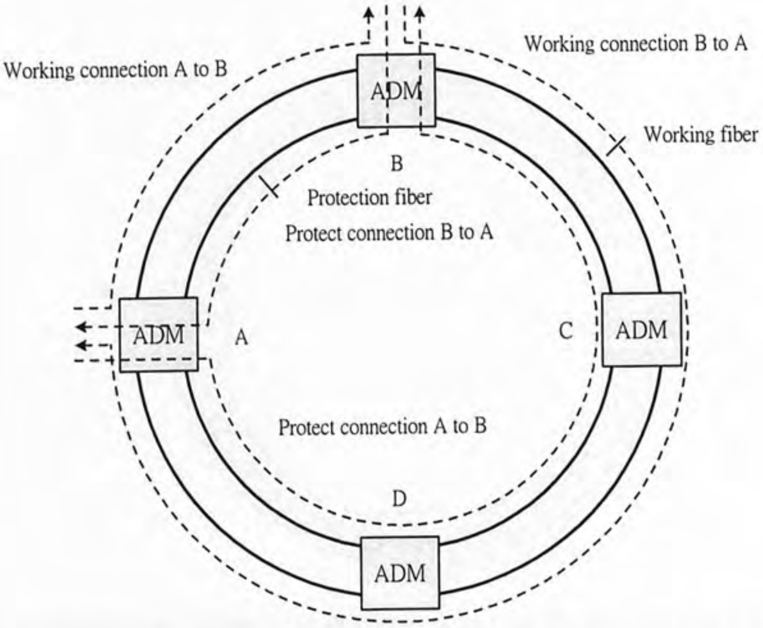


Fig 2.1 Unidirectional path-switched rings. One of the fibers is considered the working fiber and the other the protection fiber. Traffic is transmitted simultaneously on the working fiber in the clockwise direction and on the protection fiber in the counterclockwise direction. Protection is done at the path layer.

2.2.4 Bidirectional line-switched rings (BLSR) [17]

BLSRs are much more sophisticated than UPSRs and incorporate additional protection mechanisms. Unlike a UPSR, they operate at the line or multiplex section layer. The BLSR equivalent in the SDH world is called a multiplex section shared protection ring (MS-SPRing). Unlike a UPSR, working traffic in a BLSR can be carried on both directions along the ring. For example, on the working fiber, traffic from node A to node B is carried clockwise along the ring, whereas traffic from B to A is carried counter clockwise along the ring. Usually, traffic belonging to both directions of a connection is routed on the shortest path between the two nodes in the ring. In case of a fiber or cable cut, service is restored by ring switching. Suppose link AB fails. The traffic on the failed link is then rerouted by nodes A and B around the ring on the protection fibers. Ring switching is also used to protect against a node failure.

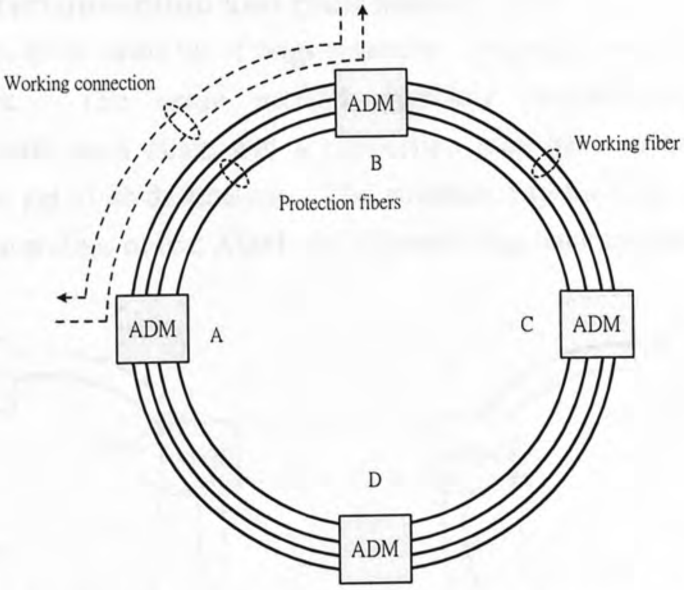


Fig 2.2 A four bi-directional line-switched ring. The ring has two working fibers and two protection fibers. Traffic between two nodes is transmitted normally on the shortest path between them, and either span or ring switching is used to restore service after a failure.

BLSRs provide spatial reuse capabilities by allowing protection bandwidth to be shared between spatially separated connections. Thus BLSRs are more efficient than UPSRs in protecting distributed traffic patterns. For this reason, BLSRs are widely deployed in long-haul and interoffice networks.

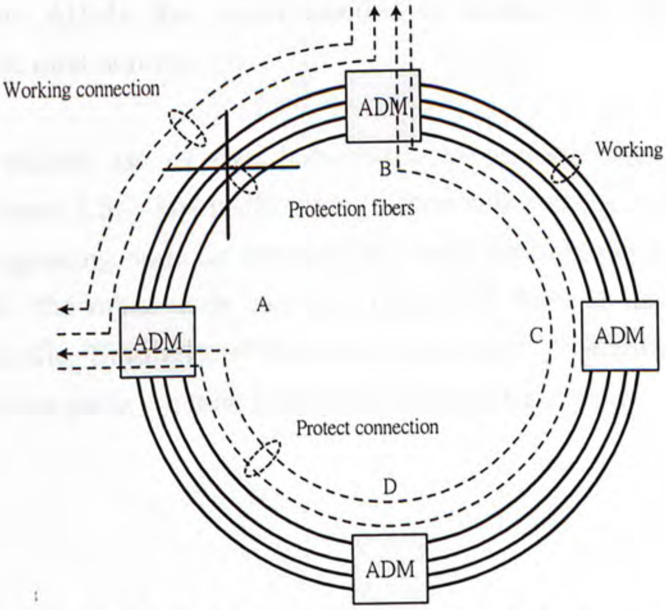


Fig 2.3 Protection route in BLSR. Traffic is rerouted around the ring by the nodes adjacent to the failure

2.2.5 Ring interconnection and dual homing [17]

Metro network is often made up of rings structure. A single ring is only a part of the overall network. The entire network typically consists of multiple rings interconnected with each other, and a connection may have to be routed through multiple rings to get to its destination. The simplest way for rings to interoperate is to connect the drop sides of two ADMs on different rings back to back.

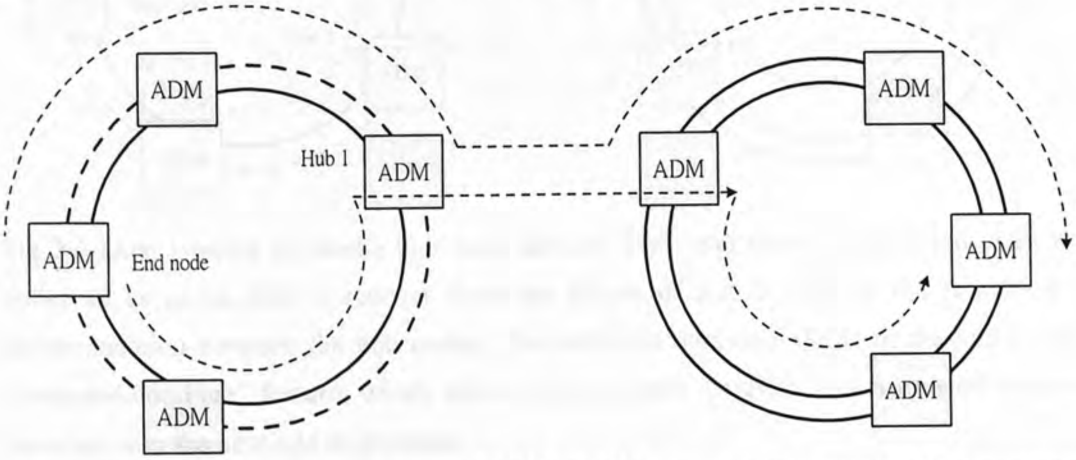


Fig 2.4 Back-to-back interconnection of SONET/SDH rings. This simple interconnection is vulnerable to the failure of one of the two nodes that form the interconnection, or of the link between these two nodes.

Figure 2.4 shows the one of the possible interconnections. One of the problems of this approach is that if one of the ADMs fails, or there is a problem with the cabling between the two ADMs, the interconnection is broken. A way to deal with this problem is to use dual homing.

Dual homing makes use of two hub nodes to perform the interconnection, as illustrated in Figure 2.5. For traffic going between the rings, connections are set up between the originating node on one ring and both the hub nodes. Thus if one of the hub nodes fails, the other node can take over, and the end user does not see any disruption to traffic. Similarly, if there is a cable cut between the two hub nodes, alternate protection paths are now available to restore the traffic.

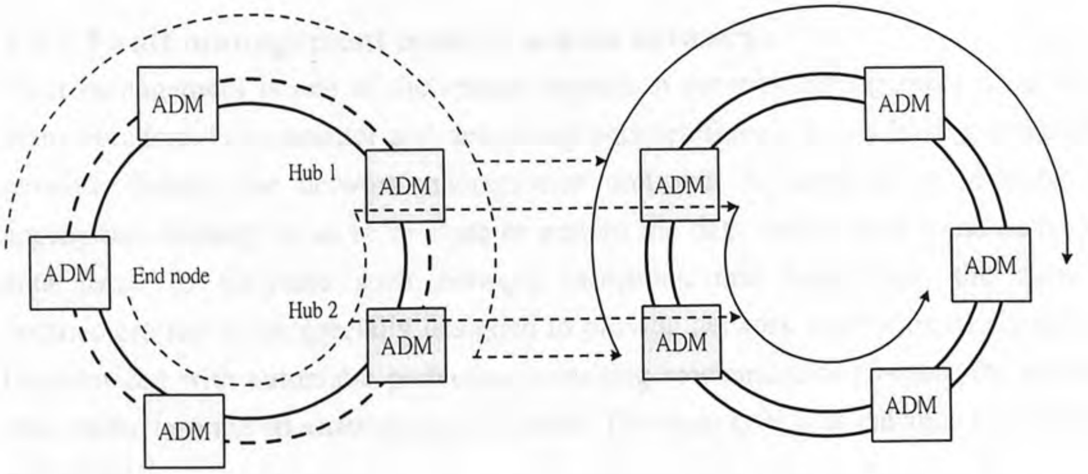


Fig 2.5 Dual homing to handle hub node failures. Each end node is connected to two hub nodes so as to be able to recover from the failure of a hub node or the failure of any interconnection between the hub nodes. The add drop module (ADM) in the nodes have a "drop-and-continue" feature, which allows them to drop a traffic stream as well as have it continue onto the next add drop nodes.

2.3 Traditional physical protection architectures in access networks

2.3.1 Basic architecture in passive optical networks

In an effort to remove the cost, powering, and complexity of the active electronics in the field, the use of totally passive remote node was proposed in the early 1980's at British Telecom Research Labs. Feeder fibers transport signals from an optical line terminal to the remote node, a passive optical power splitter. The remote node output fibers either could be further split by another layer of passive splitters or could be connected directly to the subscriber optical network units. In this approach, the fiber gain is achieved without consuming power in the field. Thus, these networks were called passive optical network (PON).

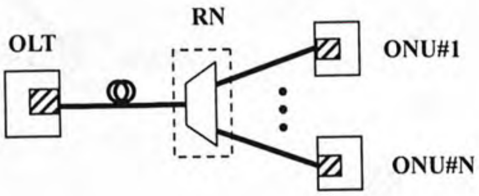


Fig 2.6 Typical passive optical network structure

2.3.2 Fault management issue in access networks

Fault management is one of the crucial aspects in network management. One of its main functions is to monitor and detect any network failure. Upon having detected a network failure, the network management unit will be alarmed to perform the appropriate remedy so as to re-route or restore the data traffic, thus minimizing the data loss. To facilitate such network protection and restoration, the network architecture has to be specially designed to provide network path redundancy and be incorporated with automatic protection switching mechanism to re-route the affected data traffic into the alternate protection paths. The main goal is to enhance the network reliability.

2.3.3 Some protection architectures

Many optical access networks employ point-to-multipoint network topology. The physical layer is shared. The major cause of network downtime is fiber breaks. To improve the availability, some fiber sections have to be duplicated. The ITU-T Recommendation on PON (G.983.1) [18] have suggested four possible fiber duplication and protection switching scenarios, as shown in Fig. 1, though they are regarded as optional protection mechanisms. Note that the RN only comprises 1×N optical power splitter(s) in ITU-T G.983.1, but those protection architectures can also be applied to multi-wavelength PON by replacing the optical power splitters by wavelength demultiplexers.

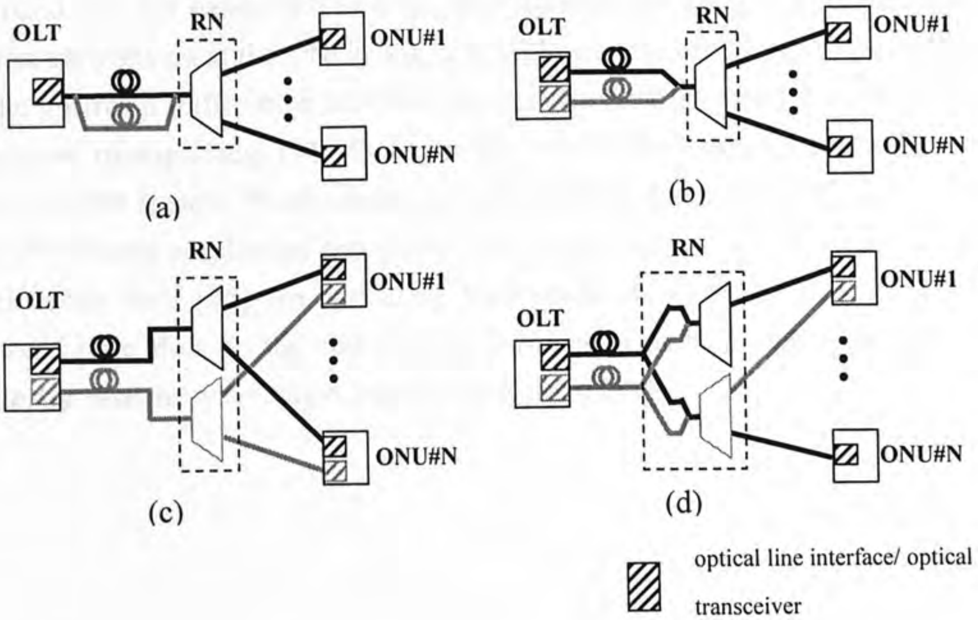


Fig. 2.7 Protection switching architectures suggested by ITU-T G.983.1

Fig. 2.7 shows the four suggested protection architectures with different levels of protection. Fig. 2.7 (a) duplicates the fiber feeder between the OLT and the RN only. Fig. 2.7 (b) doubles the optical transceivers at the OLT and also duplicates the fiber feeder between the OLT and the RN. Protection switching is done by switching the data to the backup optical transceiver at the OLT. Fig. 2.7 (c) doubles not only the OLT side facilities but also the RN and the ONU sides. Failure at any point can be recovered by switching to the backup facilities. Fig. 2.7(d) incorporates an additional power splitter circuit to cope the case that not all ONUs have duplicate optical transceivers, due to some environmental constraints.

In terms of the network architecture for WDM-PONs, various approaches have been proposed previously [19]. Most of them featured at the transmission characteristics and wavelength routing of both downstream and upstream wavelength channels. Fig. 2.8(a) shows a generic WDM-PON [20], where one wavelength router was placed at the RN to route a set of downstream wavelength channels and another set of upstream wavelength channels. The periodic transmission property of the wavelength router was employed. Fig. 2.8(b) shows a WDM-PON [21] where the downstream wavelength channels were demultiplexed by one wavelength demultiplexer while the upstream wavelength channels were multiplexed by another wavelength multiplexer at the RN. Fig. 2.8(c) shows the spectral-sliced WDM-PON [20][22] where the network architecture was similar to Fig. 2.8(b). However, the upstream data was modulated on a broadband LED at the ONU and the wavelength multiplexer at the RN filtered out a narrow band of LED bandwidth to form the upstream wavelength. This can save the cost of the transceivers at the ONUs. Fig. 2.8(d) shows the composite WDM-PON [23] where the upstream traffic from all ONUs were carried by the same wavelength using time-division multiplexing (TDM) technique while the downstream traffic were carried by WDM signals. Burst-mode receivers were needed at the OLT to detect data packets of different amplitudes and phases. Fig. 2.8(e) shows WDM-PON with fiber-loopback at the ONU [24]. An optical modulator was placed at the ONU to modulate the reserved time slots on the downstream wavelength with the upstream data. This could greatly ease the wavelength management at the ONUs.

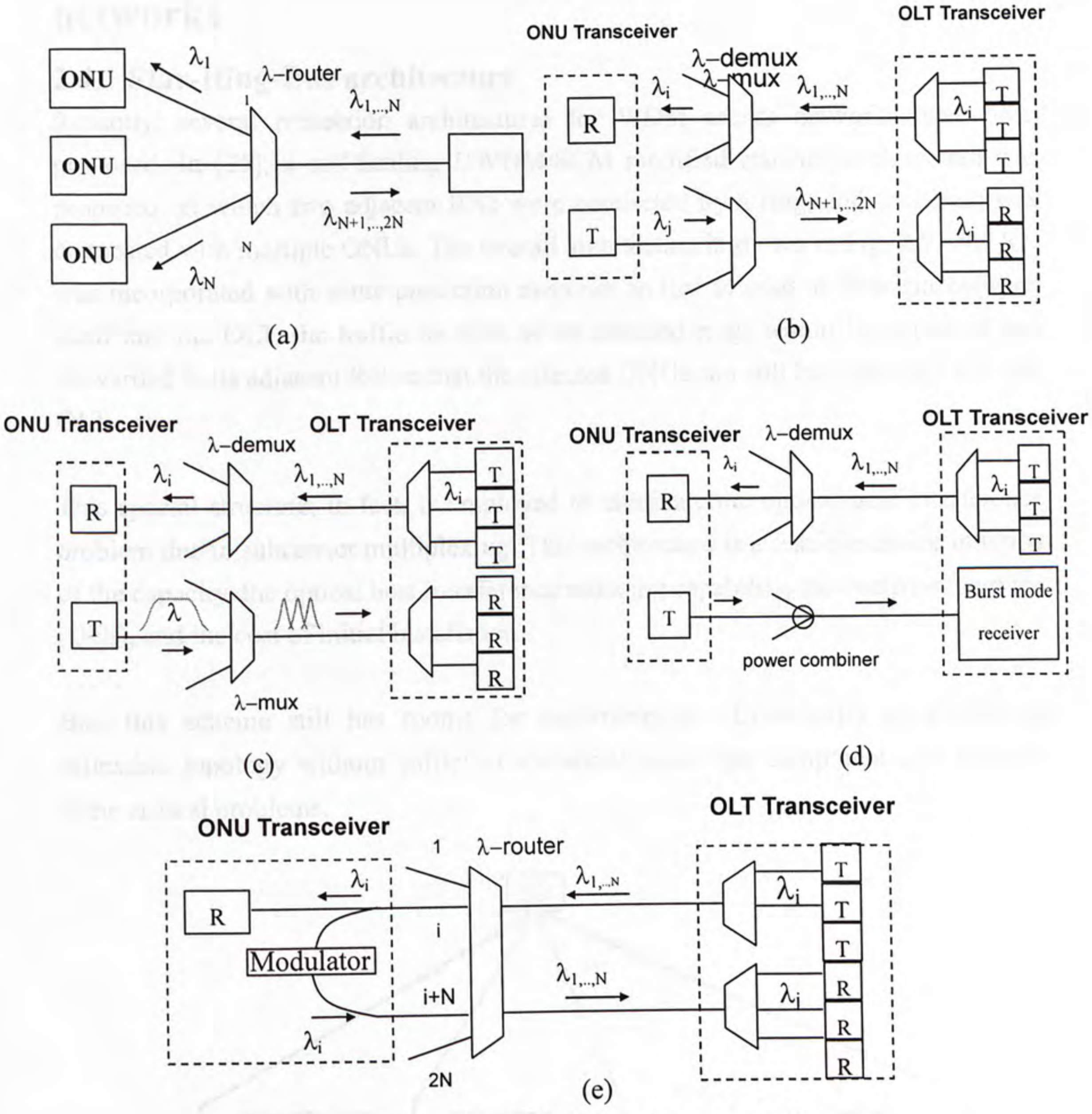


Fig. 2.8: WDM PON architectures [19]

2.4 Recent protection architectures on access networks

2.4.1 Star-Ring-Bus architecture

Recently, several protection architectures for WDM access networks have been proposed. In [25], a self-healing DWDM/SCM modified star-ring architecture was proposed, in which two adjacent RNs were connected by a ring, and each ring was connected with multiple ONUs. The overall architecture is shown in Fig. 2.9. The RN was incorporated with some protection switches so that in case of fiber cut between itself and the OLT, the traffic on both of its attached rings would be bypassed and forwarded to its adjacent RN so that the affected ONUs can still be in contact with the OLT.

This special structure, in fact, is employed to eliminate the optical beat interference problem due to subcarrier multiplexing. This architecture is a feasible choice in terms of the capacity, the optical beat interference reducing capability, the quality-of-service (QoS), and the cost of initial installation.

But, this scheme still has rooms for improvement. Complexity in scalability, inflexible topology without sufficient variations, and high equipment cost become some critical problems.

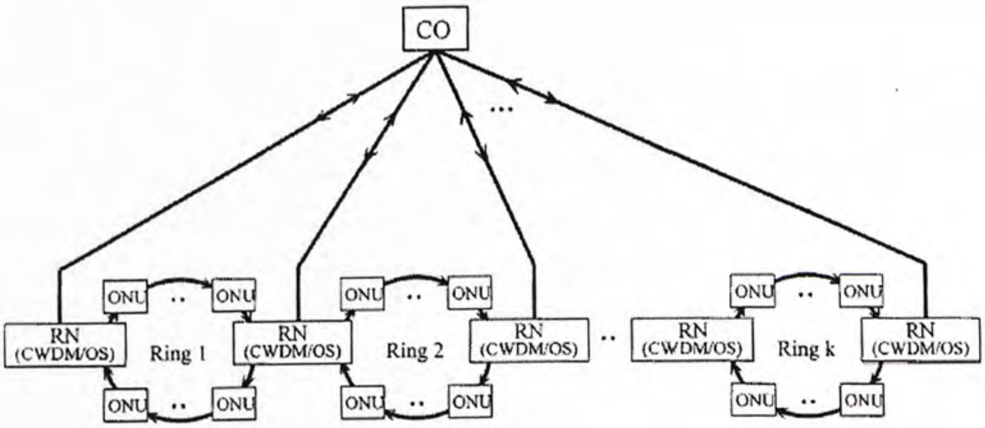


Fig 2.9 Star-Ring-Bus architecture in access network. [25]

2.5 Concluding remarks

In this chapter, we have reviewed several protection architectures in metro and access networks.

In terms of metro network architecture, we have gone through the various structures of self-healing rings in larger scale network. Unidirectional Path-switched Rings (UPSR) and Bi-directional Line-switched Rings (BLSR) are discussed.

In terms of access network architecture, we have gone through four simple protection measures as suggested in G.983.1. Those variations are simple but lack flexibility. We have also gone through two protection schemes with interesting star-ring and star-ring-bus architecture. It gives the insight that access network service can be more flexible with better protection capability.

In the coming chapter, we would start with the access network. We are going to propose a Group Protection Architecture based on Group-wise level variation. Simple Group Protection Architecture (SGPA) and Enhanced Group Protection Architecture (EGPA) scheme have similar functionality but different logical structure in both the second and third tier. The Group Concept in Chapter 3 would be generalized as Cone structure in Chapter 4.

Chapter 3

Group Protection Architecture (GPA) for Traffic Restoration in Multi-wavelength Passive Optical Networks

3.1 Background

Fibre-To-The-Home (FTTH) has been proposed as a future ultra-broadband access network and its feasibility has been widely studied over the past couple of decades. Passive Optical Network (PON), which can save the maintenance cost at the remote node, has been one of the most popular systems in the last mile network architecture.

In the past decade, the challenge of the exponential growth in capacity demand, brought about by the Internet and various multimedia services, has been one of the main issues in the last mile infrastructure design. Multi-wavelength technology has been emerging to upgrade the network capacity gracefully. Thus, multiwavelength PON has been a hot topic in the research community. Many interesting architectures have been proposed. Nevertheless, little work has been done to address the survivability problem. As the success networks nowadays has been evolving from a mere service distribution to interactive networking application, ensuring the network survivability and the quality of service are becoming essential for telecommunication companies to survive under the fierce market competition

3.2 Organization of Chapter 3

In this chapter, we propose a novel protection architecture for multi-wavelength passive optical networks. In this architecture, group protection concept will be introduced to protect against link failure between the remote node (RN) and the optical network unit (ONU). Under the protection mechanism provided, not only the bi-directional automatic protection can be provisioned, but also a very short recovery time can be achieved.

In section 3.3 of this chapter, the general architecture of our proposed Group-Protection Architecture (GPA) will be presented through illustration by a prior work proposed in our research group. In section 3.4, improved protection network architecture, called Enhanced Group Protection Architecture (EGPA) will be presented. It requires less network resources to achieve the protection against fiber link failure.

3.3 Overview of Group Protection Architecture

3.3.1 Network architecture

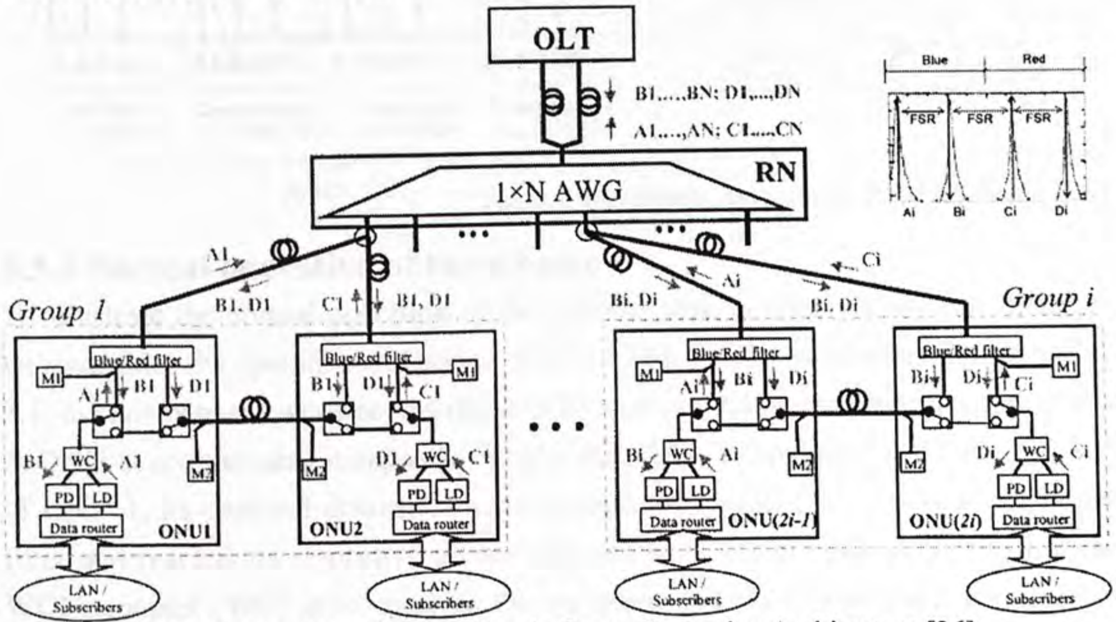
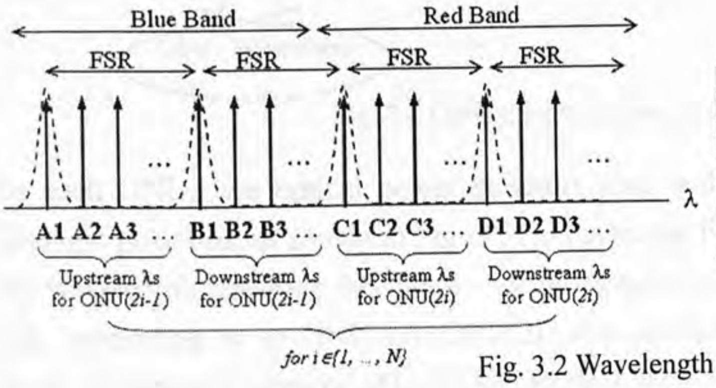


Fig 3.1 Network topology of Simple Group-Protection Architecture [26]

Fig. 3.1 shows the general architecture of the previously proposed Group-Protection Architecture [26]. The RN comprises a 1xN array-waveguide grating (AWG) and several 1x2 3-dB couplers to route the wavelength channels to the ONUs. From the OLT to the RN, there is one backup fiber link, in addition to the working fiber feeder, and automatic protection switching is done at the OLT. Every two adjacent ONUs are assigned to a group. Each ONU in a group is separately connected to the same output port of the AWG via the fiber coupler. In addition, a single piece of fiber is used to connect the two ONUs, in the same group, to provide an alternative protection path for wavelength rerouting.

3.3.2 Wavelength assignment

For each ONU, two distinct wavelengths are assigned for the upstream and the downstream signals. Moreover, as the two adjacent ONUs in the same group are actually connecting to the same output port of AWG at the RN, we make use of the spectral periodicity property of AWG to support the set of wavelength channels in each ONU group. The wavelength assignment is illustrated in Fig. 3.2. The upstream wavelengths (Ai , Ci) and the downstream wavelengths (Bi, Di) in the ith ONU group (for i=1, …, N), i.e. ONU(2i-1) and ONU(2i), are spaced by one free-spectral range (FSR) of the AWG. Therefore, one AWG port can support the transmission and routing of all four wavelength channels simultaneously.



	Upstream λs	Downstream λs
ONU1	A1	B1
ONU2	C1	D1
…		
ONU(2i-1)	Ai	Bi
ONU(2i)	Ci	Di
…		
ONU(2N-1)	AN	BN
ONU(2N)	CN	DN

Fig. 3.2 Wavelength assignment in GPA scheme [26]

3.3.3 Normal operation of the scheme

To illustrate the normal operation of the scheme, that is, when there is no fiber cut, let's consider the operation of Group 1 ONUs (ONU1 & 2), as an example. From Fig. 3.1, the downstream wavelengths (B1 and D1) are carried on the fiber link connecting to ONU 1, and the same composite signal is also delivered to ONU 2. At the front end of ONU 1, its destined downstream wavelength will be filtered out by the red–blue filter and reaches its respective photodiode and so is D1 in ONU 2. The use of the WDM coupler (WC) is to separate the upstream and the downstream wavelengths within the ONU. The upstream wavelengths (A1 and C1), from ONU 1 and from ONU 2 respectively, will pass through their own red–blue filters and their respective fiber links. They are then combined before being fed into the same output port of the AWG. Under normal operation, each ONU is serving its respective connected subscribers, and there will be no traffic running on the fiber link connecting the two ONUs in the same group.

3.3.4 Protection mechanism

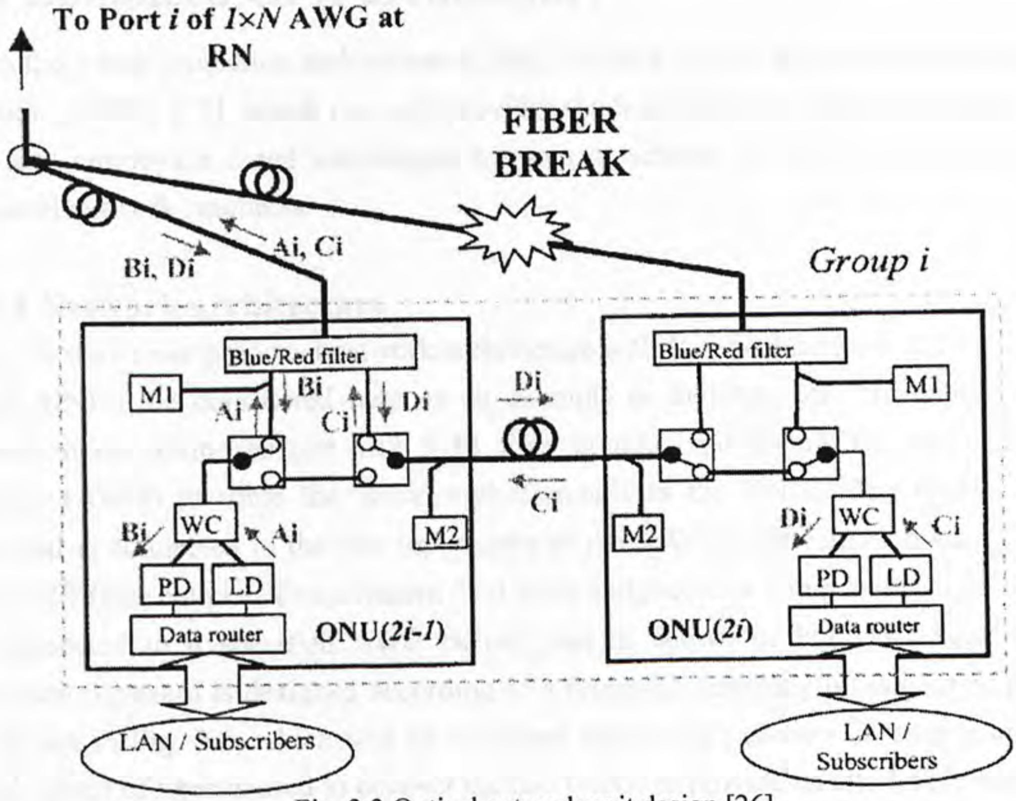


Fig. 3.3 Optical network unit design [26]

At each ONU, two optical power monitors (M1 and M2) are incorporated at the strategic positions, as shown in Fig. 3.3, to detect the fiber link failure and to activate the wavelength rerouting mechanism for protection. In case of a fiber cut at the fiber link connecting to an ONU say ONU(2i), for example, the detected optical power level of its power monitor M1 will be below a certain threshold level. An electrical control signal will then be generated to trigger the two optical switches inside the ONU to change their respective switching states, as illustrated in Fig. 3.3. Thus, the upstream wavelength from ONU(2i) will be rerouted toward ONU(2i-1) via the fiber link connecting the two ONUs. At the same time, the power monitors M2, inside the ONU (2i-1), will detect the presence of a rerouted signal and, thus, it will reconfigure its respective optical switch as shown in Fig. 3.3. In this way, the rerouted signal can be connected back to the RN via the red–blue filter at the ONU. As a result, both the upstream and the downstream wavelengths of the isolated ONU can still be communicating with the OLT via its adjacent ONU in the same group. Conversely, ONU (2i) protects ONU (2i-1) in a similar way. Thus, an ONU can protect its adjacent ONU from being isolated due to such fiber cut, although each of them can still serve its respective connected subscribers in both normal and protection modes. The OLT is transparent to such fiber failure. As a result, mutual 1:1 protection and fast restoration are achieved, with minimal effect on the existing traffic.

3.4 Enhanced GPA architecture

With the group protection architecture (GPA), we have further proposed an enhanced version (EGPA) [27], which not only provides the bi-directional fiber link protection, but also employs a novel wavelength assignment scheme to reduce the amount of required network resources.

3.4.1 Network architecture

Fig. 3.4 shows our proposed network architecture with *N* optical network units (ONU). Eight ONUs are considered here as an example to facilitate our illustration. The remote node comprises one 1x2 3-dB fiber coupler and a 2x*N* array-waveguide grating (AWG) to route the wavelength channels to the ONUs. The optical line terminal is connected to the two input ports of the AWG at the remote node via the 1x2 3-dB fiber coupler. Two adjacent ONUs are assigned to a group and each of them is connected to a specified AWG output port as shown in Fig. 3.4. Such fiber connection pattern is designed according to a proposed wavelength assignment plan, as shown in Fig. 3.5, which will be described later in this section. In each group, a single piece of fibre is used to connect the two ONUs to provide an alternative path.

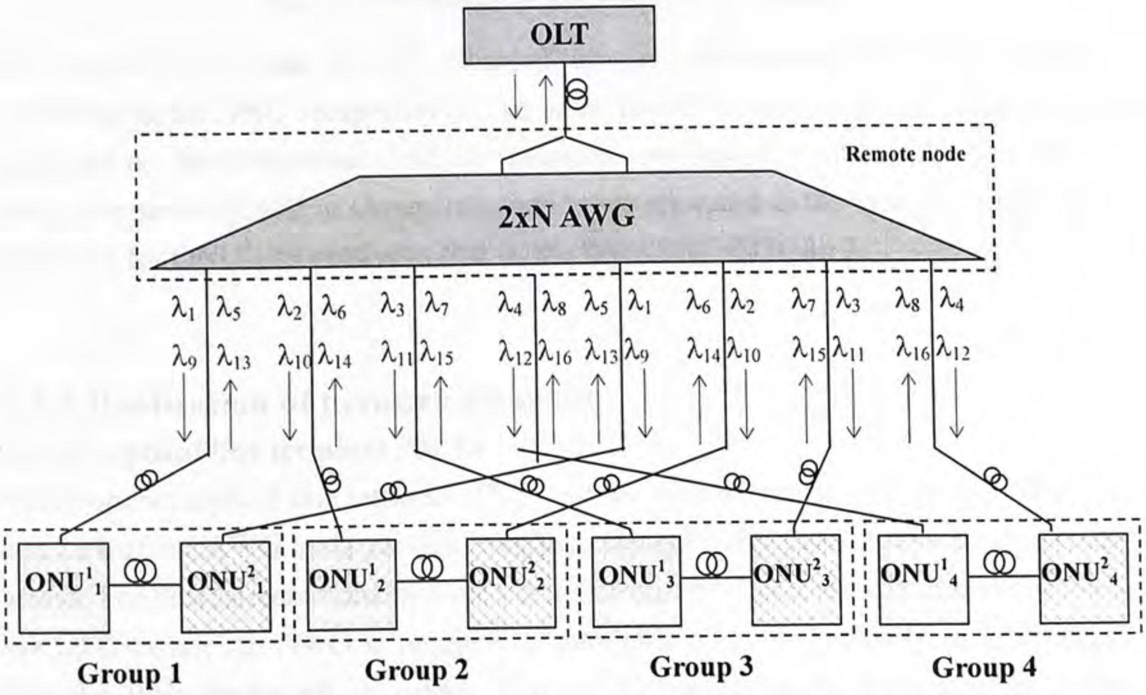


Fig 3.4 Proposed network topology of EGPA scheme

Whenever there is a possible fiber cut between an ONU and the remote node, it can still route its upstream and downstream traffic to/from the optical line terminal via its neighboring ONU in the same group, thus traffic restoration is achieved. As a result, an ONU can protect its adjacent ONU in the same group from being isolated due to fiber cut, although each of them can still serve their respective connected subscribers in both normal and protection modes. Mutual 1:1 protection is therefore achieved.

3.4.2 Wavelength assignment

To support such protection scheme, a novel wavelength assignment plan, as shown in Fig. 3.5, is proposed to allocate the downstream (in wavebands A & C) and the upstream (in wavebands, B & D) wavelengths for each group of ONUs. The adjacent wavebands are spaced by half of the FSR of the AWG at the remote node.

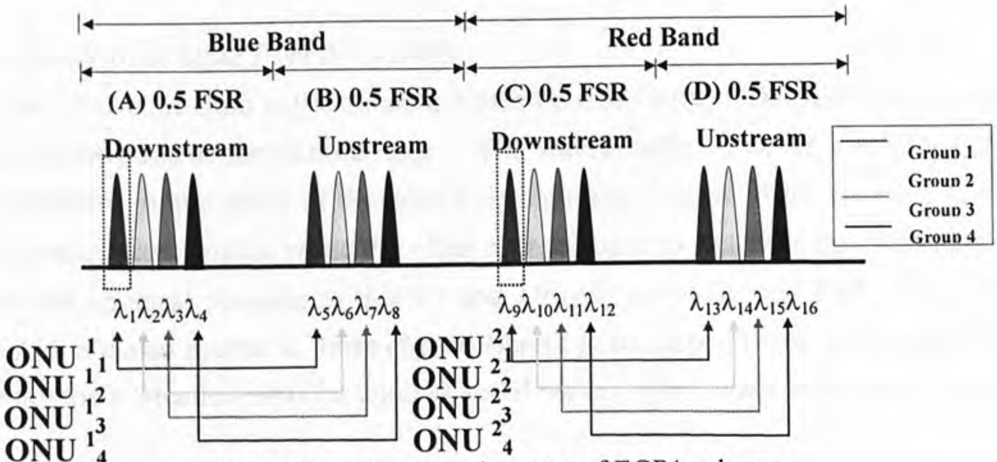


Fig. 3.5 Wavelength assignment of EGPA scheme

For instances, λ_1 and λ_5 are allocated as the downstream and the upstream wavelengths for ONU^1_1 respectively, that is the first ONU of group one; λ_9 and λ_{13} are allocated as the downstream and the upstream wavelength, respectively for ONU^2_1, that is the second ONU of Group 1; λ_2 and λ_6 are allocated as the downstream and the upstream for ONU^1_2 respectively, that is, the first ONU of Group 2.

3.4.3 Realization of network elements

3.4.3.1 Optical line terminal (OLT)

The proposed optical line terminal (OLT), which is to be placed in a central office, it consists of an AWG, data routers, multiwavelength DFB laser arrays and receiver arrays. For downstream transmission, the data from the data routers is modulated onto the DFB lasers. An AWG is required to multiplex all wavelengths from laser array into the fiber feeder which carries them to the remote node (RN). Similarly, for upstream transmission, the upstream data from the remote node would travel up the fiber feeder. The upstream wavelengths are then demultiplexed and detected at the OLT.

3.4.3.2 Remote node (RN)

At the remote node, the spectral transmission peaks of the two AWG input ports have to be spaced by half of the free-spectral range (FSR) of the AWG. With the wavelength assignment plan as illustrated in Fig. 3.5, each downstream data wavelength will be duplicated and directed to two distinct AWG output ports. With the wrap-around spectral periodicity property of the AWG, each AWG output port will be supporting two downstream wavelengths as well as two upstream wavelengths. The principles of the wavelength routing at the RN are illustrated as follows, assuming an 8x8 AWG. Note that only Input Ports #1 and #5 are used.

Data signals from Input Port #1 of AWG

Fig. 3.6a shows the light path connection plan between port, of the AWG and the eight AWG output ports at the remote node. The wavelengths λ1 to λ8 are routed to the eight different output ports of the AWG, respectively. Four of them are used to route the upstream wavelengths while the other four are used to route the downstream ones. Due to the spectral periodicity that λ1 and λ9 are spaced by one FSR of the AWG, λ9 to λ16 are also routed to those eight different ports respectively. These eight light-paths are the protection path for another set of wavelength routed in the Fig. 3.6b.

Data signals from Input Port #5 of AWG

Fig. 3.6b shows the respective light path connection plan when port 5 of the AWG is used to route the wavelengths, connection plan. The wavelengths λ1 to λ8 are routed to the AWG's output ports in another connection pattern, as shown in Fig. 3.6. These eight light paths serve as the protection paths for λ1 to λ8 in Fig. 3.6a. Due to the spectral periodicity, λ9 to λ16 are also routed as shown.

Formation of ONU groups

In our proposed network architecture, the Input Ports #1 and #5 of the AWG at the remote node are connected to the fiber feeder via a 3-dB coupler. Therefore, the light path connection plan shown in Fig. 3.6a and b are combined as depicted in Fig. 3.6c. In this way, four sets of wavelengths are duplicated. For instance, the set of wavelengths from output port #1 of the AWG is exactly the same as that at output #5. Thus, the two ONUs (ONU 1, ONU 2) which are connected to these two AWG output ports (#1 and #5), respectively, are assigned to an ONU group. Using similar principle, three other ONU groups can be formed. In general, given a 2xN AWG, it is shown that there are *N*/2 pairs of AWG output ports, each of which supports an identical set of downstream and upstream wavelengths. Thus, each of them will be connected to a pair of ONUs in a group and form the fiber connection pattern, as shown in Fig 3.6c.

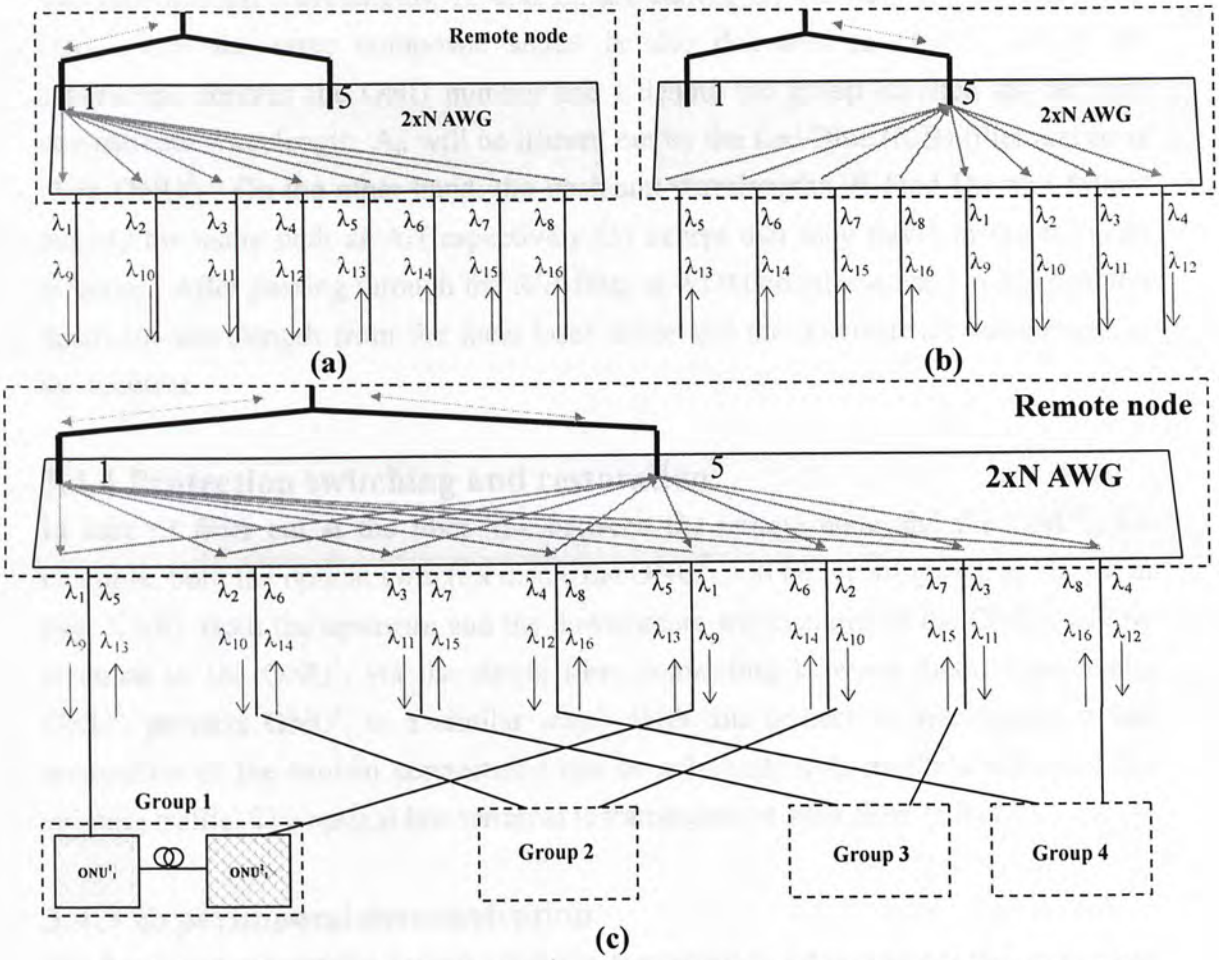


Fig. 3.6 (a) Wavelength distribution in AWG due to input ports 1 (b) Wavelength distribution in AWG due to input ports 5 (c) Group formation due to lightpath from 2 input ports

3.4.3.3 Realization of optical network unit (ONU)

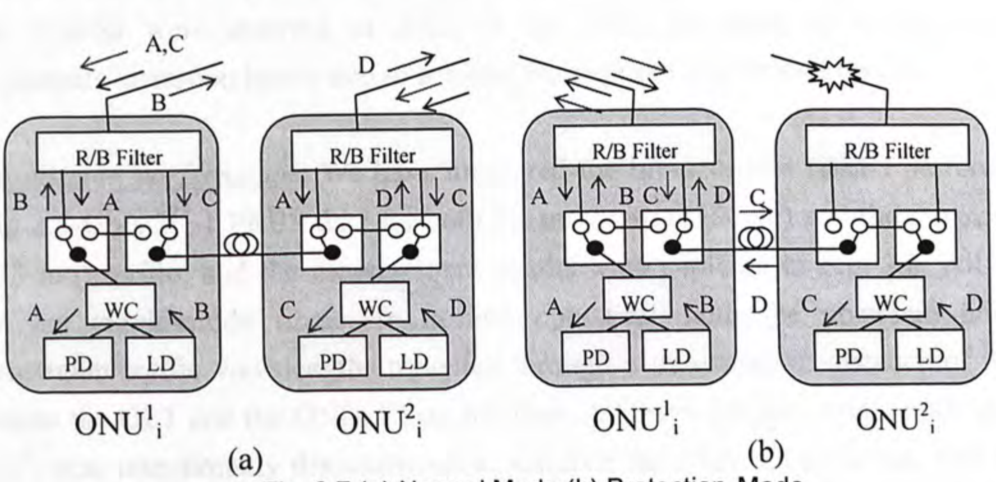


Fig. 3.7 (a) Normal Mode (b) Protection Mode

Fig. 3.7(a) illustrates the internal structure of the ONUs under normal operation mode. The downstream wavelengths, A_i and C_i, are carried on the fibre link connected to ONU^1_i and the same composite signal is also delivered to ONU^2_i, where the superscript denotes the ONU number and i denote the group number. Its destined downstream wavelength, A_i, will be filtered out by the Red/Blue (R/B) filter and so is C_i in ONU^2_i . On the other hand, the upstream wavelengths, B_i (and D_i) will follow exactly the same path as A_i (respectively C_i) except that they travel in the opposite direction. After passing through the R/B filter, a WDM coupler is used to separate the upstream wavelength from the local laser diode and the downstream wavelength to the receiver.

3.4.4 Protection switching and restoration

In case of fiber cut at the fiber link between the remote node and the ONU^2_i, for example, both the optical switches inside the ONU^2_i will be reconfigured, as shown in Fig. 3.7(b). Both the upstream and the downstream wavelengths of the ONU^2_i will be rerouted to the ONU^1_i via the single fiber connecting between them. Conversely, ONU^2_i protects ONU^1_i in a similar way. With this protection mechanism, a fast restoration of the broken connections can be achieved, with minimal effect on the existing traffic. The optical line terminal is transparent to such fiber failure.

3.4.5 Experimental demonstration

We have experimentally investigated the transmission performance and protection switching of our proposed network. The experimental configuration is similar to Fig. 3.4 and a pair of ONUs, as shown in Fig. 3.7, was implemented. The data rate for both the upstream and the downstream channels is 2.5-Gb/s. A 16×16 AWG with 100-GHz channel spacing and an FSR of 12.8nm was used for the remote node. At the ONUs, each Red/Blue filter had a bandwidth of about 18 nm in each passband. On the OLT side, EDFAs were inserted in front of the AWG in order to compensate the components' insertion losses and to achieve the required transmitted power.

Transmission performance: We have measured the bit-error-rate (BER) performance using 2.5-Gb/s 2^{23}-1 PRBS data for both the upstream (1550nm) and the downstream (1553 nm) traffic; and the measurement results were depicted in Fig. 3.8. All fibers used are single-mode fibers. In normal operation, both the upstream and the downstream traffic wavelengths travelled through a transmission distance of 20 km between the OLT and the ONU. Then, the fiber link between the remote node and the ONU^1_i was intentionally disconnected to simulate the fiber cut scenario. The single piece of fiber connecting the two ONUs was 2 km. In all cases the measured receiver sensitivities at 2.5-Gb/s varied from –31.5dBm to –32.6dBm. The small (<1 dB) induced power penalty was mainly due to chromatic dispersion.

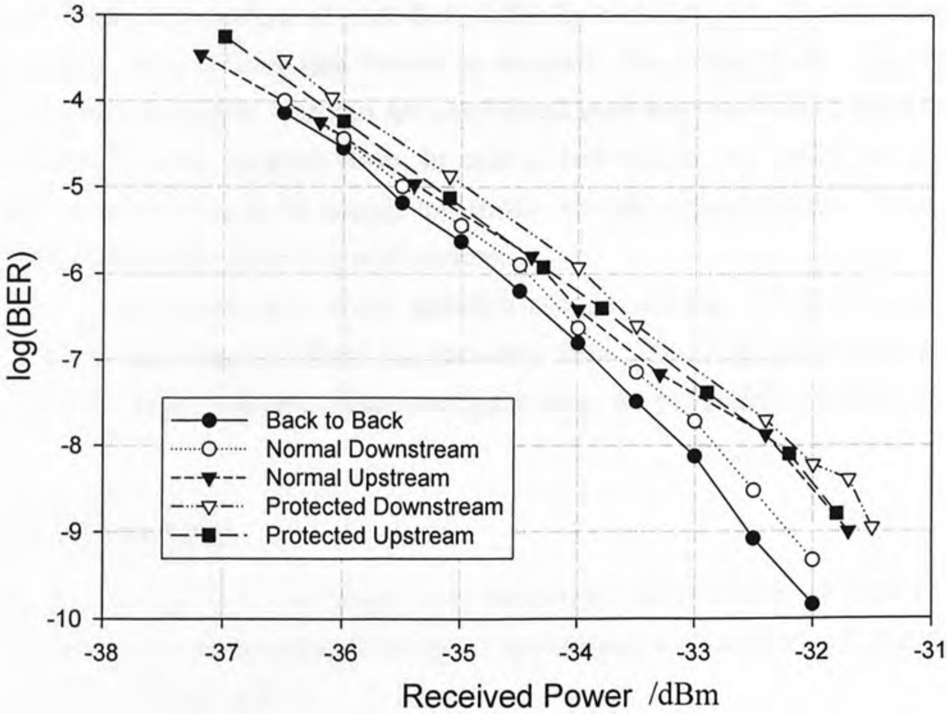


Fig. 3.8 BER performance of Enhanced GPA scheme

Switching/Restoration Time: We have also measured the switching time or the restoration time in case of the simulated fiber cut between the ONU^1_i and the remote node. The optical powers of the downstream signals from the remote node and from the ONU^2_i were monitored and the result was shown in Fig. 3.9. The lower waveform showed the downstream signal from the RN to the ONU^1_i while the upper was the re-routed downstream signal via the ONU^2_i. Normally, the restoration time (range from 50ms to few minutes) is limited by the detection mechanism. Our scheme' switching time was measured to be about 9 ms and this corresponded to the network traffic restoration time.

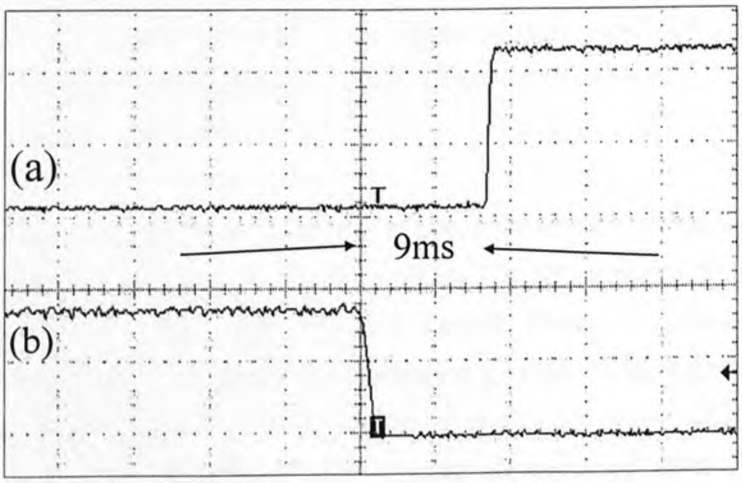


Fig. 3.9 BER performance of Enhanced GPA scheme

The great improvement of switching time of 18ms in GPA is due to the different default optical switch configuration. In the GPA scheme, under normal condition, optical switches are configured such that traffic for adjacent node is not rerouted. And traffic start to reroute after link failure is detected. But in the EGPA scheme, under normal condition, optical switches are configured such that traffic for adjacent node is start to reroute to the adjacent node. In case of link failure, the optical switch of the affected node only needs to accept the traffic for the adjacent node. Thus, the re-routing time after link detection is eliminated.

SONET in metro area has been standardized to provide 99.999% uptime and availability. It also requires 50ms for recovery time. Therefore, the recovery time of 9ms in our protection scheme is fast enough to meet the practical requirement.

3.5 Conclusion

In this chapter, we have proposed two protection architectures in passive optical network. We have gone through the group protection architecture and the enhanced group protection architecture.

We have established a group protection concept. Duplicating and redistributing wavelengths in different ports at the remote node can introduce many group possibilities. We have demonstrated the wavelength duplication with AWG input port separation with half free-spectral range. Wavelengths are grouped in a group of four and shared between two access network nodes.

We have demonstrated this group pattern concept in two protection schemes. Protection architecture in passive optical network has been difficult to design. Prompt restoration with short restoration time, low equipment cost, automatic protection switching without manual intervention, minimum maintenance efforts by using all-optical are difficult criteria to meet at the same time in protection architecture in access network. We have proposed two novel group protection architecture based on this new group pattern concept.

In the next Chapter, we propose another network architecture called Cone Protection Architecture based on the group pattern concept. Group concept in Chapter 3 and Cone in Chapter 4 are some basic building blocks. Group concept focuses on the wavelength-sharing and provisioning on different groups. It also produces different clustering on end-user node. Cone can be one of the nodes in the cluster. These two techniques can be used together to build a great diversity of networks with multi-wavelength capability.

Chapter 4

A Novel Cone Protection Architecture (CPA) Scheme for WDM Passive Optical Access Networks

4.1 Introduction

Thanks to the recent optoelectronic technology advances, we expect the application of wavelength-division multiplexing (WDM) in passive optical networks (PON) as a promising approach to meet the ever-increasing bandwidth demand from enterprises and households. Even though WDM-PON [28] have been extensively studied throughout the past decade for last mile applications, little work has been done to enrich the protection capability in this domain [29]. In the previous chapter, we have demonstrated a set of protection schemes. In this chapter, we will introduce another network topology, Cone, to build a hierarchical access network.

In this chapter, we propose and investigate a new family of network architecture, called Single-sided Cone Protection Architecture (SS-CPA), so as to integrate and extend the capability to protect against link failure between the RN and the ONUs, as well as that between the RN and the OLT simultaneously. It not only provides short restoration time of 9ms by automatic switching, but also offers a simple and low-cost solution. All possible disturbance to the existing traffic is negligible.

Chapter 4

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4.1 Introduction

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4.2 Single-side Cone Protection Architecture (SS-CPA)

4.2.1 Network topology of SS-CPA

Our proposed SS-CPA architecture for passive optical networks is shown in Fig. 4.2. The remote node comprises one $2\times N$ array-waveguide grating (AWG) to route different wavelength channels to the N different ONUs.. The value of N is chosen to be an even number. Two fibers, denoted as F_1 and F_2 in Fig. 4.2, is connected from the OLT to two adjacent input ports of the AWG, at the RN. Each ONU(i) (for $i=1,..N$) is connected to the i^{th} output port of the AWG at the RN by a piece of optical fiber, denoted as L_i. A piece of protection fiber, denoted as $P_{i,(i+1)}$, is connected between the ONU(i) and the ONU($i+1$), except that the $P_{N,1}$ will be connecting ONU(1) and ONU(N) to close the ring. The resultant network topology can be visualized as a three-dimensional cone structure as shown in Fig. 4.2.

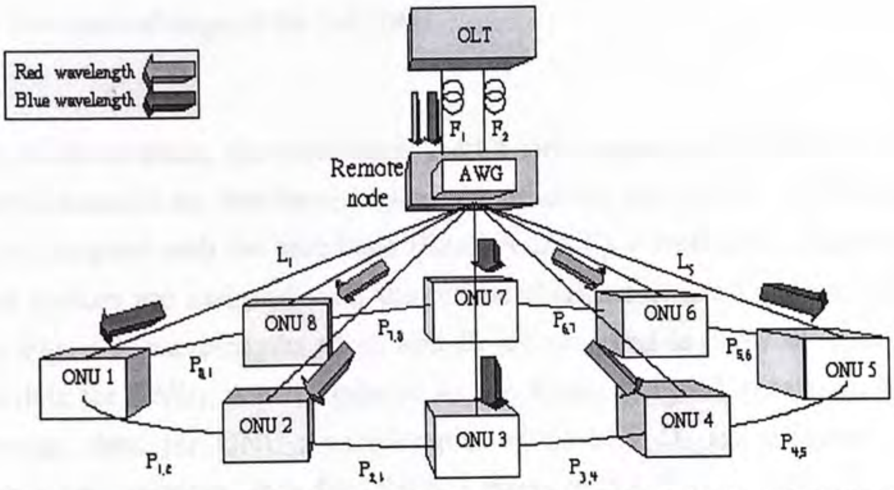


Fig. 4.2. Proposed Single-side Cone Protection Architecture for WDM-PON for 8 ONUs

4.2.2 Wavelength assignment of SS-CPA

In order to make the best use of passive routing property of the low-cost components, special wavelength assignment scheme has to be employed. Fig.4.3 illustrates the wavelength assignment plan. For a network with N ONUs, four wavebands labelled as bands A, B, C and D are sectored in the C-band ITU-T grid. For each waveband, $N/2$ wavelengths are utilized. Bands A and B are selected from the blue wavelength band (1531.94-1542.94nm) whereas the rest are chosen from the red wavelength band (1547.72-1558.98nm).

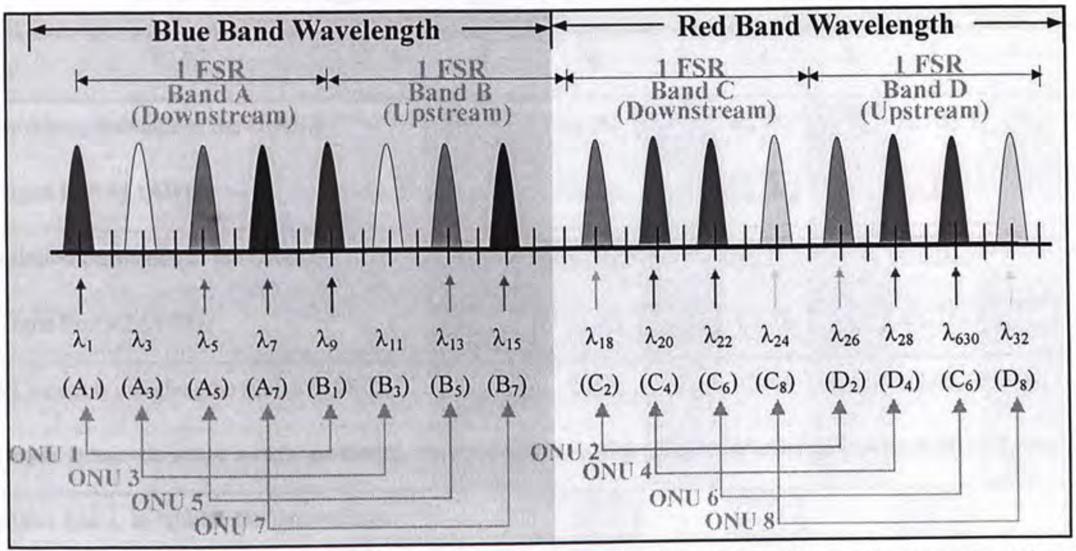


Fig. 4.3. wavelength assignment plan for N=8. Note λ_j, (for j=1,..,32) are the wavelength grid indices, and {A_k, B_k, C_k, and D_k} are the data wavelength channels assigned to the ONUs. FSR stands for free-spectral range of the *2×N AWG*.

Two sets of downstream (in wavebands A&C) and upstream (in wavebands, B&D) wavelength channels are interleaved with each other for the ONUs. ONUs with odd indices are assigned with the blue band (Band A and B) wavelengths, whereas ONUs with even indices are assigned with the red band (Band C and D) wavelengths. As shown in Fig. 4.3, wavelengths of A_1 and B_1 are assigned to carry downstream and upstream data for ONU_1; wavelengths of A_3 and B_3 are assigned to carry downstream and upstream data for ONU_3; wavelengths of C_2 and D_2 are assigned to carry downstream and upstream data for ONU_2. Generally, for ONU i (where i is an odd number), A_i and B_i are assigned to carry its downstream and upstream data respectively. For ONU i (where i is an even number), C_i and D_i are assigned correspondingly.

In order to achieve this wavelength assignment, special fiber connection pattern must be designed. And it is described in the next section for a WDM-PON with eight ONUs.

4.2.3 Realization of remote node

Under normal operation, the downstream wavelengths A_i (for i is odd) and C_i (for i is even), destined for the ONU(i)s are carried via fiber F_1, AWG and fiber L_i. Due to the presence of the additional fiber feeder, F_2, the same WDM downstream signal is also delivered to the respective adjacent ONU($i+1$)s, according to the channel-shifting input-output property of the AWG, as illustrated in Table 4.1.

Table 4.1 Wavelengths Routing path in AWG remote node for 2×8 SS-CPA

I	1	2	3	4	5	6	7	8
Transmission passbands to the ONU(*i*)	$\boxed{A_1, B_1}$	$A_2, B_2,$	$\boxed{A_3, B_3,}$	$A_4, B_4,$	$\boxed{A_5, B_5,}$	$A_6, B_6,$	$\boxed{A_7, B_7}$	$A_8, B_8,$
From Input Port #1 (AWG)	C_1, D_1	C_2, D_2	C_3, D_3	$\boxed{C_4, D_4}$	C_5, D_5	$\boxed{C_6, D_6}$	C_7, D_7	$\boxed{C_8, D_8}$
Transmission passbands to the ONU(*i*)	$A_2, B_2,$	$\boxed{A_3, B_3,}$	$A_4, B_4,$	$\boxed{A_5, B_5,}$	$A_6, B_6,$	$\boxed{A_7, B_7,}$	$A_8, B_8,$	$\boxed{A_1, B_1,}$
From Input Port #2 (AWG)	$\boxed{C_2, D_2}$	C_3, D_3	$\boxed{C_4, D_4}$	C_5, D_5	$\boxed{C_6, D_6}$	C_7, D_7	$\boxed{C_8, D_8}$	C_1, D_1
Down/Upstream wavelengths routed to ONU(*i*):	A_1/B_1	C_2/D_2	A_3/B_3	C_4/D_4	A_5/B_5	C_6/D_6	A_7/B_7	C_8/D_8
(wavelengths in brackets will be used for protection)	(C_2/D_2)	(A_3/B_3)	(C_4/D_4)	(A_5/B_5)	(C_6/D_6)	(A_7/B_7)	(C_8/D_8)	(A_1/B_1)
When fiber link L_i is broken, the intermediate ONU that the respective up/downstream wavelengths for ONU(*i*) are routed from:	8	1	2	3	4	5	6	7

*Note: The wavelength grids which contain an assigned wavelength channels are marked with the boxes.

Thus, with the wrap-around spectral periodicity property of the AWG, at any particular ONU, two downstream wavelengths, $\{A_i, C_{(i+1)}$; for i is odd$\}$ or $\{A_{[(i+1) \bmod N]}, C_i$; for i is even$\}$ can be received. Similarly, the respective upstream wavelengths $\{B_i, D_{(i+1)}$; for i is odd$\}$ or $\{B_{[(i+1) \bmod N]}, D_i$; for i is even$\}$, which travel exactly the opposite path as their downstream signals, can be supported. Thus, two up- and downstream wavelength pairs are assigned to each ONU, for which one is for normal operation while the other is for protection purpose, as illustrated in Table 4.1.

Let's consider a RN with N(=8) in Fig. 4.4. A_1, C_2 and A_3, which are the downstream wavelengths for the ONU_1, ONU_2 and ONU_3 respectively, travel through the F_1. Meanwhile, C_2 and A_3, which carry the respective downstream data of ONU_2 and ONU_3, would also be delivered to ONU_1 and ONU_2, respectively, from F_2.

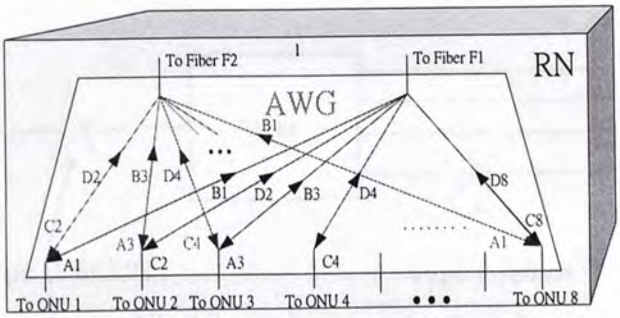
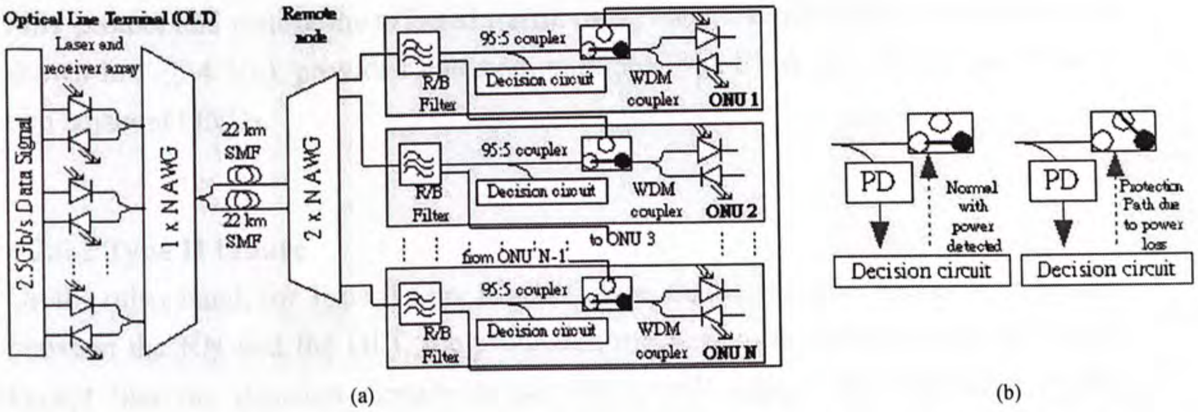


Fig 4.4. The routing path of different wavelength in AWG at RN is illustrated. Routing path in along the F_1 is the normal upstream and downstream path whereas that along the F_2 represents the alternate path to adjacent ONU.

4.2.4 Realization of optical network unit

Fig. 4.5(a) illustrates the structure of the ONUs in our proposed SS-CPA. At the front-end of each ONU, a Red/Blue filter is used to separate the blue wavelengths {A,B} from the red ones {C,D}; while a WDM coupler is further used to separate the downstream wavelength {A} from the upstream wavelength {B} and similar operation applies to wavelengths {C} and {D}. The adjacent ONUs are connected by a piece of protection fiber in a ring form. Under normal operation, there will be no traffic running on the protection fiber links connecting the ONUs.



(a)

(b)

Fig.4.5. (a) SS-CPA with the ONUs; (b) optical switch configuration in normal and protection modes. PD: photodiode for power monitoring

4.2.5 Two types of failures

A 1×2 optical switch is incorporated in each ONU to facilitate the re-routing of wavelength channels to its adjacent connected ONU. There are two types of fiber failures as in Fig.4.6: Type I (link failure(s) between ONU and RN) and Type II (fiber feeder failure between RN and OLT).

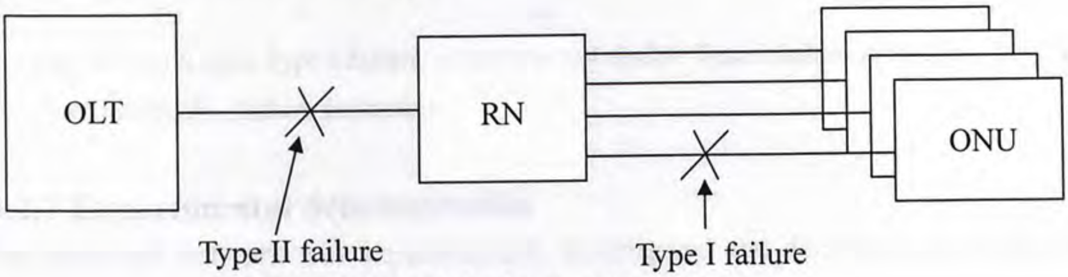


Fig. 4.6 Two type of fiber failures

4.2.6 Protection mechanism against failure

4.2.6.1 Multi-failures of type I failure

For a Type I link failure with ONU(*i*), a drastic drop in power at the decision circuit will be detected. Thus, the optical switch inside the ONU(*i*) will be automatically reconfigured to the protection mode, as illustrated in Fig. 4.5(b). Both the upstream and the downstream wavelengths of the isolated ONU(*i*) will be routed to the ONU $(i+1)$ via the protection fiber connecting between them. Thus, they can still be routed to the OLT via the $(i+1)$th output port and the input port #2 of the AWG at the RN, using the channel-shifting property of the AWG, and also the fiber feeder F_2, as shown in Fig. 4.7(a). With this protection mechanism, a fast restoration of the broken connection can be achieved, without any disturbance on the existing traffic and other ONUs. If there exists more than one Type I link failures, the CPA can still be able to fully protect and restore the affected traffic using the above mentioned mechanism, as shown in Fig. 4.7(b), provided that such multiple Type I link failures do not occur at two adjacent ONUs.

4.2.6.2 Type II failure

On the other hand, for Type II fiber feeder failure, that is, the fiber feeder F_1 is broken between the RN and the OLT, the protection mechanism is similar to that in Type I except that the decision circuits in all ONUs will trigger the respective optical switches simultaneously. The wavelength channels for each ONU will be routed via its adjacent ONU and all wavelengths from all the ONUs will be routed back to the OLT via the fiber feeder F_2, as illustrated in Fig. 4.7(c).

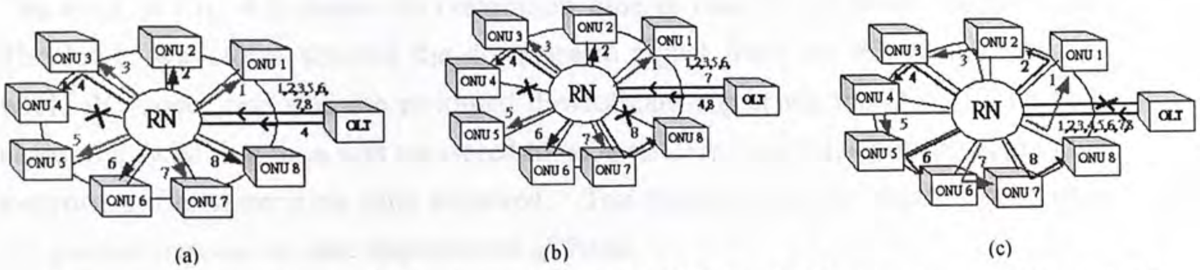


Fig. 4.7 (a) Single Type I failure protection; (b) double Type I failure protection; (c) Type II fiber feeder, F_I , failure protection

4.2.7 Experimental demonstration

Our proposed network was experimentally investigated and demonstrated, using the configuration similar to Fig 4.4. Two ONUs have been implemented to demonstrate the operation principle. 2.5-Gb/s directly modulated DFB laser diodes were used at the OLT and the ONUs. A 16×16 AWG, with 100-GHz channel spacing and a free-spectral range (FSR) of 12.8nm, was used at the RN. It was also connected to the 1×16 AWG, as the channel multiplexer, at the OLT via a pair of 22-km standard single-mode fibers (SMF), as the fiber feeders. The Red/Blue filters used at the ONUs had 18-nm passband at both red and blue bands. A piece of 4-km protection fiber was used to connect the two ONUs. Each ONU was incorporated with one 1×2 optical switch to re-route the wavelength under the protection mode. Under this configuration, the optical power of the downstream and upstream signals from the OLT to the ONU(I) was monitored. Both single Type I and Type II fiber link failures were simulated by intentionally disconnecting the fiber connections. The bit-error-rate (BER) performance under both the normal and the protection path were measured and was depicted in Fig. 4.8. In all cases, the measured receiver sensitivities at BER=10-9 were very close to each other.

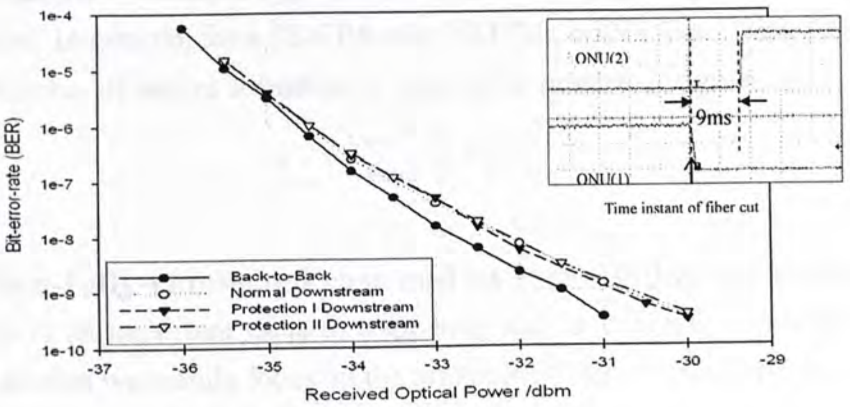


Fig. 4.8 BER performance of SS-CPA

The inset of Fig. 4.8 shows the restoration time in case of the simulated fiber cut. The lower waveform showed the downstream signal from the RN to the ONU(1) while the upper one was the re-routed downstream signal via the ONU(2). In both cases, the switching time was measured to be about 9 ms and this corresponded to the network traffic restoration time achieved. This proves to be far much shorter than the general restoration time requirement of 50ms.

4.2.8 Power budget

Assuming the transmitted powers from the LDs in the ONUs are 0dBm, the receiver sensitivities of the photodiodes at the OLT are –32dBm (at 2.5Gb/s). The required power budget would be around 23dB from OLT to ONU for normal path whereas that for protection path is around 24.5dB. The optical margin is around 7-8 dB. Therefore, a transmission distance of more than 30km can be achieved.

4.2.9 Protection capability analysis

As discussed in the previous section, the proposed SS-CPA scheme can protect against multiple Type I fiber link failures and also Type II fiber feeder failures. For a WDM-PON with 8 ONUs, up to 9 cases of single link failure (8 for Type I, 1 for Type II) and 32 combinations of multiple Type I link failure, or simply altogether 41 scenarios can be protected. In general, for a SS-CPA with *N* ONUs, with *k* Type I link failures occur, the total number of failure scenarios, *S*, that can be protected is given by:

$$S = 1 + \sum_{k=1}^{\frac{N}{2}} \frac{N}{k} C_{k-1}^{N-k-1} \qquad (1)$$

4.2.10 Non-fully-connected case and its extensibility for addition

Scalability is an important issue in a growing and an evolving access network. The previous section we mainly focus on the principle of fully connected case of N ONUs. The network we proposed in this letter actually can extend to non-fully-occupied case.

Consider the case of non-fully-occupied case with N(=8), for we have even number of ONUs (e.g. 4). Only one more red/blue filter at the remote node is needed to separate the red/blue stream so as to adapt to the proposed protection scheme. Therefore, in case 2 more subscribers are needed as shown in Fig. 4.9. In view of this, the proposed network design is robust towards the increasing number of users.

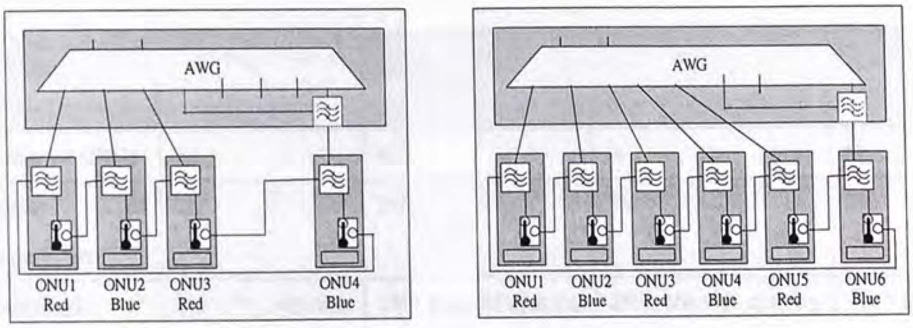


Fig. 4.9. (a) The special arrangement of incomplete ONU is shown. Only 1 additional Red/Blue filter added in RN is required (b) The upgrade is shown on the right which no modification is needed to all existing components.

4.2.11 Scalability

Apart from this, network design is robust towards upgradeability. Almost no components need to be replaced when the number of subscribers increases significantly. Suppose our original network targets only for 32 ONUs with a 2x32 AWG. The network can be upgraded to support 64 ONUs by simply replacing the AWG from 32 ports to 64 ports. The only remark for the initial wavelength selection is that each band should be selected to cover with m FSR, where m is an integer and relates to the increase in the number of ONUs to be supported.

4.2.12 Summary

We have proposed a novel Single-Sided Cone Protection Architecture (SS-CPA) for WDM-PONs. By incorporating simple optical switches and filters into the ONUs, and by connecting ONUs in the star-ring structure, full-transmission protection capability in local access can be achieved. Thus the isolated ONUs can still communicate with the OLT in case of any fiber cut in the PON with minimum disturbance to its neighborhood.

4.3 Comparison between GPA and SS-CPA scheme

4.1 Resources comparison

In order to facilitate our comparison between GPA and CPA scheme, we focus on the access network with N ONUs. As shown in Table 4.2, GPA can provide bidirectional protection capability with negligible increase in resource when it is compared with the conventional WDM PON. EGPA, which has similar protection capability with GPA, has reduced the use of one fiber link and N couplers. EGPA has also improved the protection recovery time from 18 ms to 9 ms. For CPA, the optical switches and the couplers is further saved at the expense of more fiber links required. But these additional resources make the protection capability much stronger as shown in Table

4.3.

	Conventional WDM PON	GPA	EGPA	CPA
Number of ONUs	N	N	N	N
Number of wavelengths	2N	2N	2N	2N
Wavelength range	2N * channel spacing of AWG	2N * channel spacing of AWG	2N * channel spacing of AWG	4N * channel spacing of AWG
AWG	1 x N ports	1 x (N/2) ports	2 x N ports	2 x N ports
Upstream /Downstream Wavelength separation	No restriction	1 FSR of AWG	1 FSR of AWG	1 FSR of AWG
Number of fibers between OLT and RN	1	2	1	2
Number of fibers between ONUs and RN	N	(3/2)* N	(3/2)* N	2N
Additional Resources in RN	No	N+1 (1x2 coupler)	1 (1x2 coupler)	No
Number optical switches	No	2 optical switches	2 optical switches	1 optical switches
Protection recovery time	No protection	18 ms	9 s	9 ms
Receiver sensitivity	-31.5 dBm (Depends on receiver)	-31.5 dBm	-31.5 dBm	-30.5 dBm

Table 4.2 Resource comparison between GPA, EGPA and CPA schemes

4.2 Protection capability comparison

As shown in the Table 4.2, for both GPA and EGPA schemes, each ONU is protected by one adjacent ONU according to the group protection concept. For CPA, the protection capability can be extended to make each ONU be protected by one or more adjacent ONUs. Secondly, GPA and EGPA mainly focus on protecting the fiber links between RN and ONUs while CPA focuses on the link between the RN and OLT, in addition. CPA is clearly a much stronger protection access network. The tradeoff is surely on the cost of the additional resources and the complexity.

	GPA	EGPA	CPA
Protection method	Each ONU is protected by one adjacent ONU without redundant fibers	Each ONU is protected by one adjacent ONU without redundant fibers	Each ONU is protected by one ore more adjacent ONUs without redundant fibers
Scheme Complexity	Simple	Simple	Comparatively complicated
Type of protection	Protect between RN and ONUs	Protect between RN and ONUs	Protect between RN and ONUs; between OLT and RN
Multi - failure	YES	YES	YES
Scalability	Scalable with the same topology	Scalable with the same topology	A family of CPA schemes available with topology variations

Table 4.3 Protection capability comparison

4.4 Concluding remarks

In this chapter, we have proposed Single-Sided Cone Protection Architecture (SS-CPA) for WDM-PONs. By incorporating simple optical switches and filters into the ONUs, and by connecting ONUs in the cone structure, full-transmission protection capability in local access can be achieved. Thus the isolated ONUs can still communicate with the OLT in case of any fiber cut in the PON with minimum disturbance to its neighborhood.

In the next chapter, we will demonstrate the possibility of physical layer data-sharing by further exploding the the connection pattern in multicast scheme.

Chapter 5

Multi-wavelength Multicast Network in Passive Optical Network

5.1 Introduction

As multimedia technologies become more and more popular, efficient information dissemination to thousands of users covering from local to wide area is indispensable. Recent advances in photonic technologies, such as wavelength division multiplexing (WDM), have made optical communication a promising choice to meet the increasing demand for higher bandwidth. Broadcasting in ATM-PON, where the same piece of information is delivered from the optical line terminal (OLT) to all optical network units (ONUs), lacks security and selection flexibility. Multicast, with implementation mostly done in the medium access control (MAC) or higher network layers [29], can solve the flexibility problem but will make the network protocol more complicated or induce unacceptable high-cost in access networks. Typical multicast applications including video lectures, multi-party conferencing and distributed database updates may actually involve a regional distribution of data packets. Thus, effective groupings of bandwidth with re-configurable flexibility seem to be able to solve the dilemma by bridging the gap between all-node broadcast and arbitrary-destination multicast.

5.2 Organization of this chapter

In this chapter, we propose a set of multicast network architecture by using the wavelength-selection power in OLT and duplication in RN.

In section 5.3, we investigate a new data sharing multicast network. The flexibility of the multicast group is rather low, but the concept in providing an advantage in high-speed, all-optical switching, robust, wavelength spectrum-packed features are well described.

In section 5.4, we propose an architecture called Re-configurable Multicast Network with much enhancement in flexibility. Given a particular connection pattern, ONUs can be grouped into different multicast groups to share data channels. OLT can select the multigroup by using different wavelengths. In this sense, the group selection and switching mechanism is actually centralized at the OLT. In order to generalize the connection pattern, a second level of re-configuration is added in the remote node. Not only the multicast group be selected by the wavelength used in OLT, but multicast group combination also increases to incredibly much flexibility by changing the connection pattern directly.

This powerful two level reconfiguration makes the connection pattern and duplication principle to be extra-ordinary tools for data sharing access network.

5.3 Simple Group Multicast Network (SGMN) scheme

5.3.1 Network design principle

Fig. 5.1 shows our proposed network architecture with N ONUs. Eight ONUs are considered here as an example to facilitate our illustration. Both the remote node (RN) and the ONUs comprise FBGs to handle the routing of point-to-point and multicast data streams. An mxm array-waveguide grating (AWG) at remote node is used to route the wavelength channels to the ONUs, where ($m=N*4/3$). The OLT is connected to the input port of the R/B filter at the remote node after the feeder fiber. Each ONUi, where the subscript i denotes the ONU number, is connected to the ith output port of AWG.

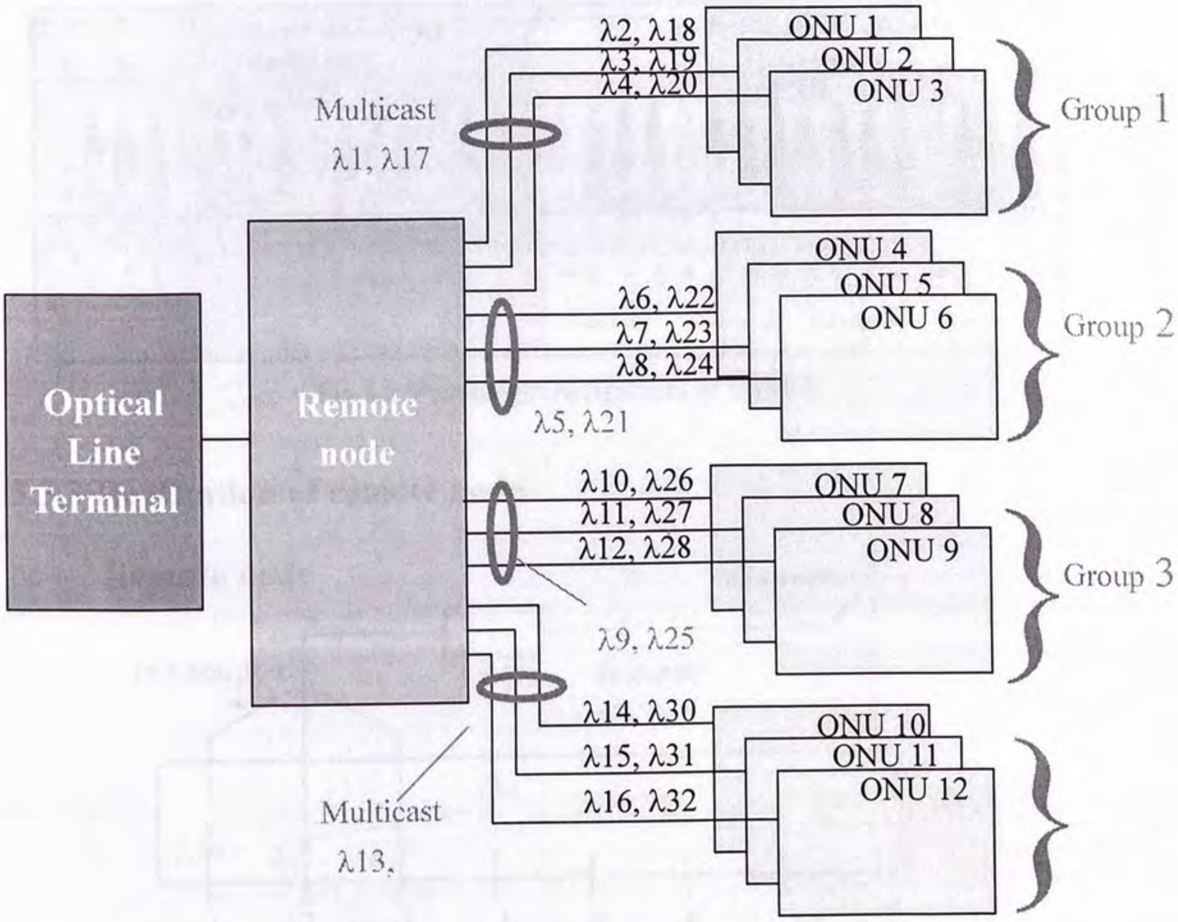


Fig 5.1 Proposed architecture of Simple Group Multicast Network (SGMN)

5.3.2 Wavelength assignment of SGMN

To support such a multicast scheme, a novel wavelength assignment plan is proposed as follows. ONUs from the access network is grouped into a group of 3 ONUs. M (=3) wavelengths in the red band from ITU-T C-band are allocated for downstream data of normal traffic, whereas m wavelengths in the blue band from ITU-T C-band are allocated for upstream data of normal traffic. 2x(N-m) wavelengths from in the C-band are allocated from multicast data. Fig 5.2 illustrates the wavelength assignment of the 16-port AWG with 100Ghz. λ1 to λ4 and λ17 to λ20 are allocated for Group 1 of ONUs. λ2, λ3 and λ4 are upstream of ONU1,ONU2, ONU3 from Group 1, whereas λ18, λ19 and λ20 are downstream of ONU1,ONU2, ONU3 from Group 1. λ1, λ17 are multicast wavelengths that data signals from OLT can reach all three ONUs of Group 1. As shown in the figure, wavelengths for ONU i are denoted as O_i and multicast wavelengths for ONU i are denoted as M_i. Channel spacing should match with that of the AWG. And all upstream and downstream wavelengths are separated exactly by one free spectral range (FSR) of the AWG, so that they can travel exactly the same path throughout the transmission path.

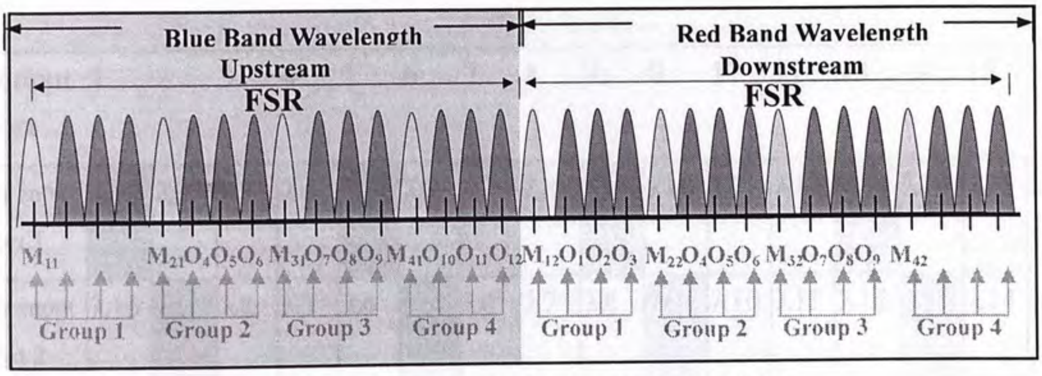


Fig 5.2 Wavelength Assignment of SGMN

5.3.3 Realization of remote node

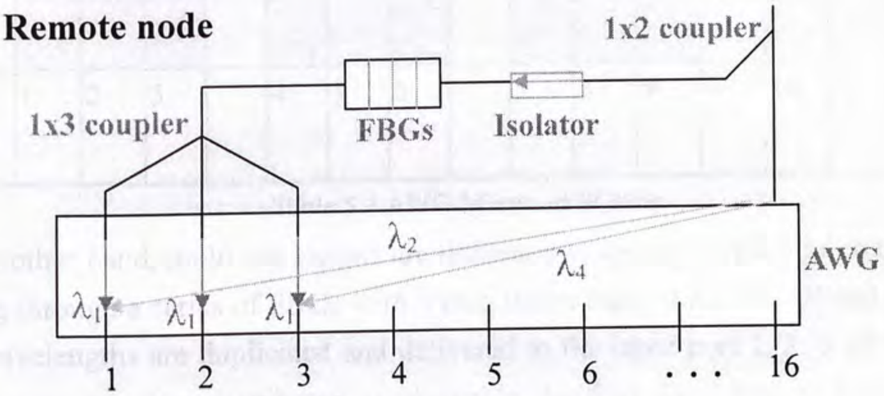


Fig. 5.3 Remote node design of SGNM

As depicted in Fig. 5.2, multicast signals from the OLT will be handled separately by the two arms of 1x2 couplers. Point-to-Point downstream signal is delivered to the input port N (=16) of AWG at remote node after passing through the 1x2 coupler. As shown in the table 5.1, blue band wavelengths (λ1 to λ16) are distributed to the different output ports of AWG. The shaded wavelengths in the row of input port N indicate the upstream wavelengths for the particular ONU written in the fifth row. For instance, λ2 is the upstream wavelength for ONU1 and λ6 is that for ONU4. Similarly, by the wrap-around spectral periodic property, each another wavelength from red band which is separated by one FSR is delivered to the same output port of AWG.

Output Port	1	2	3	4	5	6	7	8	9	0	11	12	13	14	15	16
By input port 1	$\lambda1$	$\lambda2$	$\lambda3$	$\lambda4$	$\lambda5$	$\lambda6$	$\lambda7$	$\lambda8$	$\lambda9$	$\lambda10$	$\lambda11$	$\lambda12$	$\lambda13$	$\lambda14$	$\lambda15$	$\lambda16$
By input port 2	$\lambda16$	$\lambda1$	$\lambda2$	$\lambda3$	$\lambda4$	$\lambda5$	$\lambda6$	$\lambda7$	$\lambda8$	$\lambda9$	$\lambda10$	$\lambda11$	$\lambda12$	$\lambda13$	$\lambda14$	$\lambda15$
By input port 3	$\lambda15$	$\lambda16$	$\lambda1$	$\lambda2$	$\lambda3$	$\lambda4$	$\lambda5$	$\lambda6$	$\lambda7$	$\lambda8$	$\lambda9$	$\lambda10$	$\lambda11$	$\lambda12$	$\lambda13$	$\lambda14$
By input port N	$\lambda2$	$\lambda3$	$\lambda4$	$\lambda5$	$\lambda6$	$\lambda7$	$\lambda8$	$\lambda9$	$\lambda10$	$\lambda11$	$\lambda12$	$\lambda13$	$\lambda14$	$\lambda15$	$\lambda16$	$\lambda1$
Deliver to ONU	1	2	3		4	5	6		7	8	9		10	11	12	

Table 5.1 AWG Matrix of SGNM

On the other hand, multicast signals are delivered to another branch of coupler. After passing through a series of FBGs with transmission band at $\lambda1$, $\lambda5$, $\lambda9$ and $\lambda13$, these four wavelengths are duplicated and delivered to the input port 1, 2, 3 of AWG. The wavelengths are then distributed as shown in the first three row of the table. The shaded $\lambda1$, $\lambda5$, $\lambda9$ and $\lambda13$ indicated that they are shared inside Group 1 (ONU 1, 2, 3), Group 2 (ONU 4, 5, 6), Group 3 (ONU 7, 8, 9) and Group 4 (ONU 10, 11, 12) respectively. They are denoted as M_{11}, M_{21}, M_{31} and M_{41} in the Fig. 5.2. Similarly, by the wrap-around spectral periodicity property, $\lambda17$, $\lambda21$, $\lambda25$ and $\lambda29$ acts as other multicast wavelengths, which are denoted as M_{12}, M_{22}, M_{32} and M_{42}. Therefore, for each output port of AWG that connected to ONU, one upstream, one downstream and two multicast wavelengths can be delivered.

5.3.3 Realization of optical network unit

Fig. 5.4 illustrates the internal structure of an ONU. The downstream wavelength for point-to-point traffic is differentiated by the red/blue filter and is delivered to the red output port. The signal is then received after the WDM coupler. Similarly, the upstream point-to-point traffic is transmitted from the Laser Diode (LD). The signals pass through the 1x2 coupler to the blue port of red/blue filter, in turns, to the remote node. Data signals from multicast wavelengths would be received after passing through the red/blue filter and one of the WDM coupler.

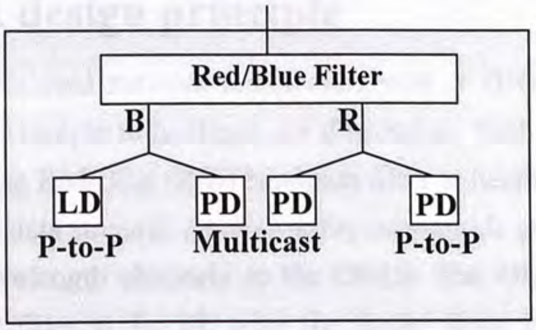


Fig 5.4 Optical Network Unit design in the simple multicast network

5.3.4 Power budget

Assuming the transmitted powers from the LDs in the ONUs are 0dBm, the receiver sensitivities of the photodiodes at the OLT are –32 dBm (at 2.5Gb/s). The required power budget would be around 22dB from OLT to ONU for normal upstream and downstream point-to-point traffic. The power budget for the multicast would around 29dB from OLT to ONU. Therefore, EDFA at the OLT can be added if power is not enough for multicast signals. The optical power margin is around 8-dB. Therefore, a transmission distance of more than 40km can be achieved.

5.4 A multi-wavelength access network with reconfigurable multicast

5.4.1 Motivation

We propose a re-configurable multicast network architecture and wavelength assignment scheme for multi-wavelength access networks. Multicast services can be delivered to groups of optical network units by means of reconfigurable routing of the multicast wavelength.

5.4.2 Background

Typical multicast applications including video lectures, multi-party conferencing and distributed database updates may actually involve a regional distribution of data packets. Thus, effective groupings of bandwidth with re-configurable flexibility seem to be able to solve the dilemma by bridging the gap between all-node broadcast and arbitrary-destination multicast. In this thesis, we propose a novel network architecture that can support C_m^N multicast groups, where N is the output port count of AWGs used and m is the number of ONUs per multicast group.

5.4.3 Network design principle

Fig. 5.5 shows our proposed network architecture with *N* ONUs. Sixteen ONUs are considered here as an example to facilitate our illustration. Both the remote node (RN) and the ONUs comprise Red/Blue (R/B) bandpass filter to handle the routing of point-to-point and multicast data streams. An *N*x*N* array-waveguide grating (AWG) at RN is used to route the wavelength channels to the ONUs. The OLT is connected to the input port of the R/B filter at the RN after the feeder fiber. Each ONU$_i$, where the subscript *i* denotes the ONU number, is connected to the i^{th} output port of AWG.

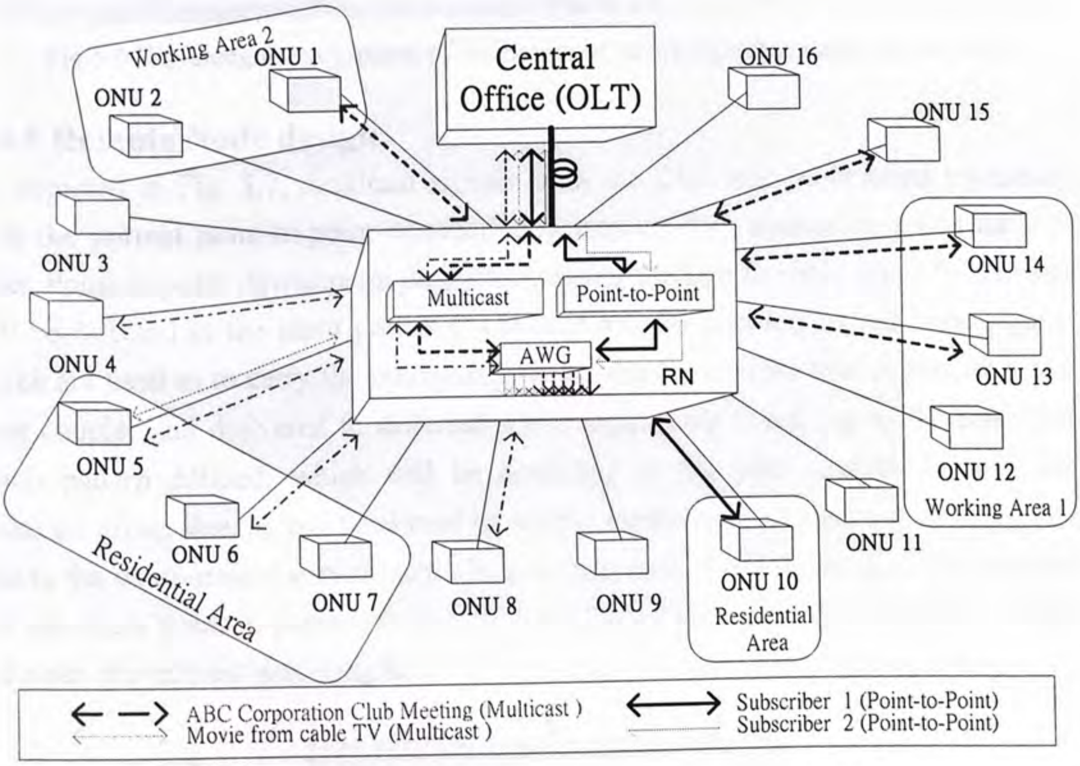


Fig 5.5 Proposed multicast network architecture.

5.4.4 Wavelength assignment

To support such multicast scheme, a novel wavelength assignment plan is proposed as follows. *N* wavelength in the red band are allocated for multicast downstream data, and 2*N* wavelengths in blue band are for point-to-point upstream and downstream signals for *N* ONUs in the access network. Channel spacing should match with that of the *N*-port AWG. Fig. 5.6 illustrates the wavelength assignment of the 16-port AWG with 100GHz. One wavelength from the filter's red band are chosen for the multicast signals while thirty-two wavelengths from the blue band are chosen for ONU's point-to-point upstream and downstream signals. Point-to-point upstream {U_i: for i=1,...N} and downstream {D_i: for i=1,...N}signals are separated by one free spectral range (FSR) of the AWG, so that they can travel exactly the same path throughout the transmission path.

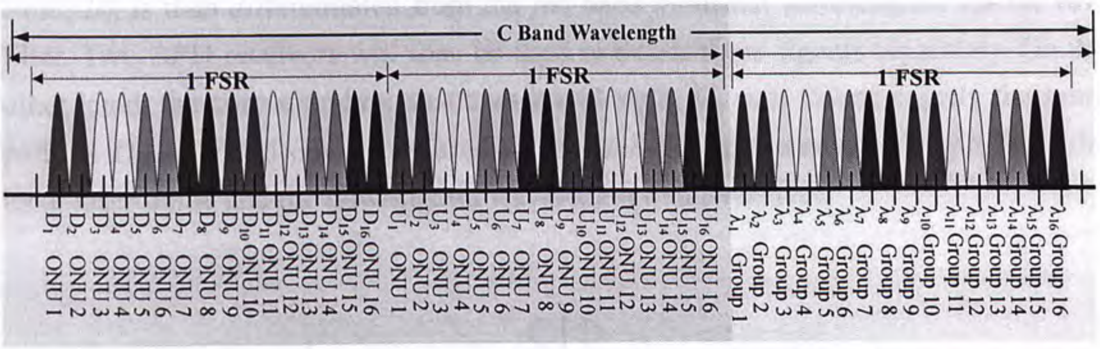


Fig 5.6 Wavelength Assignment of the proposed re-configurable multicast network

5.4.5 Remote Node design

As depicted in Fig. 5.7, multicast signals from the OLT will be handled separately with the normal point-to-point upstream/downstream data signals by using an R/B filter. Point-to-point downstream data after passing through the blue port of R/B filter will be directed to the input port N (=16) of AWG. Its counterpart red band signals which are used as to carry the multicast data are duplicated into four copies by a 1x4 fiber coupler and delivered to different AWG input ports according to the multicast group pattern defined, which will be described in the next section. In fact, the multicast group size, m, can be altered by simply replacing the 1x m coupler at the RN. Due to the wrap-around spectral periodic property, each AWG output port will support one upstream point-to-point wavelength, one downstream point-to-point wavelength and a set of multicast wavelengths.

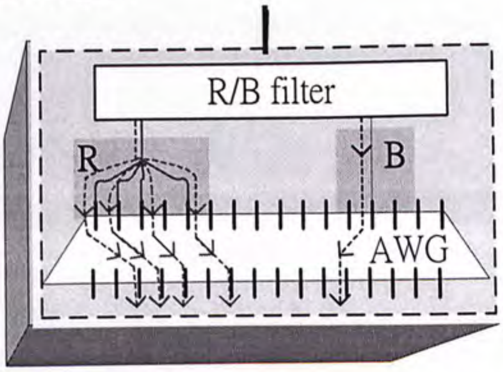


Fig. 5.7 Remote node design in the proposed network

5.4.6 Optical network unit design

Fig. 5.8 illustrates the internal structure of an ONU under normal operation. The downstream wavelength and the multicast wavelength(s) are carried on the fiber link connected to the ONU. Its destined point-to-point downstream wavelength in blue band, D_i, is then differentiated from the red band multicast wavelengths, via the R/B filter. Two APD receivers will then be used to detect these signals separately. On the other hand, the corresponding upstream wavelength, U_i, will follow exactly the same path as D_i. A WDM coupler is used to separate the upstream wavelength from the local laser diode and the downstream wavelength to the receiver.

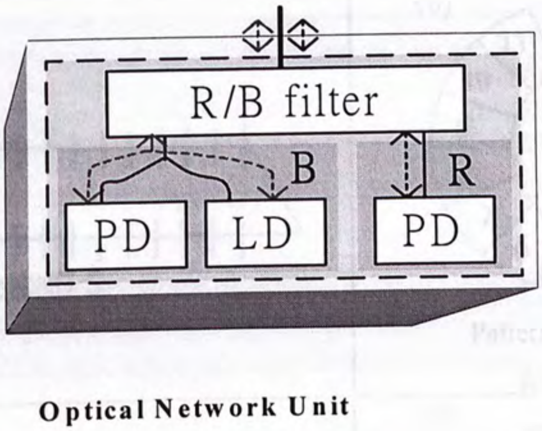
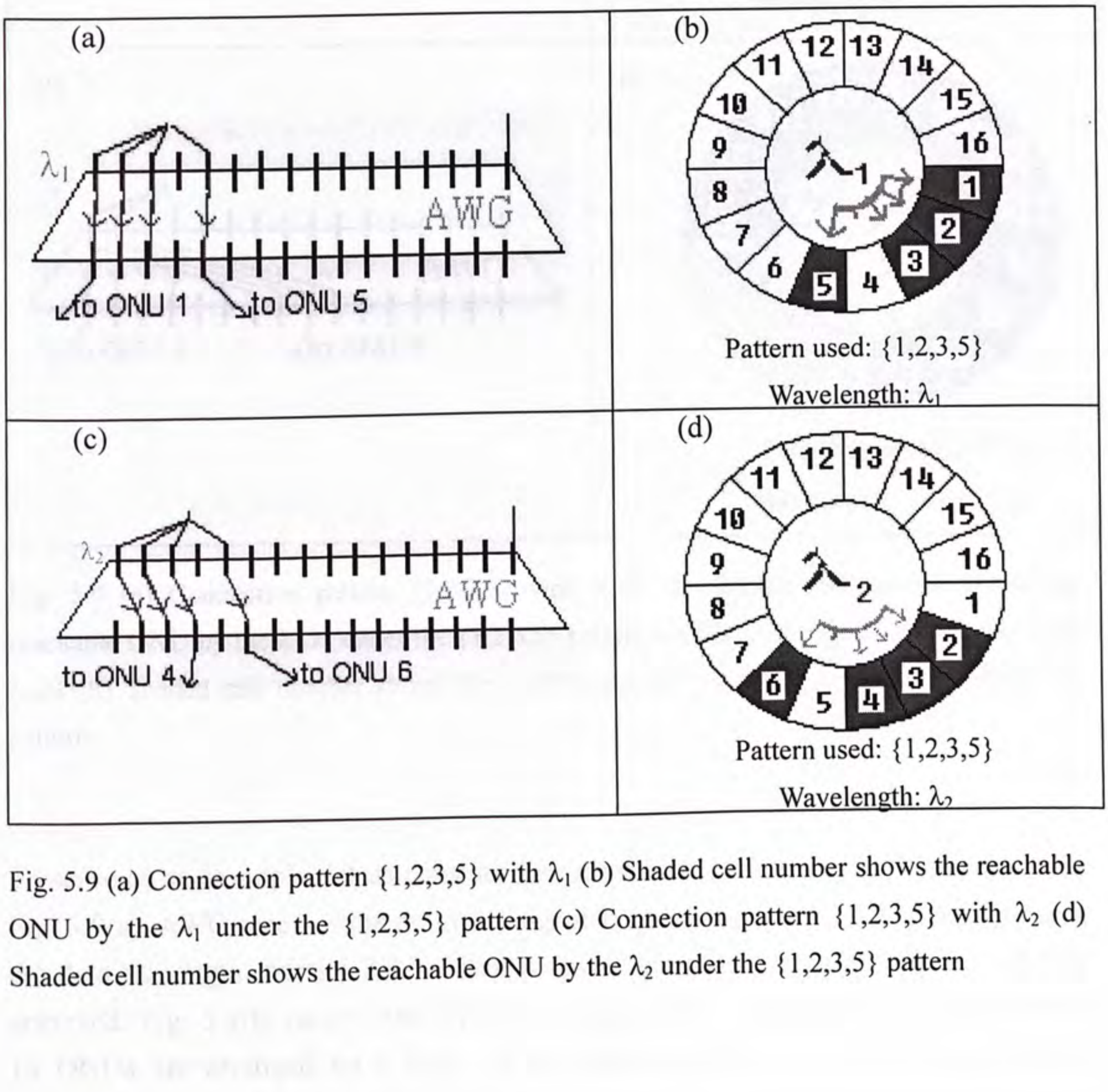


Fig 5.8 Optical network unit design in the proposed network

5.4.7 Multicast connection pattern

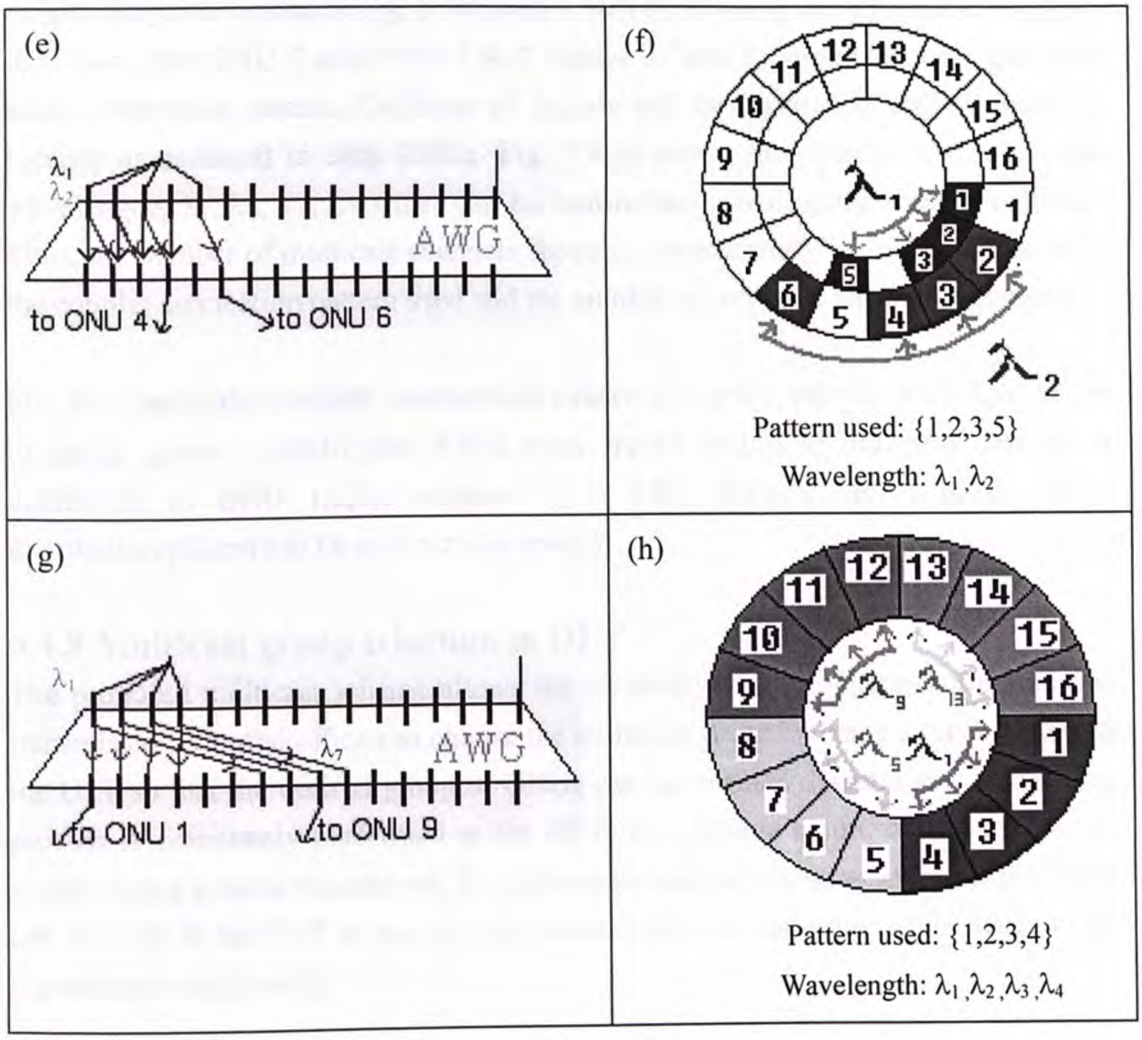
A multicast connection pattern is actually realized by the connection mapping between the 1x*m* coupler and the AWG input port at the RN. We denote the connection pattern as (I_1,I_2,I_3, … I_n), if there is a 1 x *n* coupler, with coupler's output port 1, 2, 3 … *n* connect to AWG's input port I_1, I_2, I_3 … I_n respectively. For instance, connection pattern {1,2,3,5} means the 1x4 coupler connects to AWG's input ports 1,2,3,5 correspondingly, as shown in Fig. 5.9(a).



Pattern used: {1,2,3,5}
Wavelength: λ_1

Pattern used: {1,2,3,5}
Wavelength: λ_2

Fig. 5.9 (a) Connection pattern {1,2,3,5} with λ_1 (b) Shaded cell number shows the reachable ONU by the λ_1 under the {1,2,3,5} pattern (c) Connection pattern {1,2,3,5} with λ_2 (d) Shaded cell number shows the reachable ONU by the λ_2 under the {1,2,3,5} pattern



Pattern used: {1,2,3,5}
Wavelength: λ_1, λ_2

Pattern used: {1,2,3,4}
Wavelength: $\lambda_1, \lambda_2, \lambda_3, \lambda_4$

Fig. 5.9 (e) Connection pattern {1,2,3,5} with λ_1,λ_2 (f) Shaded cell number shows the reachable ONU by the λ_1,λ_2 under the {1,2,3,5} pattern (g) Connection pattern {1,2,3,4} with λ_1,λ_7 (h) Shaded cell number shows the reachable ONU by the λ_1,λ_7 under the {1,2,3,4} pattern

To serve as an example, let us consider the connection pattern {1,2,3,5}, as shown in Fig. 5.9(a). AWG receives the multicast signal λ_1 at input ports 1,2,3,5, and distributes the data via output ports 1,2,3,5. Thus, a multicast group comprises ONU 1,2,3,5 is achieved. Fig. 5.9(b) depicts the ONUs coverage of λ_1 with pattern {1,2,3,5} where 16 ONUs are arranged on a ring. These destined ONUs (ONU 1,2,3 and 5) are indicated as shaded sector. Given the same connection pattern, due to the channel shifting property of AWG, multicast signal λ_2 would distribute the data via the output ports 2,3,4,6, as illustrated in Fig. 5.9(c). And the corresponding ONUs coverage is shown in Fig. 5.9(d).

Fig. 5.9(e) shows the multicast-ring graph for λ_1 and λ_2 for pattern {1,2,3,5}, which is simply the joint version of Fig. 5.9(b) and 5.9(d) by aligning the same ONU together. It is clear that ONU 2 and ONU 3 will receive λ_1 and λ_2 simultaneously under the same connection pattern. Collision of signals will be resulted if only 1 multicast receiver is assumed in each ONUs. Fig. 5.9(g) shows four multicast groups (with wavelengths λ_1, λ_5, λ_9, λ_{13}) that can be transmitted concurrently without collision. Thus, the number of multicast channels supported concurrently is, in fact, depends on the coupler connection pattern used and the number of receivers the ONU equipped.

For any particular coupler connection pattern (consider pattern {1,2,3,5} as an example), given a 16x16 port AWG, there are 16 groups of multicast data (λ_1 is distributed to ONU 1,2,3,5 whereas λ_2 to ONU 2,3,4,6...etc) with the same distribution pattern can be sent simultaneously.

5.4.8 Multicast group selection in OLT

The proposed multicast scheme allows the flexibility of multi-channel simultaneous transmission. Central office can choose the multicast group by using a tunable laser at the OLT so that the desired group of ONUs can be selected dynamically. The tuning process is completely performed at the OLT. The passive nature of RN makes the whole tuning process transparent. To enhance the scalability, an array of tunable laser can be used at the OLT to increase the number of multicast groups that needs to be transmitted concurrently.

5.4.9 Scalability

The proposed multicast network architecture is capable to support a larger number of ONUs by using all available wavelengths in the C-band for the point-to-point wavelength channels while the L-band wavelengths are used as the multicast wavelength channels. The necessary upgrade to the OLT, the RN and the ONUs are simply replacing all R/B filters by L/C filters.

5.4.10 Experimental configuration

The transmission performance and multicast capability of the proposed network were experimentally investigated. The experimental setup, as shown in Fig. 5.10, was implemented. A 16 x 16 AWG with 100-GHz channel spacing and an FSR of 12.8nm were used for the RN. All R/B filters had a bandwidth of about 18nm in each passband.

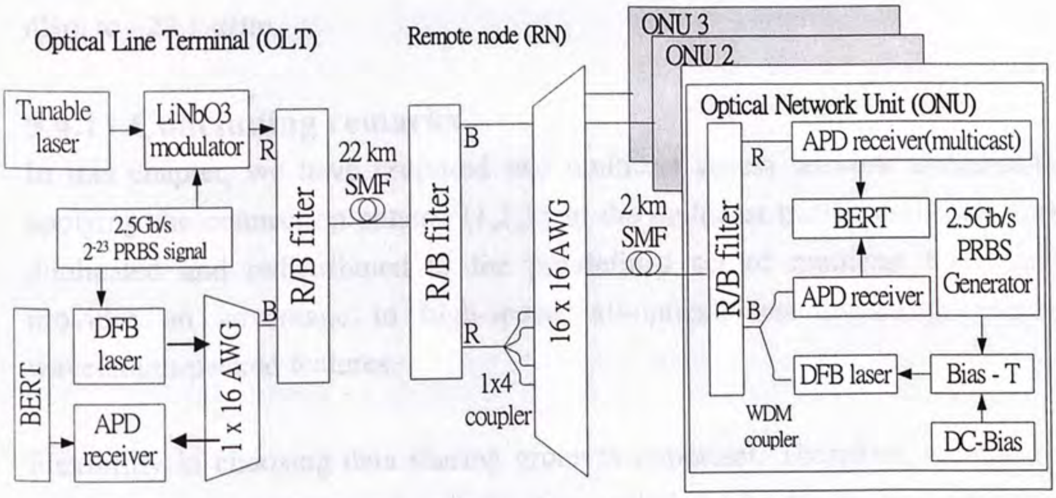


Fig 5.10 Experimental configuration of the proposed re-configurable multicast network

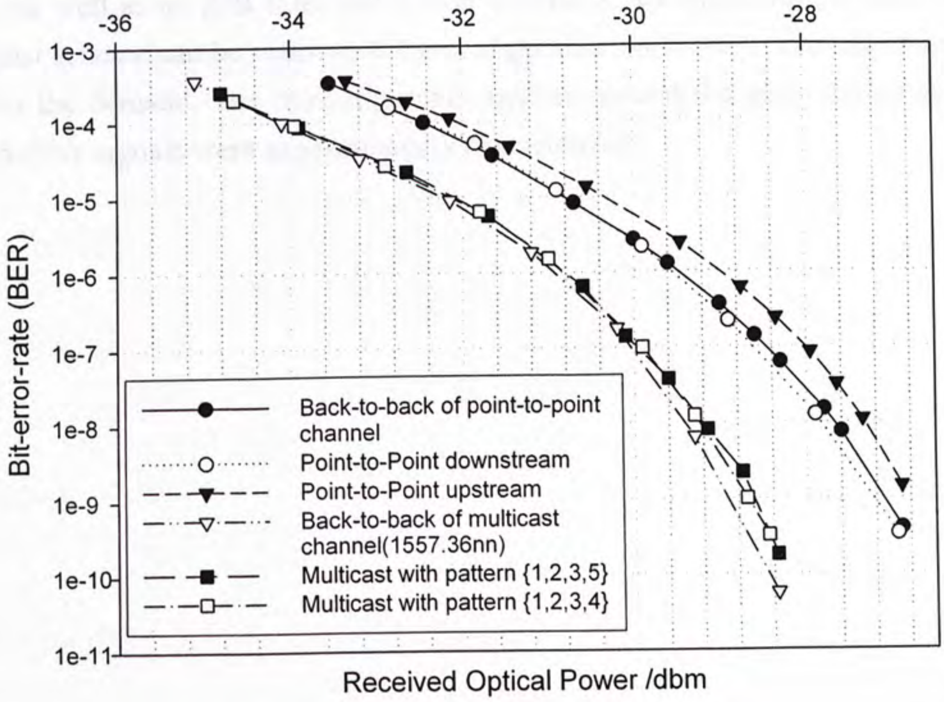


Fig. 5.11. Bit-error-rate measurement results

We have measured the normal point-to-point upstream and downstream bit-error-rate (BER) performance by using 1552.52 nm directly modulated DFB laser diodes (LD) with 2.5-Gb/s 2^{23}-1 PRBS data; and the measurement results were depicted in Fig. 5.11. Measured receiver sensitivities ranged from –27 to –27.3 dBm. 0.3-dB penalty in upstream signal was mainly due to chromatic dispersion. Multicast signal BER performance was also measured. The tunable laser at 1557.36 nm with multicast pattern {1,2,3,5} and 1559.79 nm with pattern {1,2,3,4} were externally modulated by a $LiNbO_3$ modulator using 2.5-Gb/s 2^{23}-1 NRZ pseudorandom binary sequence (PRBS). In all cases, the measured receiver sensitivities at 2.5-Gb/s varied from –28.8 dBm to –29.1 dBm.

5.4.11 Concluding remarks

In this chapter, we have proposed two multicast access network architectures. By applying the connection pattern {1,2,3} in the multicast traffic, multicast traffic are duplicated and redistributed to the pre-defined set of multicast ONU group. It provides an advantage in high-speed, all-optical, fast switching, robust, and wavelength-packed features.

Flexibility in choosing data sharing group is important. Therefore, we make use of both connection pattern and redistribution techniques to design an architecture that can accommodate two level of multicast group reconfiguration. For a network with *N* ONUs, by incorporating an R/B optical bandpass filter and one more receiver at each ONU, as well as an R/B filter and a 1x*m* coupler at the RN, a simple and low cost multicast scheme can be realized. *N* Re-configurable multicast groups can be assigned to meet the demand. The re-configurable mechanism and the transmission aspect of the 2.5-Gb/s signals were experimentally characterized.

Chapter 6

Conclusions

The framework for the protection of optical access network is established.

To start with, the evolution of the network services paradigm is presented. Owing to the requirement difference in different scale of network, discussions on the access and backbone network are separately addressed.

Backbone network design is a big challenge. While it has been evolved to satisfy the high-capacity requirements, the complexity to produce an extensidable mesh topology has been highly increased. Meanwhile, the emergence of different solutions in the protocol layer causes a flooding and incompatibility in technology integration. Those solutions for resource sharing in voice and data grooming and protocol stack efficiency pose a large restriction to other service provisioning. Protection and multicast are the services that we are going to address in this thesis.

Access network design is also a big challenge. Access network evolution is closely related to the service evolution. New services have brought a huge demand in network capacity.

In Chapter 1, we have stated that optical adaptation and protocol layer efficiency are new topics need to be explored. Fast services provisioning such as survivability is still not yet satisfactory.

In Chapter 2, we have reviewed some backgrounds and recent works on the physical layer optical protection architecture. We have reviewed some conventional protection architectures on ATM-PON G.983.1, as well as the self-healing rings in the metro ring networks. Besides, we have also discussed the recent work on star-ring-bus topology for access network.

In Chapter 3, we have proposed Enhanced Group Protection Architecture (EGPA). Without much modification to the existing network, a superior high-speed physical-layer protection mechanism can be achieved. The mechanism is low-cost, automatic and fast.

In Chapter 4, we have proposed a Cone Protection Architecture. Based on the duplication theory and connection pattern, an protection architecture in access network with special landscape adaptation is achieved.

In Chapter 5, we have proposed a set of multicast access networks. By exploring the connection pattern, a rich-set of features can be provisioned in multicast services. From Simple Multi-cast Network Architecture to Fully Re-configurable Multicast Architecture, it demonstrates the bright future of extra-ordinary high-speed data sharing architecture with two-level re-configurability capability.

Network architecture paradigm grows with significant potential in the coming years. This thesis serves as a self-contained document in exploring the framework of the paradigm.

Future work

In the future, we will explore the cone protection architecture in the access network deeper. Scalability, robustness and topology variations with minimized cost are some stringent requirements, which seem to be able to be solved by a family of cone protection architectures. Secondly, we will also incorporate the protection capability stated in the cone architecture into our multi-wavelength multicast network. Furthermore, we will also study the possibility of applying those physical-layer-protection concepts in backbone network. We expect that could be a promising technology in the future.

List of Publications:

1) C.M.Lee, T.J.Chan, C.K.Chan, L.K.Chen, C.L.Lin, "A Group Protection Architecture (GPA) for Traffic Restoration in Multi-wavelength Passive Optical Networks", European Conference on Optical Communications ECOC, paper Th2.4.2, Remini, Italy, Sept 2003.

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