Design of Survivable Wavelength Division Multiplexed Passive Optical Networks

BY

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Abstract

The demand for data bandwidths has been increasing steadily, despite the recent downturn of the telecommunication industry. The current trend is to provide faster and faster transmission speed in access networks and using fiber optics in the access networks is one of the best solutions in terms of the tremendous bandwidths it can provide. Passive optical networks (PONs), has emerged to be one of the most promising approaches for optical access networks. In this thesis, we will present some novel network architectures aiming at providing survivability in PONs.

Protection and restoration is very important in high bitrate transmissions, as a failed link will cause tremendous data loss, thus huge economic loss may result. By adding an extra link between the optical network units (ONUs), we are able to reroute the traffic to protect against a possible fiber break in the network. The network designs features a fast switching speed, so that there will be minimum disruption to the traffic. The smallest number of components is used in the subscriber side, so that the cost of implementation is kept to the minimum as well.

In this thesis, we propose and discuss three network architectures with bidirectional protection capability, and a comparison is made between them. The experimental works done are also be presented and the results will be analyzed.

摘要

訊息的傳播並未因受到通訊業的不景氣影響而持續增長. 相反, 現在的趨勢是給用戶提供更快的接入速度, 當中能提供最高速度的其中一個方案是光纖接入網(Optical Access Network). 無源光網絡(Passive Optical Networks)是一個最有可能實現的光纖接入網方案. 本論文提出了三種可以提供生存能力(survivibility)的方案.

在高速傳送系統中, 保護和恢復(Protection and Restoration)的能力是非常重要, 因爲任何一個光纖出現故障時, 都可能會導致嚴重的數據及經濟上的損失. 我們在基本的無源光網絡上, 加入一些額外的光纖連接光網絡單元(Optical Network Units, ONUs), 以保護有可能出現故障的光纖. 這設計的好處有: 快速的保護速度和簡單的光網絡單元設計, 因此可以用很小的額外資源去提供良好的保護功能.

在本論文中, 我們會提出並討論三個網絡設計, 然後再加以比較. 我們亦會用實驗來分析三個設計的好處與壞處.

Acknowledgement

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Chapter 1

Introduction

1.1. Introduction

Access networks, or sometimes referred to the "last mile" or the "first mile" networks, are currently dominated by copper twisted-wire pair technology in the telecommunication network and coaxial cable technology in the cable television network. Digital Subscriber Line (xDSL) is very successful in telecom operators' network in many parts of the world, while in the United States, cable television (CATV) networks employing the cable modems over their hybrid-fiber coax networks are occupying a major portion of the access network market. However, there is an increased amount of attention in the development of using optical fiber in the local loop (FITL) [1] in recent years, mainly due to the reduction of the cost of optical components and the ever-increasing bandwidth requirement by business and residential users.

The first Fiber-to-the-home (FTTH) network was deployed in the U.S. in 1986 by AT&T [2]. The most common architectures for FTTH at that time were the single star (SS) and the active double star (ADS). Although there were some successful field trials, it has failed to gain much momentum. The reason is mainly down to the cost issue, in which the delivery of digital video and data traffic over fiber is clearly much more expensive and difficult than the existing CATV architecture. Passive optical networks (PONs) were therefore proposed in 1987 to reduce the active components in the network, and a point-to-multipoint architecture was employed. It can economically connect all the optical network units (ONUs) in the subscriber side to the central office (CO). The simplest type is the passive double star (PDS), in which a passive splitter/combiner is used in place of an active remote terminal (RT). PONs save much cost because the feeder fiber and the optical interface at the CO are shared by multiple subscribers. It is also simpler to deploy and manage, as there are no active components in the remote node (RN) between the CO and the subscriber.

Most of the PONs being studied and deployed are time-division multiplexing (TDM) [3] based. In this project, we focused on studying the use of wavelength division multiplexing (WDM) in PONs [5][6]. The main advantages are larger bandwidth, higher security, no ranging effect and easy provision of differentiated services. In addition, we designed several protection and restoration schemes in order to ensure survivability in cases of fiber cut.

1.2. Background

1.2.1. Introduction

The developments in the technologies used in optical communication have been extremely fast. In this section, we will briefly discuss some of the important concepts that are essential to the project. These include passive optical networks, wavelength division multiplexing and arrayed waveguide gratings.

1.2.2. Wavelength Division Multiplexing (WDM)

Wavelength Division Multiplexing [1][2][5][13]is an important concept in today's optical communication world. Using WDM, the optical transmission spectrum is divided into a number of non-overlapping wavelength bands, with each wavelength supporting a single communication channel operating at any bitrate one desires. Thus, by allowing multiple WDM channels to coexist on a single fiber, one can tap into the huge bandwidth of fiber. Terabits per second (Tbs/s) transmissions have been demonstrated using WDM. An implementation of a typical point-to-point WDM transmission system with amplifiers is depicted in Fig. 1.1.

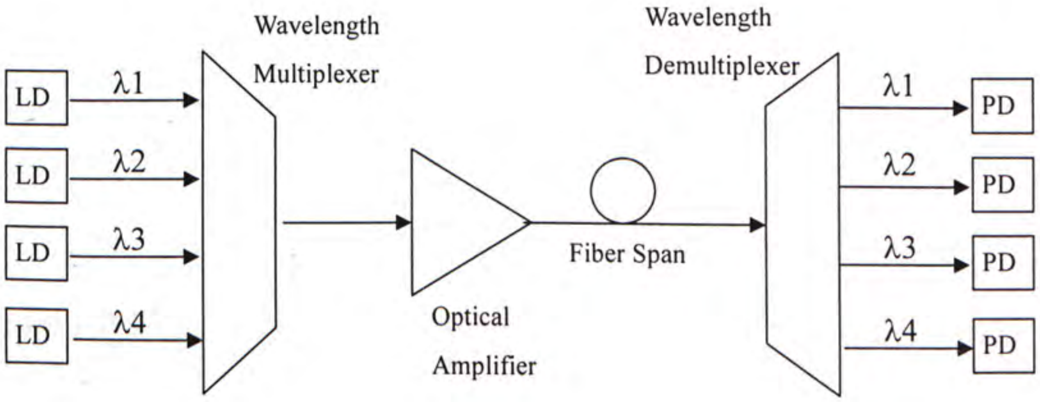


Fig. 1.1 A typical point-to-point WDM transmission system

WDM is an approach that can exploit the huge optoelectronic bandwidth mismatch by requiring that each end-user's equipment operate only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber. There are currently two different WDM standards set by the International Telecommunication Union (ITU):

Dense WDM (DWDM)

In a DWDM, the channel spacing of the WDM channels are usually very condensed, typically values are 50 GHz or 100 GHz. As a result of the dense allocation of channels, a DWDM system requires high precision in different components, such as lasers, filters, multiplexers/demultiplexers, wavelength routers and wavelength converters. Many need temperature control in order to stabilize the wavelength, according to the ITU grid (G.694.1). It has the advantage of high channel count within a single band (C, S or L), which in turn leads to higher channel efficiency. On the down side it is more expensive and some crosstalk issues may arise.

Coarse WDM (CWDM)

Coarse WDM is a relatively new standard set by ITU in 2002 (G. 694.2). The CWDM grid consists of 18 wavelengths, spaced at 20nm apart, from 1270 nm to 1610 nm. The wider channel spacing eliminates the need for the thermoelectric cooler, and thus is much less expensive. It has attracted a lot of attention, particularly in the metro and access networks. There are still limited varieties for CWDM components at this stage, but there are certainly a lot of potential applications, especially in transmission systems up to the 50 km distance.

1.2.3. Arrayed Waveguide Grating (AWG)

Arrayed waveguide grating (AWG)[9][10][15], is also referred to waveguide grating router (WGR). It provides a fixed routing of an optical signal from a given input port to a given output port based on the wavelength of the signal. Signals of different wavelengths coming into an input port will each be routed to a different output port. Also, different signals using the same wavelength can be input simultaneously to different input ports, and still not interfere with each other at the output ports. Therefore, an AWG with N input and N output ports is capable of routing a maximum of N^2 connections, as opposed to a maximum of N connections in a passive-star coupler. Also, because the AWG is an integrated device, it can easily be fabricated at low cost. A simplified AWG structure is shown in Fig. 1.4. [9] It consists of two passive-star couplers connected by a grating array.

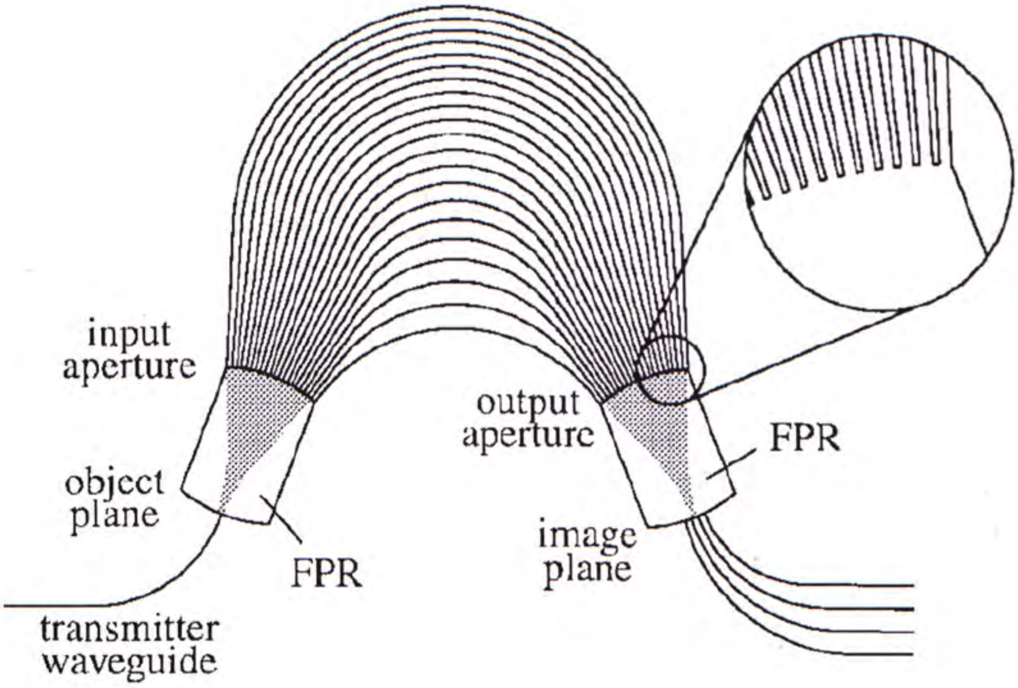


Fig. 1.2 The Arrayed Waveguide Grating (AWG)

Two signals of the same wavelength coming from two different input ports will not interfere with each other in the grating because there is an additional phase difference between the two input ports. The transmission power from a particular input port to a particular output port is maximized when the total phase difference Φ is an integer multiple of 2π. Thus, only wavelengths for which Φ are a multiple of 2π will be transmitted. This leads to the concept of free spectral range (FSR), which means that one input port can pass multiple wavelengths to an output port, provided that they are separated by multiples of FSR. This is illustrated in Fig. 1.3:

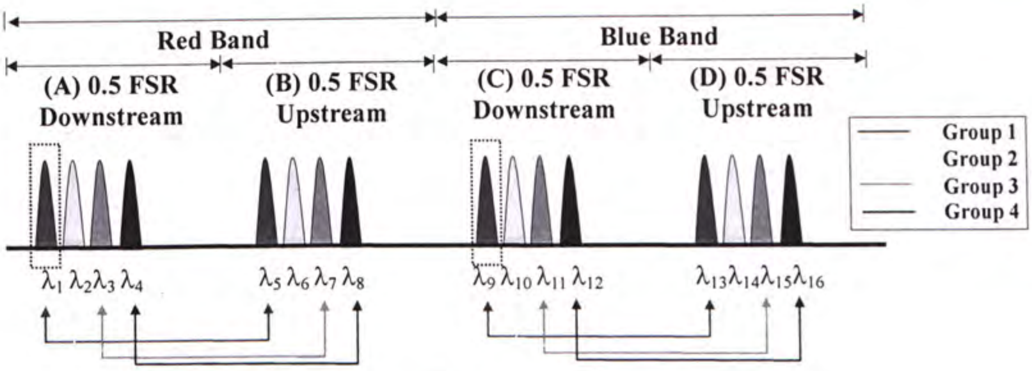


Fig. 1.3 Figure illustrating the FSR of the AWG.

1.2.4. Passive Optical Networks

Passive Optical Networks, or PONs, refer to passive, point-to-multipoint access networks that use small, inexpensive, passive optical splitters. The basic functional blocks are the optical line terminals (OLTs), the remote notes (RNs), the optical network terminals (ONTs) and optical network units (ONUs). A typical example of PON is illustrated in Fig. 1.3.

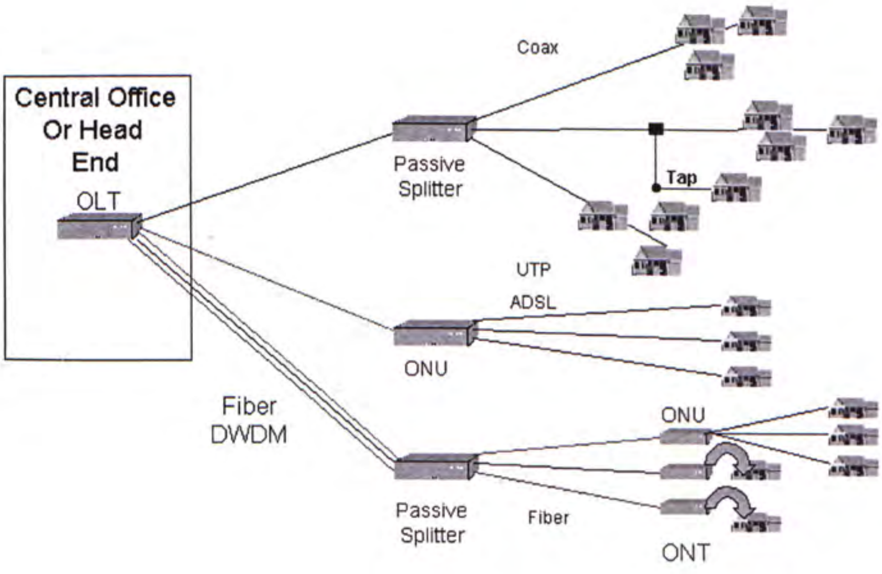


Fig. 1.4 An illustrative example of a PON architecture

The OLT is located inside the operators' central office (CO). It can either generate optical signals, or pass optical signals from an optical crossconnect, broadcasting them downstream through one or more ports. The signals then pass through a passive splitter to the ONU or ONT. The ONU or ONT terminates the circuit at the far end.

An ONT is used to terminate the circuit inside the premises in a Fiber-To-The-Building (FTTB) network, where it will interface signal from the optical fiber to the copper-based inside wire. An ONU is used in a Fiber-To-The-Curb (FTTC) or an FTTH network, in which the fiber terminates at the curb side or at the subscriber's premises.

The RN typically consists of a passive optical splitter that sits in the local loop between the OLT and the ONUs or ONTs. The splitter divides the downstream signal from the OLT at the network edge into several identical signals that are broadcasted to the ONTs/ONUs in the user end. Each OLT/ONU is responsible for determining which data are intended for it, and for ignoring all others.

There are a few types of PON that are being studied. The two most common ones are the ATM-PON (APON) and the Ethernet-PON (EPON), which are both TDM based. APON, (or Broadband PON, BPON) is being developed and standardized by the Full Service Access Network (FSAN) consortium, and later being incorporated into the G.

983.1 recommendation by ITU-T. It employs ATM as protocol in the data link layer, and each ONU will have its own timeslot in receiving the downstream signal and transmitting its upstream data. However, some believe that using ATM in PON has many disadvantages: its lack of video capabilities, complexity and higher protocol overhead. EPON addresses these issues by employing Ethernet in place of ATM. The Ethernet in the First Mile (EFM) study group of the IEEE is formed in order to form a standard of EPON.

However, both APON and EPON have the fundamental limitations in that they are TDM based, in which both the upstream and downstream signals have to be time-shared by all the ONUs in the same access network. Therefore each ONU can receive signals that are sent to other ONUs as well. This creates a potential security hole in the network, and needs upper layer control such as encryption to address this problem. In addition, as the bandwidth is shared between ONUs, this will limit the bandwidth available for each user. Moreover, as different ONUs are of different distances from the OLTs, and this causes the ranging problem, which means that the power of the signals received from each ONU is different, and it will be harder to synchronize all the ONUs in one PON.

To overcome these problems, we proposed several PON architectures that employed WDM instead of TDM. These WDM-PONs can easily solve all the above shortcomings encountered by APON and EPON. Moreover, they are both bit rate and protocol transparent, so that we can easily deliver multi-service in different bit rates to different ONUs in a single PON. A generic WDM-PON architecture is as follows:

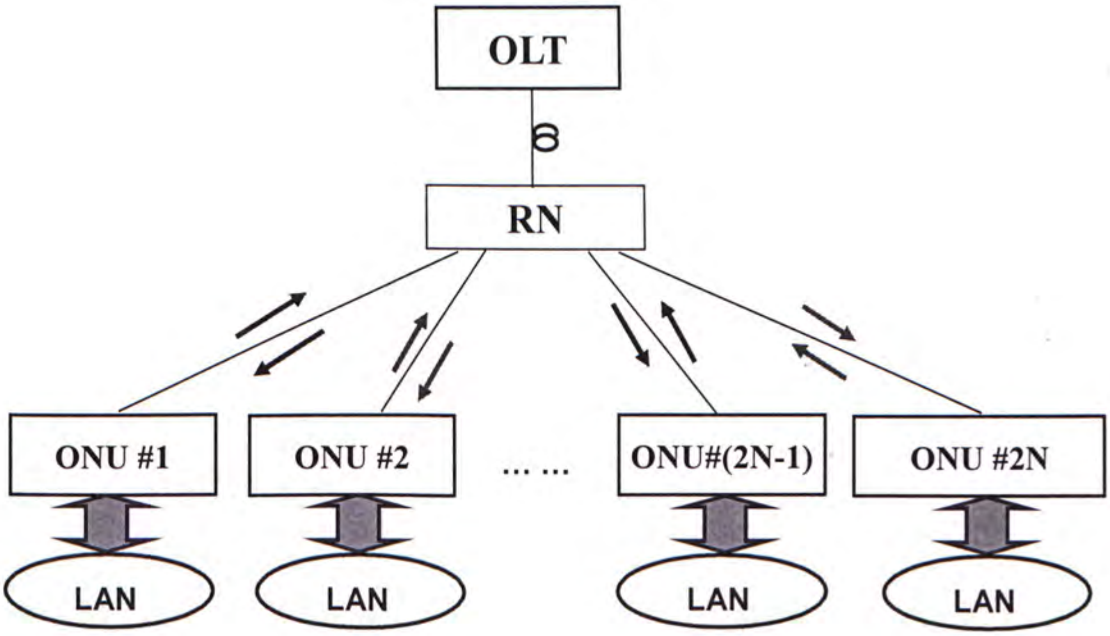


Fig. 1.5 A generic WDM-PON

1.3. Outline of the thesis

The structure of this dissertation is as follows:

Chapter one describes the current trend of optical access network, and an introduction to some enabling technologies for our project. In chapter two, we will review some of the important protection and restoration schemes proposed by other researchers.

Chapter three will present the three proposed WDM-PON network architectures with protection capability. We will discuss various aspects of the schemes, including the protection mechanism, wavelength assignments and crosstalk analysis. We will also make a comparison of the three schemes. In chapter four, we will present the experimental setup, and the experimental results will be analyzed to characterize the system performances of the three schemes.

In the last chapter, chapter five, we will draw some conclusions on the entire project, and some recommendations on future works will be made.

Chapter 2

Review of Protection and Restoration Schemes

2.1 Introduction

In a WDM network such as shown in Fig 2.1 [7], the bandwidth of a fiber is divided into many non-overlapping wavelengths called wavelength channels. Each channel can be operated asynchronously and in parallel at any desirable speed, e.g. a few Gbps. The number of WDM channels is typically a few tens today, but it is expected to grow to a much larger number to fully exploit the entire bandwidth in a fiber. In such a network, the failure of a network component, for example a fiber link, may lead to the failure of all the lightpaths that passes through that failed link. Since each channel may operate at a rate of up to 40 Gbps, such a failure can lead to a severe disruption in the network's traffic, and enormous loss of data.

In view of this, several approaches are proposed to ensure fiber network survivability. Such architectures are either based on dedicated resources, or on dynamic restoration. In dedicated resources protection, network service is restored by using the extra network resources dedicated for the protection purpose only. Alternatively, the

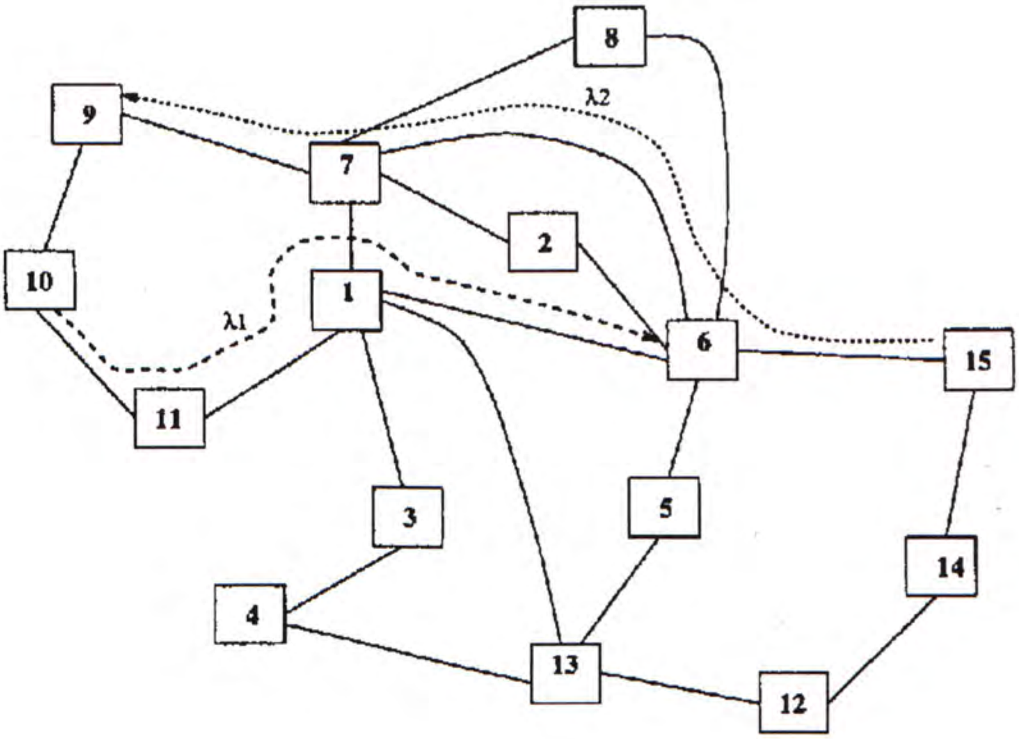


Fig. 2.1 Architecture of a wavelength routed optical network

dedicated network resources used for protection can be shared among different failure scenarios. In dynamic restoration, the spare capacity available within the network is utilized for restoring services affected by a failure. Generally, dynamic restoration schemes are more efficient in utilizing capacity due to the multiplexing of the spare capacity requirements, and provide resilience against different kinds of failures, while dedicated protection schemes have a faster restoration time and provide guarantees on the restoration ability. The classification of different approaches is illustrated in Fig. 2.2.

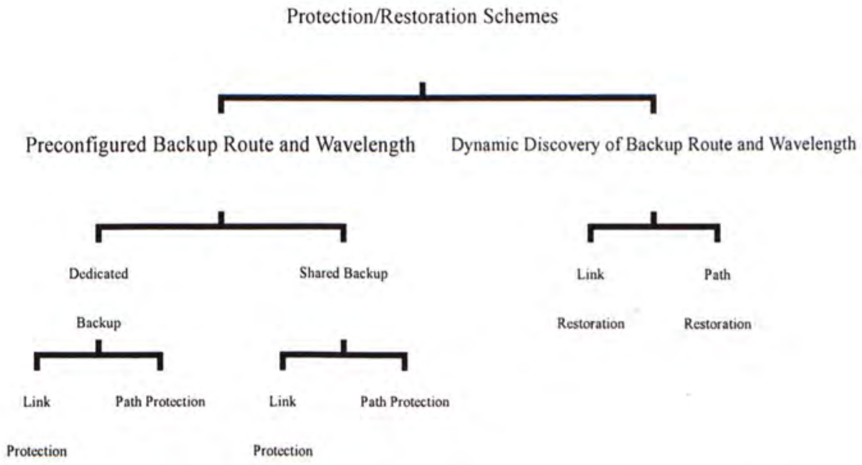


Fig 2.2: Schemes for protection/restoration against single failures.

In section 2.2 and 2.3, we will conduct a brief review on different approaches to survive single-link failures in an optical network. In particular, the protection and restoration schemes in passive optical networks are presented in section 2.4.

2.2 Protection Schemes

2.2.1 Path Protection

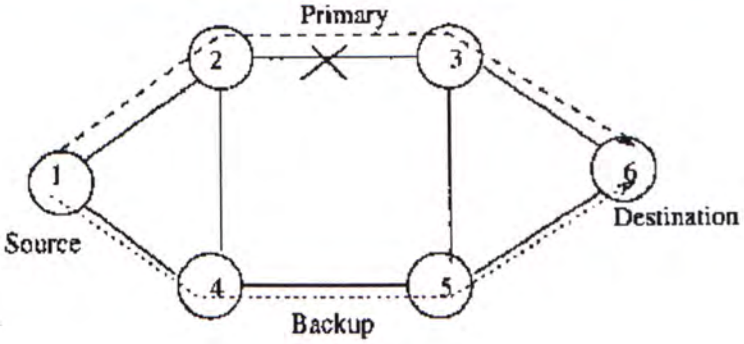
In path protection, the source and destination nodes of each connection statically reserve backup paths on an end-to-end basis during call setup. It can be divided into two categories:

a. Dedicated path protection (also known as 1+1 protection)

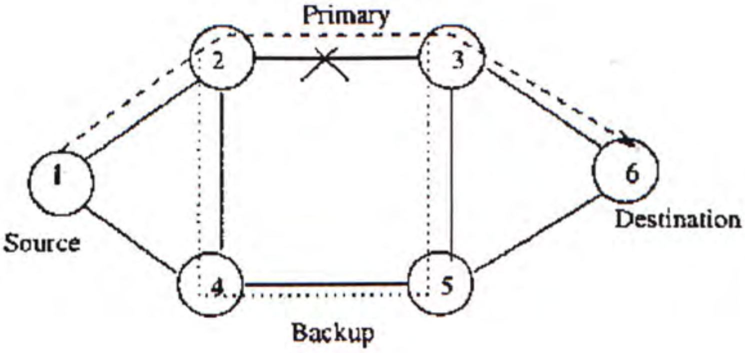
In dedicated path protection, at the time of call setup for each primary path, a link-disjoint backup path and wavelength are reserved, and dedicated to that call. Link-disjoint means that the backup path for a connection has no fiber-links in common with the primary path for that connection. The backup wavelength reserved on the links of the backup path are dedicated to that call, and are not shared with other backup paths.

b. Shared-path protection

In shared-path protection, at the time of call setup for a primary path, a link-disjoint backup path and wavelength are also reserved. However, the backup wavelength reserved on the links of the backup path may be shared with other backup paths. As a result, backup channels are multiplexed among different failure scenarios, and therefore shared-path protection is more capacity efficient when compared with dedicated-path protection.



(a) Path protection



(b) Link protection

Fig 2.3 Protection Schemes

2.2.2 Link Protection

In link protection, all the connections that traverse the failed link are rerouted around that link. The source and destination nodes of the connections traversing the failed link are oblivious to the link failure. They are also categorized into two classes:

a. Dedicated-link protection

In dedicated-link protection, at the time of call setup, for each link of the primary path, a backup path and wavelength are reserved around that link, and are dedicated to that call. In general, it may not be possible to allocate a dedicated backup path around each link of the primary call, and on the same wavelength as the primary path.

b. Shared-link protection

In shared-link protection, at the time of call-setup, for each link of the primary path, a backup path and wavelength is reserved around the link. However, the backup wavelengths reserved on the links of the backup path may be shared with other backup paths. As a result, backup channels are multiplexed among different failure scenarios, and therefore shared-link protection is more capacity efficient when compared with dedicated-link protection.

2.3 Restoration Schemes

2.3.1 Path Restoration

In path restoration, the source and destination nodes of each connection traversing the failed link participate in a distributed algorithm to dynamically discover a backup route and wavelength on an end-to-end basis. Such a backup path could be on a different wavelength channel. If no new route or wavelength is discovered for a broken connection, that connection is blocked.

2.3.2 Link Restoration

In link restoration, the end-nodes of the failed link participate in a distributed algorithm to dynamically discover a route around the link, for each wavelength that traverses the link. If no new route or wavelength is discovered for a broken connection, that connection is blocked.

2.4 Protection and Restoration Schemes in PONs

In this section, we will examine a few common approaches to provide survivability in PONs. In particular, we will present the existing protection schemes described in the BPON standard G.983.1, as well as some recently proposed architectures that provide new methods to give protection and restoration capability.

2.4.1 Protection Schemes in G.983.1

The tree structure of PONs is more vulnerable to single failures when compared with ring networks like SONET or SDH. Therefore, in an appendix of ITU-T G.983.1 [11], four redundant network architectures are proposed for APONs, and we will now briefly introduce each type:

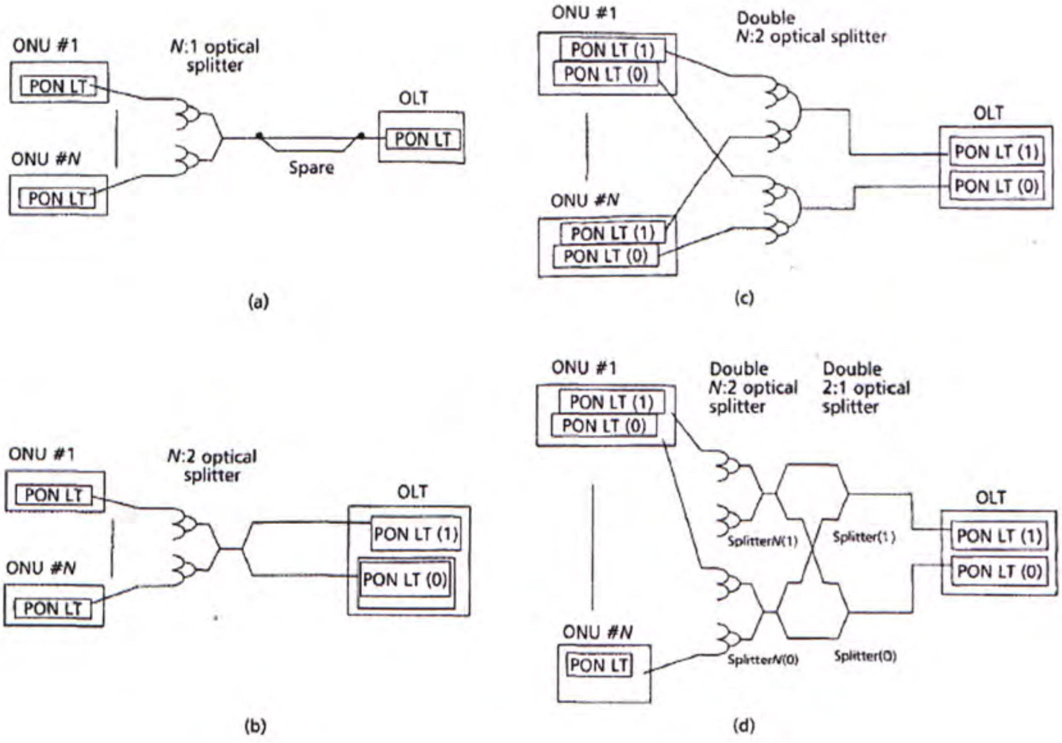


Fig. 2.4 Protection Schemes in G. 983.1 [16]

a. Protection Type A

In Fig. 2.4(a), a spare fiber is installed between the OLT and the splitter. The APON interface can detect a fiber cut and switch to the spare fiber. During switching, signal loss or even cell loss is inevitable. There is no redundant equipment in the OLT and ONUs. A 1:2 optical switch along with a 2:N splitter will be required to implement this feature. The protection switch message will be reported to the OLT. All the connections between the service node and the terminal equipment should be held during the fiber switching, and re-ranging may be necessary.

b. Protection Type B

As shown in Fig 2.4(b), a cold standby of the spare APON circuit in the OLT side is installed to partially protect the network from an APON interface module failure or a fiber cut between OLT and splitter. However, individual ONU PON interface failure will not cause "branch" protection switching. A selector at OLT is used to switch between working and protection APON modules, and a 2:N splitter will be required. The signal loss or even cell loss is inevitable in the switching period, and all connections supported between the service node and the terminal equipment should be held after the switching.

c. Protection Type C

In Fig. 2.4(c), both the OLT and ONUs are equipped with redundant modules. In this case, the hot stand-by spare PON circuits in both ONU and OLT sides will make hitless switching possible. Constant synchronization between the working and stand-by modules is required for hitless switching. PON interface module failures at the OLT side and a fiber cut between OLT and splitter will cause a "tree" switching. Individual PON interface failure at ONU side can be recovered by single branch switching so that other ONUs will not be disturbed. In this protection scheme, single point failure scenarios in PON interface are all covered.

d. Protection Type D

As illustrated in Fig 2.4(d), a redundant RN is implemented besides using protected PON at both OLT and ONU. In this case, multiple point failure can be protected and is the most reliable network architecture. However, the cost is very high and the management of such PON interface is complicated.

In summary, protection type D is too complicated while protection type A can provide limited protection to the network. Therefore, protection types B and C are recommended by FSAN for APON systems in FTTB scenario. For FTTH, types A and B are recommended because they are more cost effective.

2.4.2 Other Proposed Schemes

There are a number of other schemes proposed for PONs, with a variety of protection capability and complexity. In this subsection, we will give a brief summary on these schemes.

a. A New Protection Mechanism of APON: Protection Type H

This protection scheme was proposed in [17], and was named Protection Type

H. In this scheme, the APON interfaces are divided into g groups, and each group are protected with an 1:n scheme where n depends on available optical switch and vendor implementation. One APON interface module in each group is assigned as protection mode at the OLT. This module can be installed in a fixed slot or any slot. All PON interface information including PON ID, the ONU's passwords, ranging intervals and current alarm status will be stored in a common control card to supervise the protection switching. The information stored at the CCC will be copied to the protecting APON module before the automatic protection switching is performed. The switching time is restricted so that the connections on the failed APON module will not be dropped. A g*(1:n) protection at an OLT is achieved. In addition to the network architecture, a uni-ranging algorithm is also proposed to enable fast automatic protection switching whenever a failure occurs.

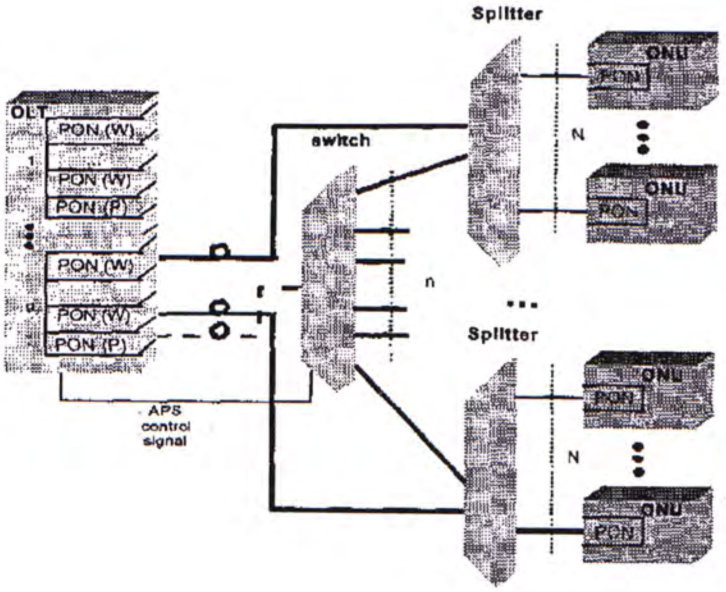


Fig. 2.5 Protection Type H

b. A Modified Star-Ring Architecture (MSRA) for Subcarrier Multiplexed (SCM) PONs

In this scheme proposed in [14], a star-ring architecture was proposed to provide cost effective self-healing function in an SCM-PONs. Although technically it is not a PON architecture, as the RN contains active optical switches, it is still very simple and can be implemented with very cost effective components.

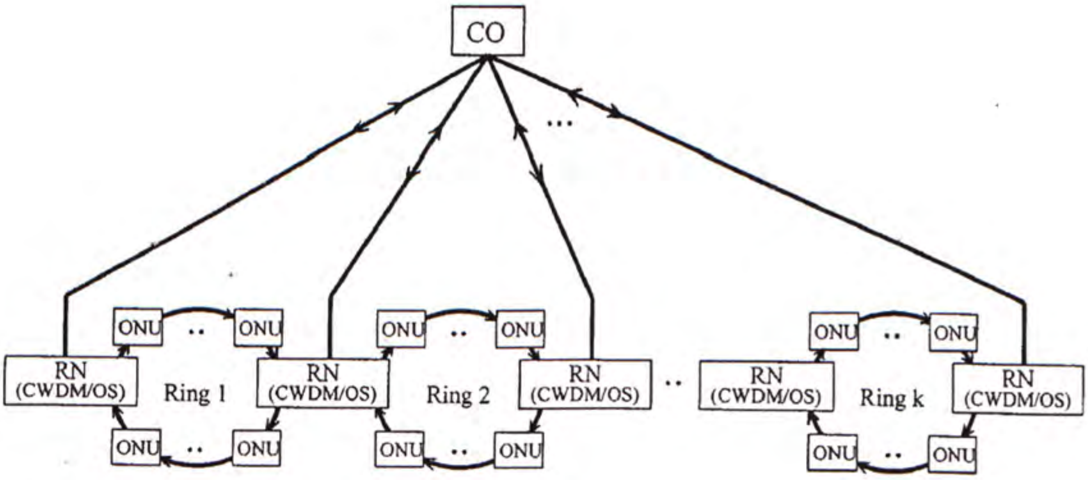
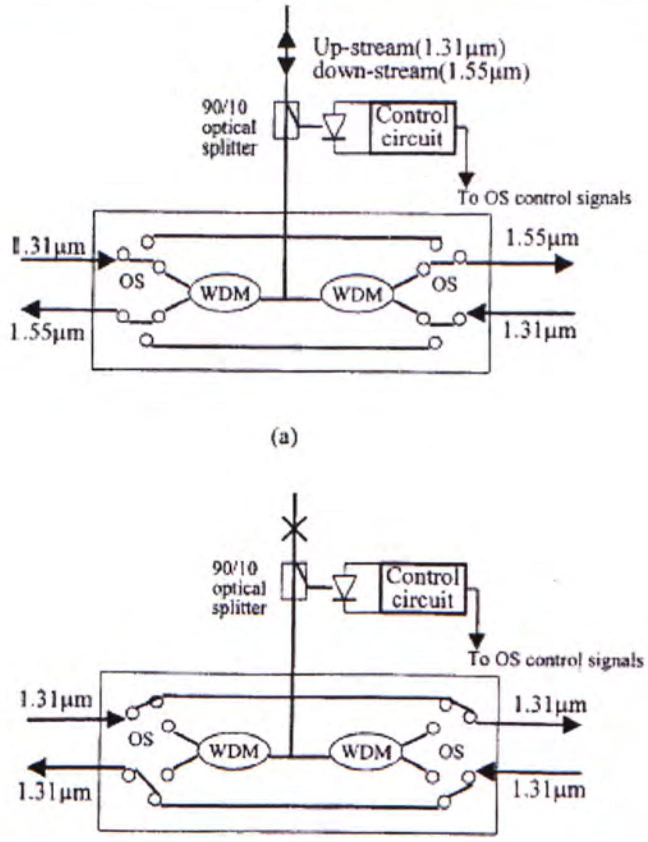


Fig. 2.6 The modified star-ring architecture for SCM-PON [14]

As illustrated in Fig. 2.6, the MSRA is a two-level network architecture having a star network on the upper level along with many concatenated ring subnets on the lower level. It uses WDM for separating the upstream and downstream traffic, and each ONU's data stream is subcarrier multiplexed (SCM) with other user's data stream. With the special arrangements of the lower level ring subnets, the network can protect the network from any failure in the upper level star network. As shown in Fig. 2.7, each ring is actually divided into two semirings by the RNs. The function of RN is to transfer signals between the CO and the lower level ring subnet in the normal operation, and to perform self-healing function if link failure occurs in the upper level star network. Each RN contains two 1.3μm/1.55μm coarse wavelength division multiplexers (CWDM) and four optical switches (OS). A signaling tone is constantly sent by the CO and detected by the control circuit in the RN. If the corresponding link in the upper level star network is broken, the signaling tone will be absent and the control circuit will reconfigure the OS functioning as Fig 2.7(b). The upstream signals can bypass the RN of interest and go to the neighboring RNs. Thus, the affected ONUs will be assisted by the two neighboring RNs whenever a failure occurs. Similarly, the downstream signals can still be transmitted from the CO to the affected ONUs through the two neighboring RNs.



(a)

(b)

Fig 2.7 Connections of the RN for (a) normal operations

and (b) fiber or component failures. [14]

Chapter 3

Design of WDM-PON Network Architectures

3.1 Introduction

In the last chapter, we have reviewed some previous works on protection and restoration in a WDM networks. In both conventional PON and WDM-PON, most of them are only duplication of either fibers or equipments, which leads to difficulty in designing the network and limited protection capability. The main goal in this project is to propose several novel network architectures for WDM-PON which offers 1:1 protection capability in both downstream and upstream fiber connections. In case of any fiber cut between the RN and an ONU, the isolated ONU can still support two-way communications with the OLT by re-routing the wavelength channels via the adjacent ONU. In this chapter, we will investigate the group protection architecture (GPA) scheme, the enhanced group protection architecture (EGPA) and the Hybrid Ring (HR) scheme..

3.2 The Group Protection Architecture (GPA)

3.2.1 Network Design

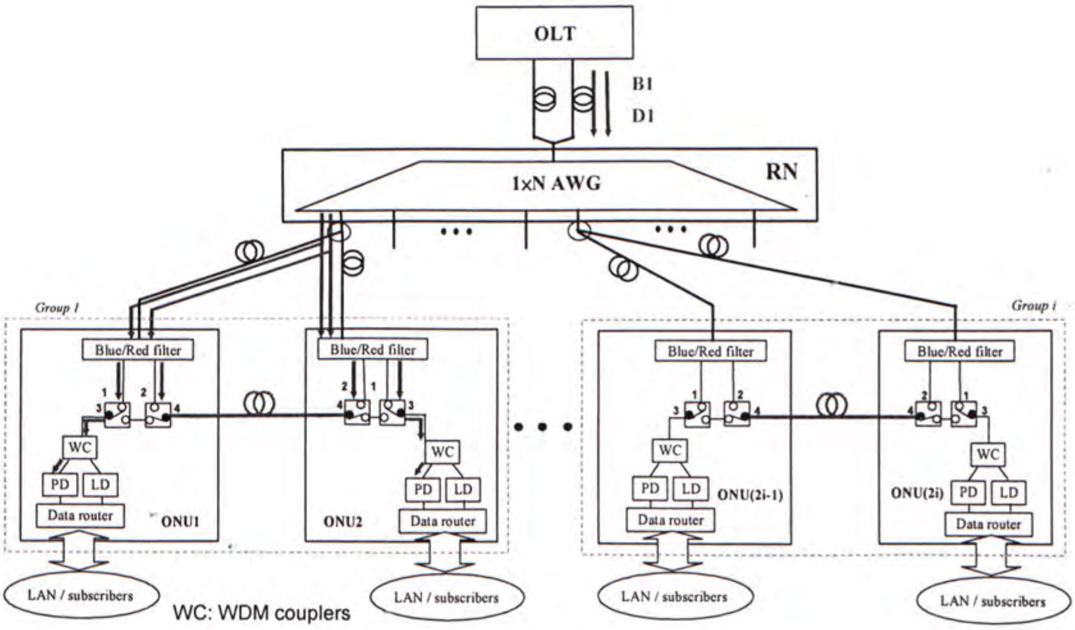


Fig. 3.1 The GPA Scheme under normal operation. (WDM: WDM Coupler; LD: laser; PD: photodiode)

Fig. 3.1 shows our proposed network architecture for a WDM-PON with bi-directional protection capability. The RN comprises an array-waveguide grating (AWG) to route the wavelength channels to the ONUs. 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 a 1x2 3-dB fiber coupler. Thus a network with a 1xN AWG at the RN can support 2N ONUs. In each group of ONU, there is a single piece of fiber connecting the two ONUs to provide an alternative path so that any isolated ONU, due to possible fiber cut between itself and the RN, can still route its upstream and downstream traffic to/from the OLT via its adjacent ONU in the same group. Thus the ONUs in each group have mutual 1:1 protection capability, that is, an ONU can protect its adjacent ONU from being isolated due to fiber cut, although each of them can still serve their respective connected subscribers in both normal and protection modes.

3.2.2 Protection Mechanism

Under normal operation (see Fig. 3.1), the downstream wavelengths, Bi and Di, are carried on the fiber link connecting to ONU(2*i*-1) and the same composite signal is also delivered to ONU(2*i*). At the front-end of ONU(2*i*-1), its destined downstream wavelength, Bi, will be filtered out by the Red/Blue filter and so is Di in ONU(2*i*). The use of the WDM coupler is to separate the upstream and downstream wavelengths within the ONU.

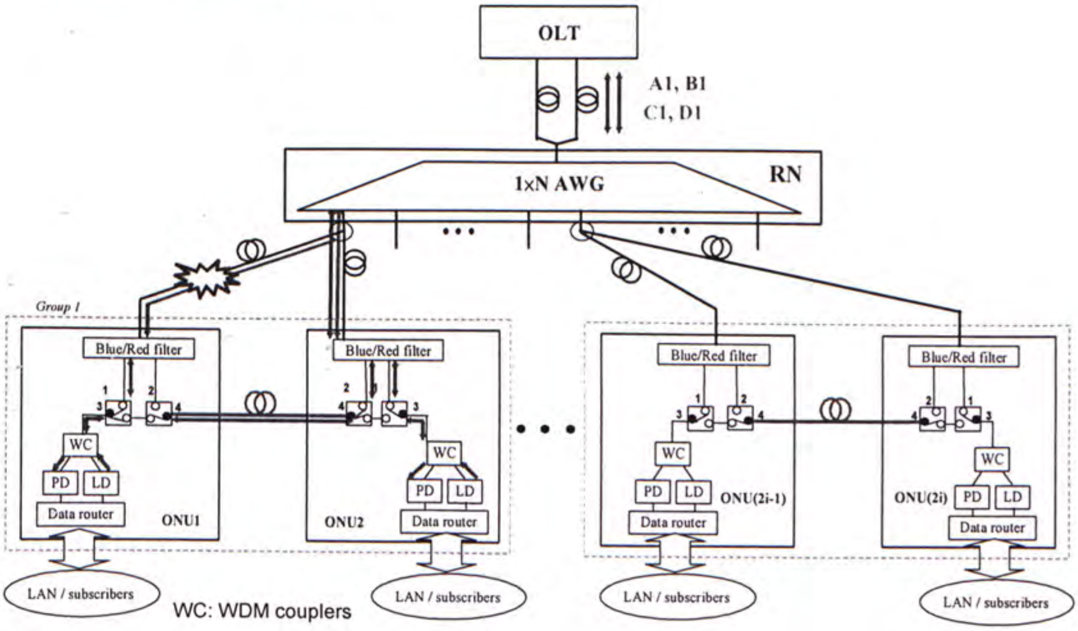


Fig. 3.2 The rerouted network when the fiber links connecting to ONU 1 is broken.

For upstream wavelengths, Ai from ONU(2*i*-1) and C*i* from ONU(2*i*) 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. In case of fiber cut at the fiber link connecting to ONU(2*i*), the ONUs in the same group would be reconfigured as illustrated in Fig. 3.2. Both upstream and downstream wavelengths of the isolated ONU(2*i*) will be routed to the ONU(2*i*-1) via the single fiber connecting between them. These re-routed wavelengths will be multiplexed with the existing wavelengths in ONU(2*i*-1) so that ONU(2*i*) can still communicate with the OLT. Conversely, ONU(2*i*) protects ONU(2*i*-1) in a similar way. With this protection mechanism, a fast restoration of the broken connection can be achieved, with minimal affect on the existing traffic.

The actual implementation of the ONUs is shown in Fig 3.3. Each ONU contains two optical switches controlled by electronic monitoring circuit. There are tap couplers tapping 10% of power from the incoming signals from the RN and from the other ONU. A low speed photodiode is used to monitor the input signal strength. The normal states of the optical switches is as Fig 3.3(a) If the input power falls below the threshold, the electronic monitoring circuit will change the states of the two optical switches to the diagram shown in Fig 3.3(b).

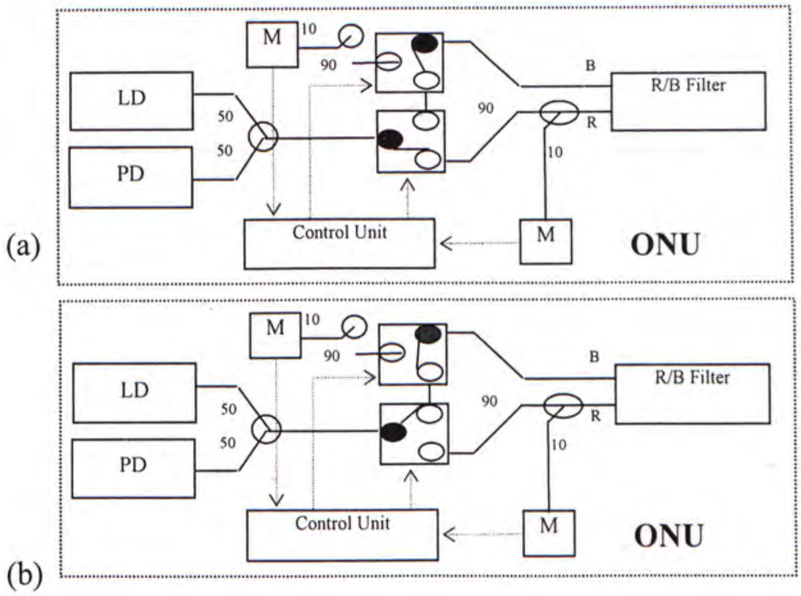


Fig 3.3 (a)Normal Switching States (b) Protection Switching States

3.2.3 Wavelength Assignments

For each ONU, two distinct wavelengths are assigned for upstream and downstream signals. Moreover, as 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 working and re-routed wavelengths, as illustrated in the figure below:

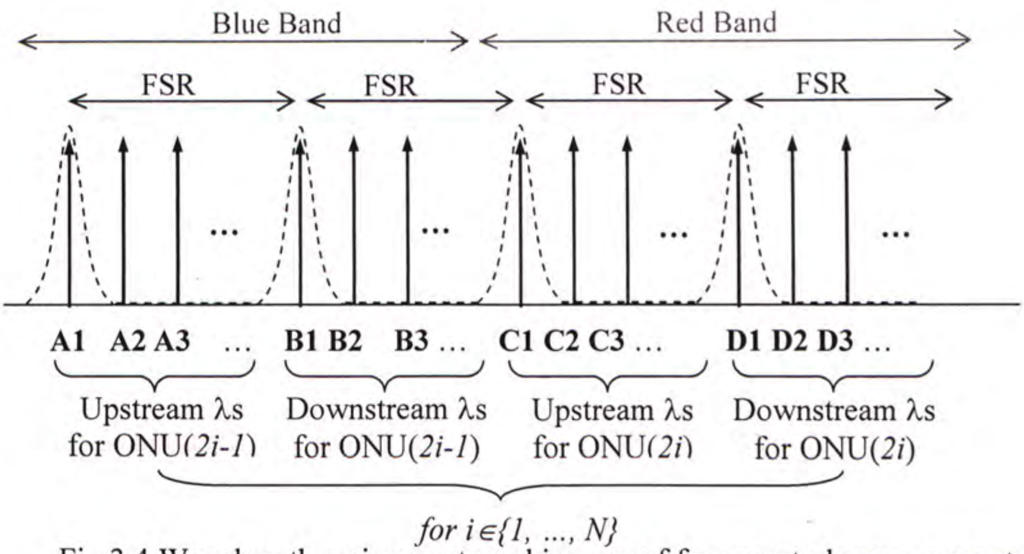


Fig 3.4 Wavelength assignments making use of free spectral range property

To illustrate the wavelength assignment, the upstream and downstream wavelengths for ONU1 are labeled as A1 and B1, respectively, while that for ONU2 (in the same group) are labeled as C1 and D1. A1 and B1 are chosen to be spectrally-spaced by one free spectral range (FSR) of the AWG and similar rule applies to C1 and D1. C1 is also one FSR away from B1, thus four wavelengths (A1, B1, C1 & D1) are equally spaced by one FSR as shown in Fig. 3.4. Using the same principle, the wavelength assignment for the other ONUs are tabulated in Table 3.1 as an example, assuming N=7 and with ITU-grid (100 GHz) wavelengths. Note that Ai and Ci are the upstream wavelengths for ONU($2i$-1) and ONU($2i$) while Bi and Di are the corresponding downstream wavelengths.

Channel no	Wavelength value	Channel no	Wavelength value	Channel no	Wavelength value	Channel no	Wavelength value
A1	1532.29	**B1**	1539.37	**C1**	1546.52	**D1**	1553.73
A2	1533.07	**B2**	1540.16	**C2**	1547.33	**D2**	1554.54
A3	1533.86	**B3**	1540.95	**C3**	1548.11	**D3**	1555.34
A4	1534.64	**B4**	1541.75	**C4**	1548.91	**D4**	1556.15
A5	1535.43	**B5**	1542.54	**C5**	1549.72	**D5**	1556.96
A6	1536.22	**B6**	1543.33	**C6**	1550.52	**D6**	1557.77
A7	1537.00	**B7**	1544.13	**C7**	1551.32	**D7**	1558.58

Table 3.1: Wavelength assignment.

3.2.4 Power Budget Calculation

We can determine how far we can transmit the signal by calculating the power budget of the system. Assuming the transmitted powers from the LDs in the ONUs are 0 dBm, the receiver sensitivities of the photodiodes at the OLT are -24 dBm (at 2.5 Gb/s), the insertion losses of optical switches, AWG, Red/Blue filters and WSC are 1 dB, 5 dB, 1 dB and 1 dB, respectively; the optical power margin will be 11 dB in the re-routing path of upstream traffic, and so is that in downstream traffic. Assuming the normal attenuation of 0.25 dB/km in SMF fiber, a transmission distance of more than 44 km can be achieved.

3.2.5 Crosstalk Analysis

Most of the components in a WDM system introduce crosstalk to the system. These include filters, wavelength multiplexers/demultiplexers, switches, and the fiber itself. Crosstalk in a WDM system exists in two forms: intrachannel crosstalk and interchannel crosstalk:

Intrachannel Crosstalk

Intrachannel crosstalk, also known as coherent crosstalk, arises when the crosstalk signal is at the same wavelength as that of the desired signal or sufficiently close to it that the difference in wavelengths is within the receiver's electrical bandwidth. It is mainly due to reflections in components.

Interchannel Crosstalk

Interchannel crosstalk arises when the crosstalk signal is at a sufficiently different wavelength from the desired signal's wavelength that the difference is larger than the receiver's electrical bandwidth. A simple example is an optical filter or demultiplexer that selects one channel and imperfectly rejects the others. It can also occur through some indirect interactions, for example, nonlinearities in fiber.

In our WDM-PON system, the major source of crosstalk is the interchannel crosstalk induced by the imperfection of AWGs. Consider an N x N AWG, there are N^2 possible combinations through which N wavelength WDM signals can be split. Therefore, at any one output port of the AWG, consider one wavelength, say λ_m, the total optical field including the in-band crosstalk is:

$$E_m(t) = (E_m + \sum_{n \neq m}^{N} E_n)\exp(-i\omega_m t) \tag{3.1}$$

where E_m is the desired signal and $\omega_m = 2\pi c/\lambda_m$

The latter terms can be neglected, and so the receiver current is approximated as:

$$I(t) \approx RP_m(t) + 2R\sum_{n \neq m}^{N} \sqrt{P_m(t)P_n(t)} \cos[\phi_m(t) - \phi_n(t) \tag{3.2}$$

The power penalty can be calculated using the following equation:

$$\delta_x = -10\log_{10}(1 - r_x^2 Q^2) \tag{3.3}$$

where

$$r_x^2 = \left\langle (\Delta P)^2 \right\rangle \Big/ P_m^2 = X(N-1) \tag{3.4}$$

and $X = P_n/P_m$ is the crosstalk level defined as the fraction of power leaking through the AWG. Q=6 for a BER of 10^{-9}.

The r_x^2 term is multiplied by another factor of 1/2 because P_n is zero on average for half of the bits for each crosstalk channel. For typical AWG, adjacent crosstalk level is below -30 dB therefore the power penalty is around 1.366 dB for N=16.

3.2.6 Discussion

There are several advantages of the GPA scheme: i) it is robust to link failure between the ONU and RN, in particular that it can protect against multiple link failure as long as the failed links are not in the same group, ii) it is very simple and ii) easy to manage.

However, there are several limitations to this scheme, apart from transmission distance and crosstalk discussed in previous sections: this scheme involves extra cost due to the addition of optical switches and filters and the need to add an additional link between the ONUs in the same group, and also there are quite strict requirements on the AWG and the optical filters. The optical switches and Red/Blue filter in each ONU will increase the cost of each ONU, however the price for MEMS switches are decreasing quickly, and we can expect the price for waveband filters including the Red/Blue filter to drop, mainly due to the increased demand for DWDM transmission.

There are actually many ways to implement the additional link between the ONUs, apart from requiring an additional duct which is used only to protect the ONU. This includes the use of Free Space Optics (FSO), for cases where the ONUs are placed in adjacent building and have the required line of sight. On the other hand, we can also adopt wireless link for the protection purpose. However, the quality of service would be degraded, as they are not as fast and vulnerable to environmental condition such as weather.

The requirements on the AWG and the optical filters used make this scheme quite inflexible, in the sense that the AWG must have a suitable FSR, so the combination of the number of channels and the channel spacing has to be carefully chosen. In addition, the bandsplitting filters such as the Red/Blue filters and the wavelength couplers have to be quite accurate and match the AWG in wavelengths. These make the addition of ONUs, especially for a larger network, much more difficult, and this limitation will be addressed in the next scheme.

3.3 The Enhanced Group Protection Architecture (EGPA)

3.3.1 Introduction

In the last chapter we have presented the GPA scheme. In this chapter, we will present an enhancement to the GPA scheme, the Enhanced Group Protection Architecture (EGPA) scheme. In this scheme, the design of the RN is simplified and the use of wavelengths is more flexible than the previous scheme.

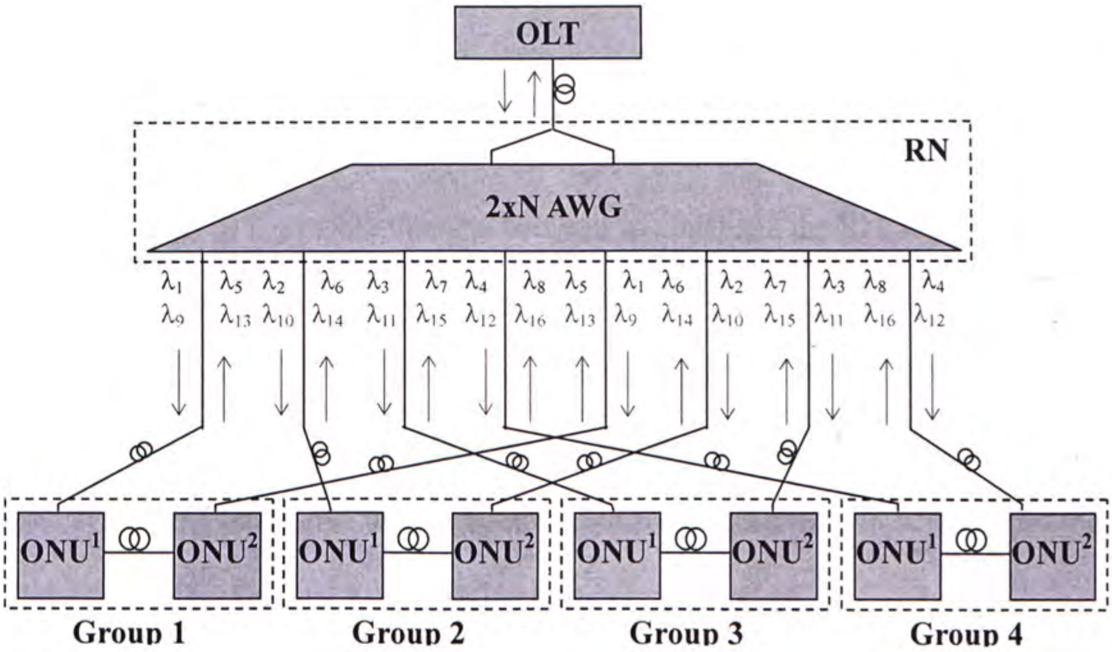


Fig. 3.5 The EGPA network architecture with 8 ONUs.

3.3.2 Network Design

Fig. 3.5 shows our proposed EGPA network architecture with N ONUs. Eight ONUs are considered here as an example to facilitate our illustration. Unlike the GPA scheme, the RN comprises only one 1x2 3-dB fiber coupler and a 2xN AWG to route the wavelength channels to the ONUs. The OLT is connected to the two input ports of the AWG at the RN 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. 3.5. Such fiber connection pattern is designed according to a wavelength assignment plan different from the one in the GPA scheme, and it will be described in later section. In each group, a single piece of fiber is used to connect the two ONUs to provide an alternative path.

3.3.3 Protection Mechanism

Whenever there is a possible fiber cut between an ONU and the RN, it can still route its upstream and downstream traffic to/from the OLT via its neighbouring 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.

Fig.3.6(a) illustrates the internal structure of the ONUs under normal operation mode. The downstream wavelengths, A_i and C_i, are carried on the fiber 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 denotes the group number. The destined downstream wavelength of ONU^1_i, 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 and the optical switch, a WDM coupler is used to separate the upstream wavelength from the local laser diode and the downstream wavelength to the receiver.

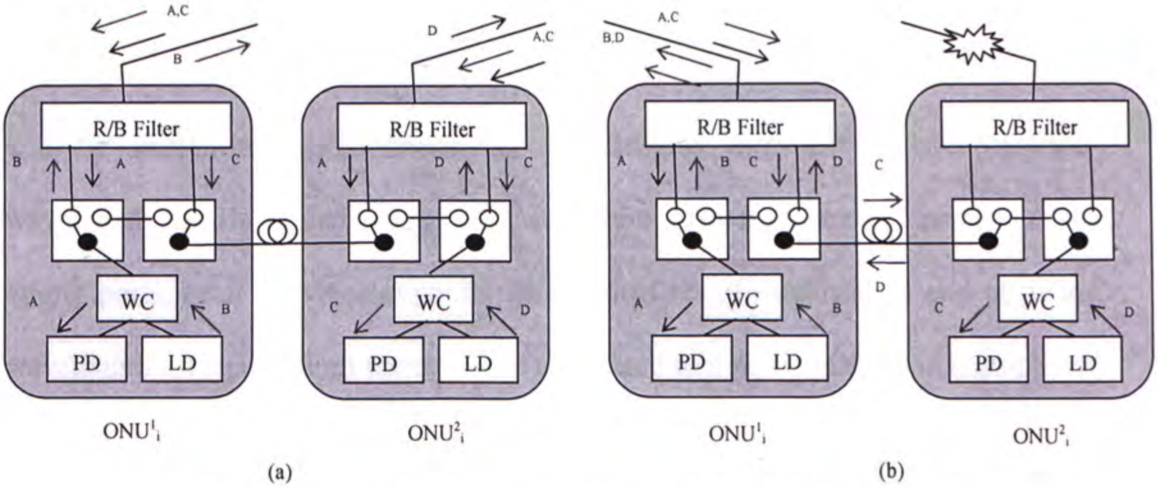


Fig. 3.6 (a) Normal Mode (b) Protection Mode of the EGPA Scheme

In case of fiber cut at the fiber link between the RN and the ONU^2_i, for example, both the optical switches inside the ONU^2_i will be reconfigured, as shown in Fig. 3.6(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 affect on the existing traffic. The OLT is transparent to such fiber failure.

3.3.4 Wavelength Assignment

To support such protection scheme, a modified wavelength assignment plan, as shown in Fig. 3.7, is proposed to allocate the downstream (in wavebands A & C) and the upstream (in wavebands, B & D) wavelengths for each group of ONUs. At the RN, 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, so that 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, as illustrated in Fig. 3.7. 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. 3.5.

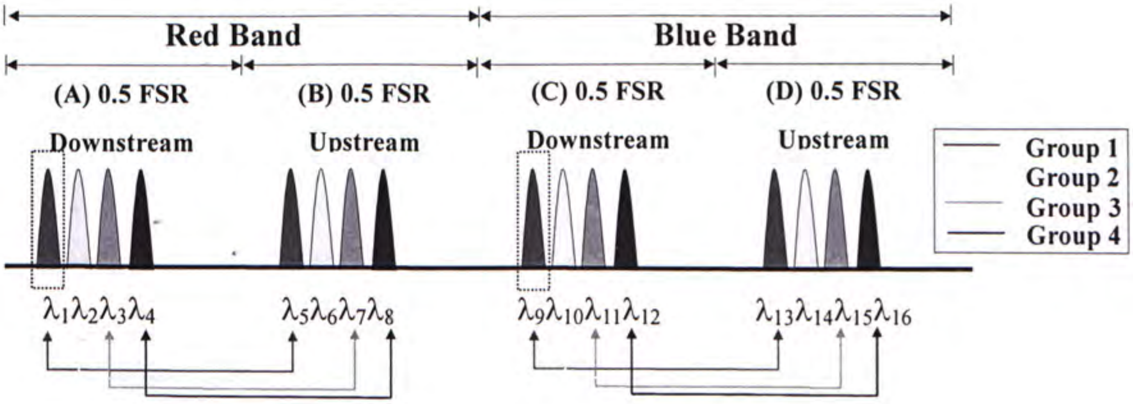


Fig. 3.7 Proposed wavelength assignment plan of the EGPA scheme. The dotted lines show an example of the transmission peaks of the AWG at the RN.

3.3.5 Power Budget Analysis

The power budget analysis is similar to the GPA scheme. Assuming the transmitted powers from the LDs in the ONUs are 0 dBm, the receiver sensitivities of the photodiodes at the OLT are -24 dBm (at 2.5 Gb/s), the insertion losses of optical switches, AWG, Red/Blue filters and WSC are 1, 5, 1 and 1 dB, respectively; the optical power margin will be 11 dB in the re-routing path of upstream traffic, and so is that in downstream traffic. Assuming the normal attenuation of 0.25 dB/km in SMF fiber, a transmission distance of more than 44 km can be achieved.

3.3.6 Crosstalk Analysis

This analysis is the same as in the GPA scheme. We only consider the crosstalk from the AWG. The power penalty can be calculated using the following equation:

$$\delta_x = -10\log_{10}(1 - r_x^2 Q^2) \tag{3.3}$$

where

$$r_x^2 = \left\langle (\Delta P)^2 \right\rangle \Big/ P_m^2 = X(N-1) \tag{3.4}$$

and $X = P_n/P_m$ is the crosstalk level defined as the fraction of power leaking through the AWG. Q=6 for a BER of 10^{-9}.

The r_x^2 term is multiplied by another factor of 1/2 because P_n is zero on average for half of the bits for each crosstalk channel. For typical AWG, adjacent crosstalk level is below -30 dB therefore the power penalty is around 1.366 dB for N=16.

3.3.7 Discussion

This scheme is an enhancement to the GPA scheme for two reasons. First, the network is greatly simplified because one 3-dB coupler displaces the *N* 3-dB coupler in the GPA scheme. Second, the requirements on the AWG are less stringent, and a higher channel count AWG can be used due to this reason. On the other hand, it requires a 2xN or NxN AWG to operate. This is no longer a standard product in the market and may lead to a higher cost to the system. More simplification, especially on the ONU side, will be made in the next scheme, the Hybrid Ring Scheme.

3.4 The Hybrid Ring Architecture

3.4.1. Introduction

In this section, we will present the Hybrid Ring (HR) Architecture. In the previous two chapters, the GPA scheme and the EGPA scheme focus on protecting against the fiber cut between the RN and the ONUs. This HR scheme has the additional ability of protecting against fiber cut between the OLT and the RN.

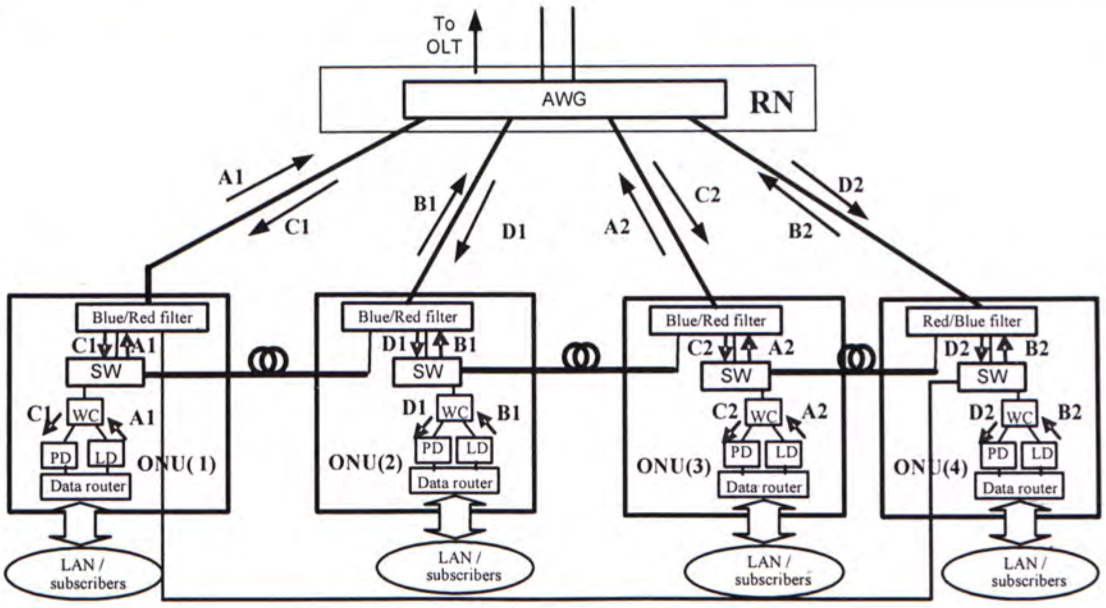


Fig 3.8 The Hybrid Ring Network

3.4.2 Network Design

The design of the hybrid ring scheme is shown in Fig. 3.8. For simplicity, only four ONUs are shown in the diagram to show how a complete ring operates. Similar to the EGPA scheme, the RN consists of a 1x2 3-dB coupler and a 2xN AWG to route the traffic to the ONUs. The OLT is connected to two ports of the AWG through the 1x2 coupler. The main difference between the hybrid ring scheme and the previous schemes is in the ONU side. No grouping is required in this scheme, and all the ONUs are connected to the adjacent ONUs through a pair of protection fiber. The design of the ONUs is simplified, as only one optical switch is required instead of two. Similar to the EGPA scheme, this scheme requires only two FSR of the RN to support bidirectional transmission.

However, this scheme may become more complicated to implement when the number of ONUs is odd. This case is a little bit tricky, as two red bands or two blue bands may appear in adjacent ONUs and they need to be combined through another device. An interleaver or an C+L band splitter can solve this problem, as shown in Fig. 3.9, which is a demonstration of the network with three ONUs:

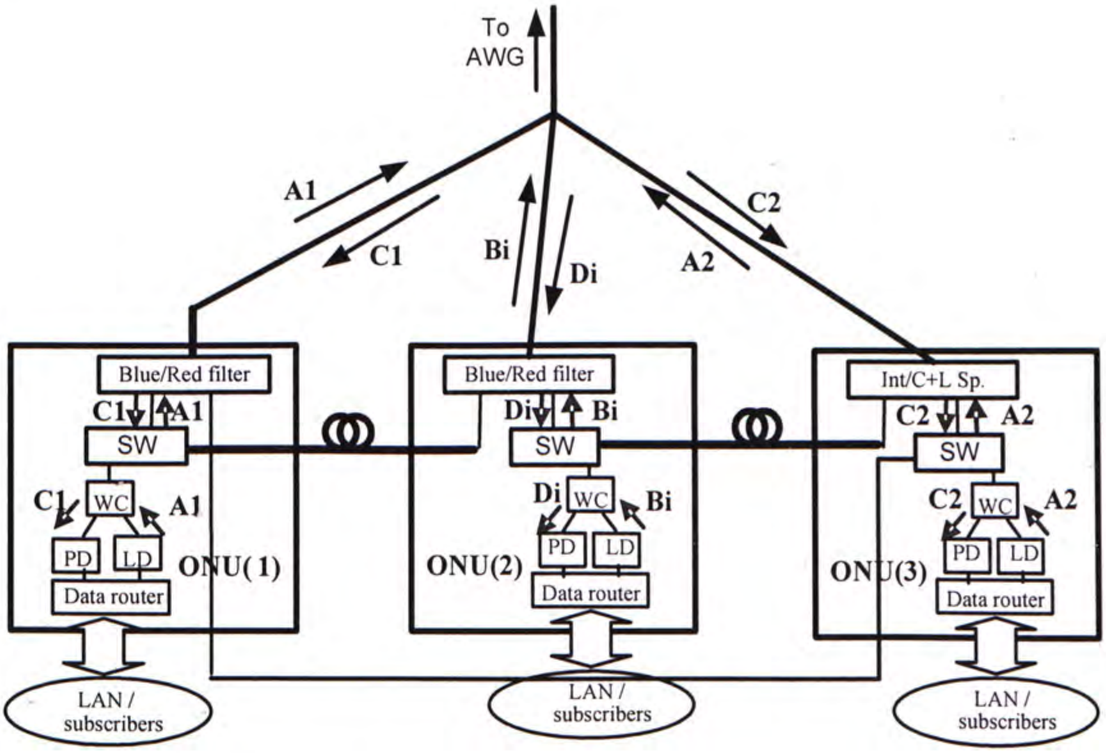


Fig 3.9 The Hybrid Ring Network with three ONUs.

3.4.3 Protection Mechanism

Whenever there is a possible fiber cut between ONU(*n*) and the RN, it can still route its upstream and downstream traffic to/from the OLT via the ONU(*n*+1), thus traffic restoration is achieved. For the last ONU(*N*), it will reroute its traffic through ONU1. As a result, an ONU can protect its adjacent ONU from being isolated due to fiber cut, although each of them can still serve their respective connected subscribers in both normal and protection modes.

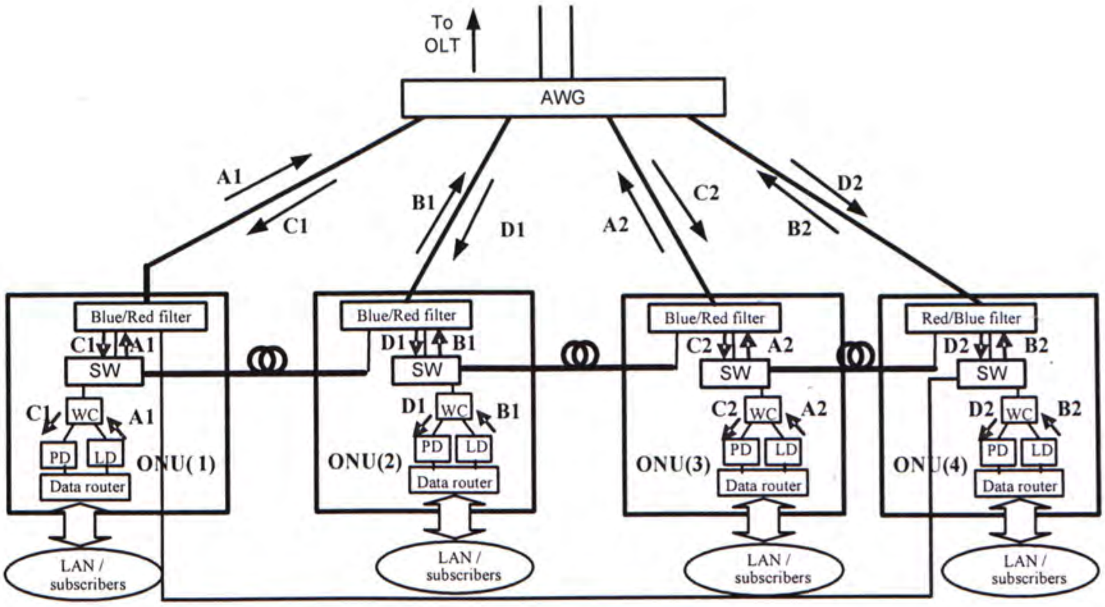


Fig 3.10 The HR scheme in protection mode

3.4.4 Wavelength Assignment

The wavelength assignment plan is similar to the EGPA scheme. We proposed to allocate the downstream (in wavebands A & C) and the upstream (in wavebands, B & D) wavelengths for each group of ONUs. At the RN, 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, so that each downstream data wavelength will be duplicated and directed to two distinct AWG output ports. However, to support the data transmission from the adjacent ONU, a we must shift the wavelengths of ONU(2*i*)s one slot to the right, as illustrated in Fig. 3.11.

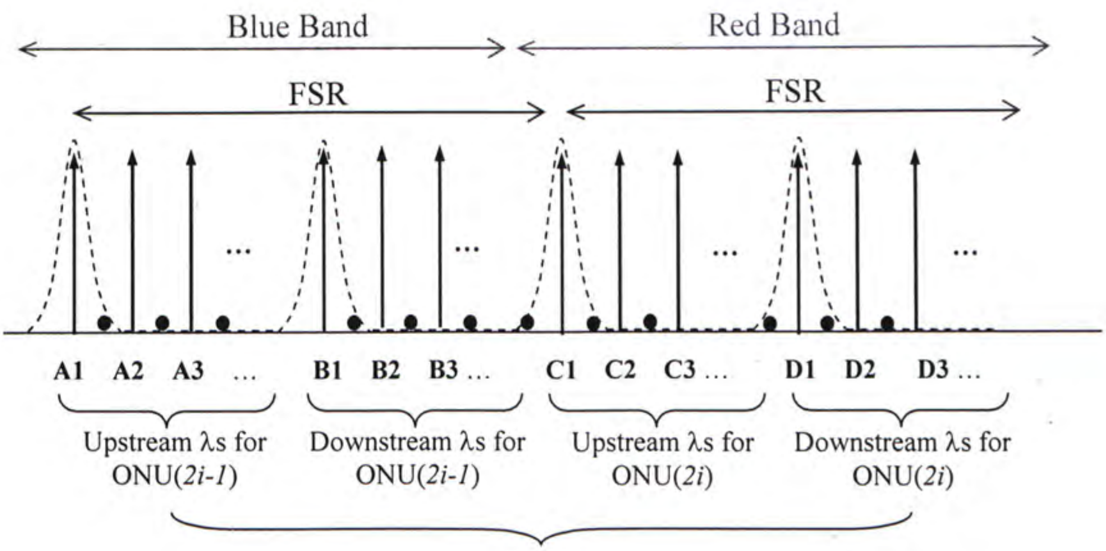


Fig. 3.11 Proposed wavelength assignment plan for the HR scheme.

3.4.5 Power Budget Analysis

This scheme is superior to the GPA scheme and the EGPA scheme in terms of power budget. Assuming the transmitted powers from the LDs in the ONUs are 0 dBm, the receiver sensitivities of the photodiodes at the OLT are -24 dBm (at 2.5 Gb/s), the insertion losses of optical switches, AWG, Red/Blue filters and WSC are 1 dB, 5 dB, 1 dB and 1 dB, respectively; the optical power margin will be 13 dB in the re-routing path of upstream traffic, and so is that in downstream traffic. Assuming the normal attenuation of 0.25 dB/km in SMF fiber, a transmission distance of more than 52 km can be achieved.

3.4.6 Crosstalk Analysis

This analysis is the same as in chapter three. We only consider the crosstalk from the AWG. The power penalty can be calculated using the following equation:

$$\delta_x = -10\log_{10}(1 - r_x^2 Q^2) \qquad (3.3)$$

where

$$r_x^2 = \left\langle (\Delta P)^2 \right\rangle \Big/ P_m^2 = X(N-1) \qquad (3.4)$$

and $X = P_n/P_m$ is the crosstalk level defined as the fraction of power leaking through the AWG. Q=6 for a BER of 10^{-9}.

The r_x^2 term is multiplied by another factor of 1/2 because P_n is zero on average for half of the bits for each crosstalk channel. For typical AWGs, adjacent crosstalk level is below -30 dB therefore the power penalty is around 1.366 dB for N=16.

3.4.7 Discussion

This scheme has two advantages when comparing to the previous two schemes : i) it has a less complicated ONU design, and ii) it has a longer transmission distance. However, this does not necessarily means that it can be less costly to deploy, as there is one more additional fiber for every two nodes, therefore it will increase the cost of laying the fiber, especially in the FTTB and FTTC cases. Moreover, this scheme has an additional advantage that it can protect against possible fiber cut between the OLT and the RN, an improvement from the previous two schemes which protects only against fiber cut between the RN and the ONU.

3.5 Comparison of the three schemes

The three proposed schemes described in previous chapters can provide various levels of protection for the WDM-PON. The GPA scheme is the simplest of the three schemes in terms of topology, with only one additional fiber between every two ONUs. It can only protect against fiber cut between the ONU and the RN. In order to provide bidirectional traffic for both ONUs, we use the concept of wavebands to divide the C-band into four wavebands. A red/blue filter is used to separate the traffic target for different ONUs. In addition, a 3-dB coupler is placed in the RN for each port, in order to pass the downstream traffics to both ONUs from each port of the AWG, and combine the upstream traffics from both ONUs back to the OLT. However, it requires the use of four FSR of the AWG, therefore the choice of AWG becomes very limited. The requirements of the Red/Blue filters and WSC are higher than the other two schemes too. It is scalable, as we can add in two ONUs for each port of AWG, therefore a 1xN AWG can support a total of 2N ONUs.

The EGPA scheme is similar to the GPA scheme, as an additional fiber is added in between every two ONUs. However, we do not need to put N 3-dB coupler at the output ports of the AWG in the RN as before. On the other hand, one coupler is used for all ONUs. We can also use two fibers instead, for two purposes: one is to protect the fiber cut between the OLT and RN, and the other is to improve the power budget by 3 dB. This scheme adds functionality to the first scheme, however, it requires a 2x*N* AWG or *N*x*N* AWG to operate, and this component is not commonly available in the market right now. The FSR requirements is reduced from 4 to 2 FSR, therefore a much wider range of AWG can be chosen, including those with very high channel count. Therefore the EGPA scheme scales better than the GPA scheme.

The Hybrid Ring scheme, similar to the EGPA scheme, requires a 2x*N* AWG or an NxN AWG to work. It can protect against fiber cut between the OLT and the RN and also between the ONUs and the RN. The cost of adding a fiber between every ONUs in the ring might be much higher, especially in the FTTB or FTTC cases. However, it has a much simpler ONU design and has a better power budget. Therefore, this scheme can benefit in the FTTH case when the cost of laying more fiber in separate duct is not very high. It is not easily scalable, as each ONU are fixed in a ring and addition of any one node will require breaking of the ring first.

3.6 Summary of the three schemes

The major characteristics for the three schemes are summarized in Table 3.2:

Scheme	GPA	EGPA	Hybrid Ring
Complexity	High	Medium-High	Medium
Transmission Distance	44km	44km	52km
Requirements on WDM components	Higher	Lower	Lowest
Cost of deployment	Higher	Lower	Lower
Crosstalk	Small	Small	Small
Switching speed	Slower	Faster	Faster
Flexibility	High	High	Low
Scalability	High	Highest	Lowest

Table 3.2 Comparison of the three schemes

Chapter 4

Experimental Evaluation

4.1 Introduction

In this chapter, we will present the experimental setup used to investigate the performances of the three proposed networks, and also the results obtained from the experiments. Two main factors are considered: the bit error rate performances of the proposed system, and the switching speed when a fiber cut occurs. In addition, the crosstalk impairment to the system is also studied.

4.2 Experimental Setup

4.2.1 GPA Scheme

Fig. 4.1 shows the experimental setup to demonstrate the principles of the bi-directional transmission and protection operations of the proposed WDM-PON network. The laser diodes (LD) used were 2.5 Gb/s, directly modulated, with the output power of 0.5 dBm. Each of the arrayed-waveguide gratings (AWGs) had 16 channels with 100-GHz channel spacing, and had an FSR of 12.8 nm. The insertion loss of the AWG is around 7 dB. Each Red/Blue filter had a bandwidth of about 18nm in each passband. On the OLT side, EDFAs with gain around 12 dB were inserted in front of the AWG in order to compensate the components' insertion losses and to achieve the required transmitted power. The fiber used are standard single mode fiber (SMF), with attenuation of 0.25 dB/km. The optical switches are 1x2 mechanical switched, controlled by an electronic protection circuit with a slow speed PIN photodiode to monitor the power level of the incoming signal.

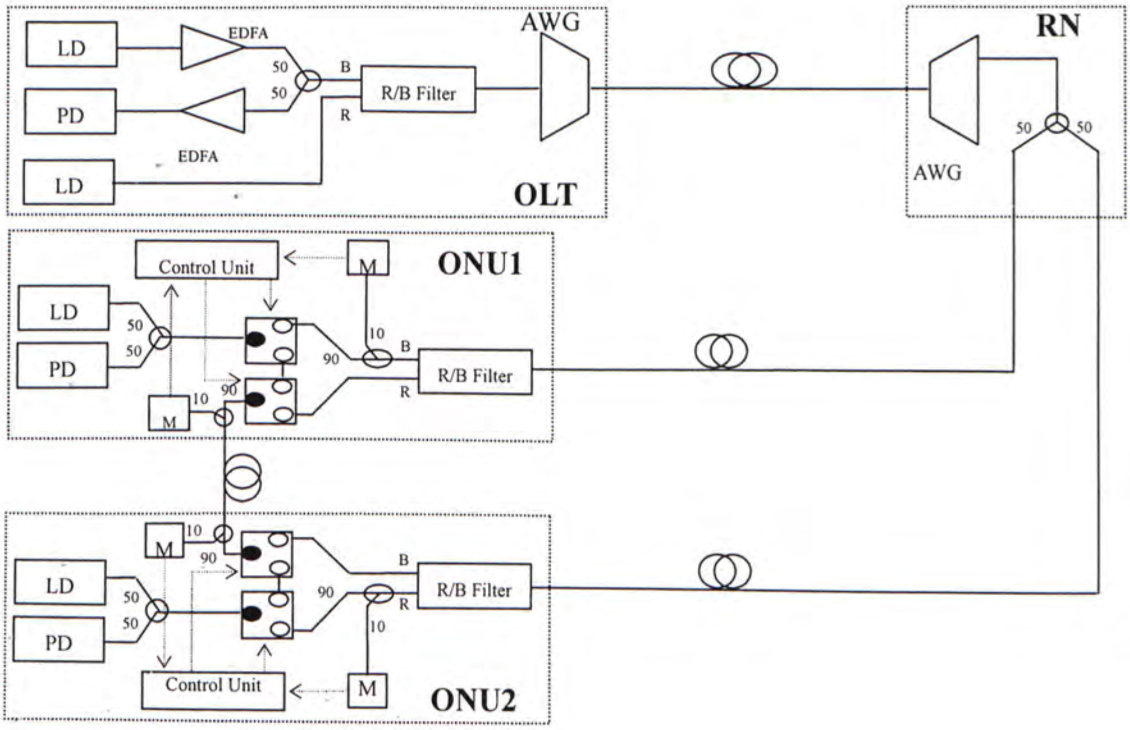


Fig. 4.1 Experimental setup for the GPA scheme

4.2.2 The EGPA Scheme

Similar to the previous scheme, we have experimentally investigated the transmission performance and protection switching of the EGPA scheme. The experimental setup is shown in Fig. 4.2. The parameters of the components are about the same as the GPA scheme. The use of avalanched photodiode (APD) instead of PIN photodiode is the only difference between the two schemes. We want to use APD instead of PIN because APD has a higher sensitivity and therefore we can transmit through a longer span of fiber. In addition, we have also carried out a study on the crosstalk performance of this scheme, using the setup as in Fig. 4.3. An external modulator is used to modulate the three adjacent channels coming from the three lasers in the OLT, and one of them are used to analyze the crosstalk penalties. 4 km of dispersion compensating fiber (DCF) is used to decorrelate the data streams.

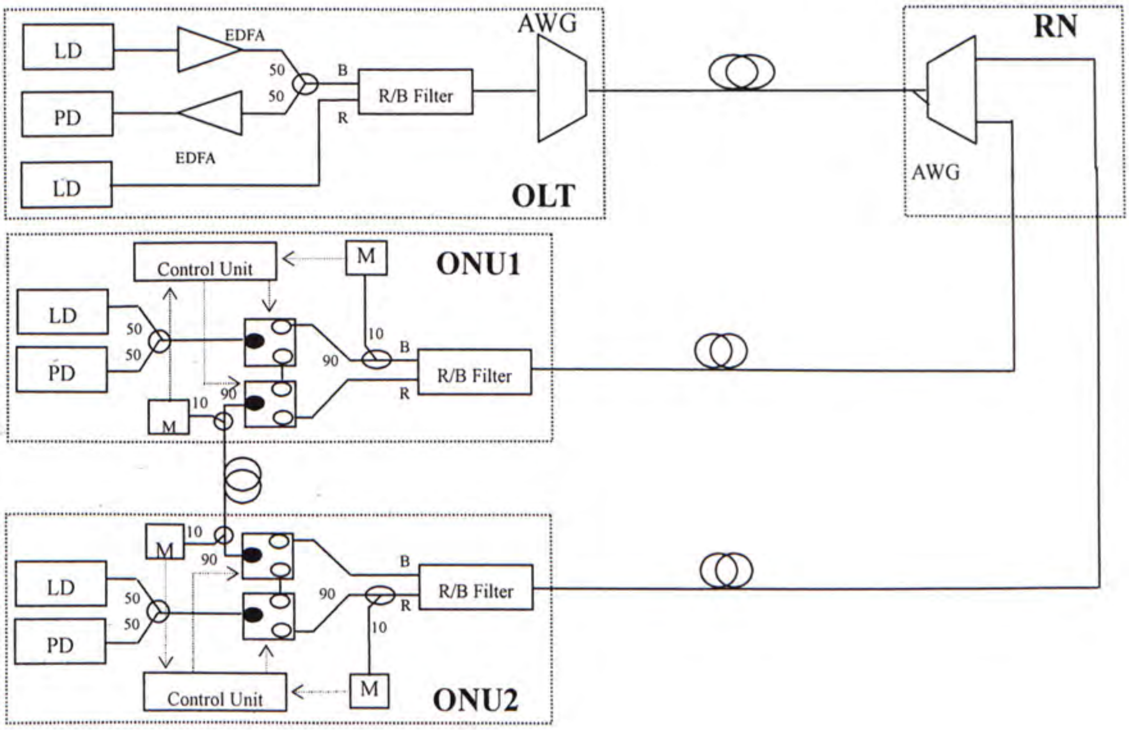


Fig. 4.2 Experimental Setup for the EGPA scheme.

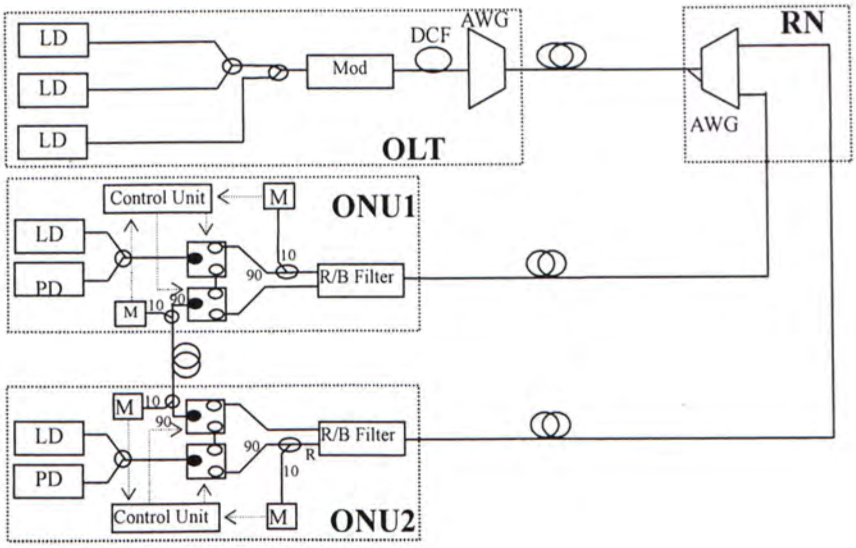


Fig 4.3 Experimental Setup for measuring the crosstalk penalty

4.2.3 The Hybrid Ring Scheme

The experimental setup for the hybrid ring scheme is shown in Fig. 4.4. Similar to the previous two schemes, 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 12.8 nm was used for the RN. At the ONUs, each Red/Blue filter had a bandwidth of about 18 nm in each passband. APD is also used in this case, and no EDFA is required for this scheme.

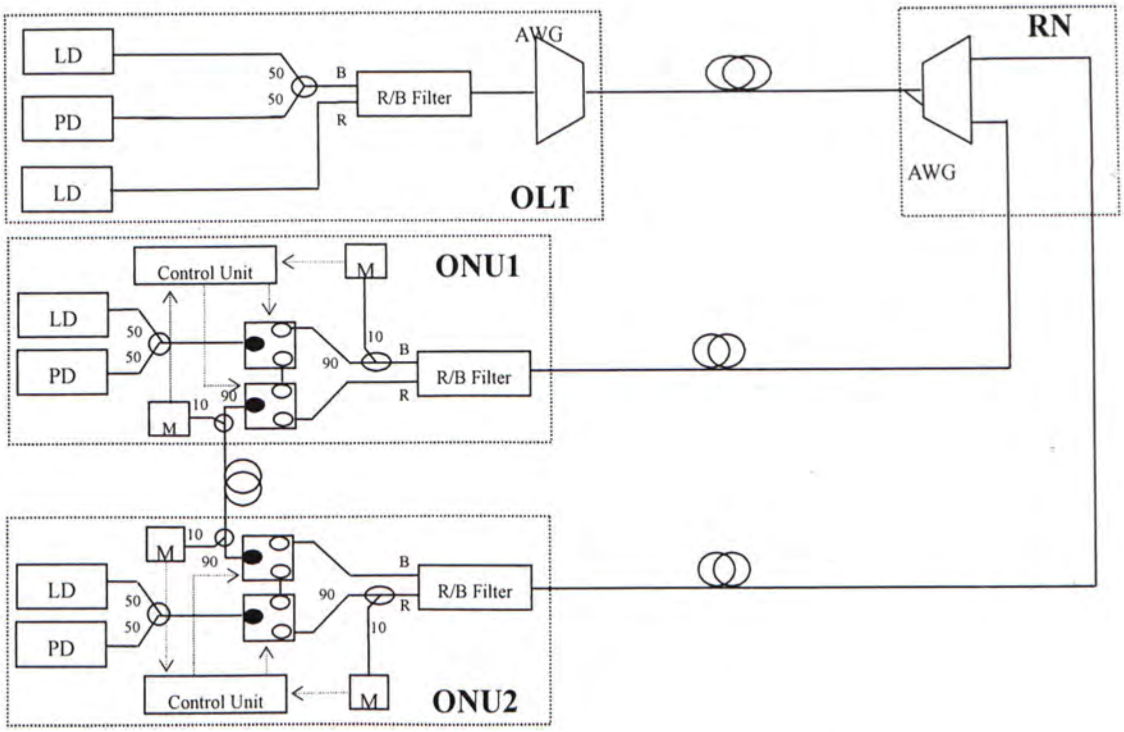
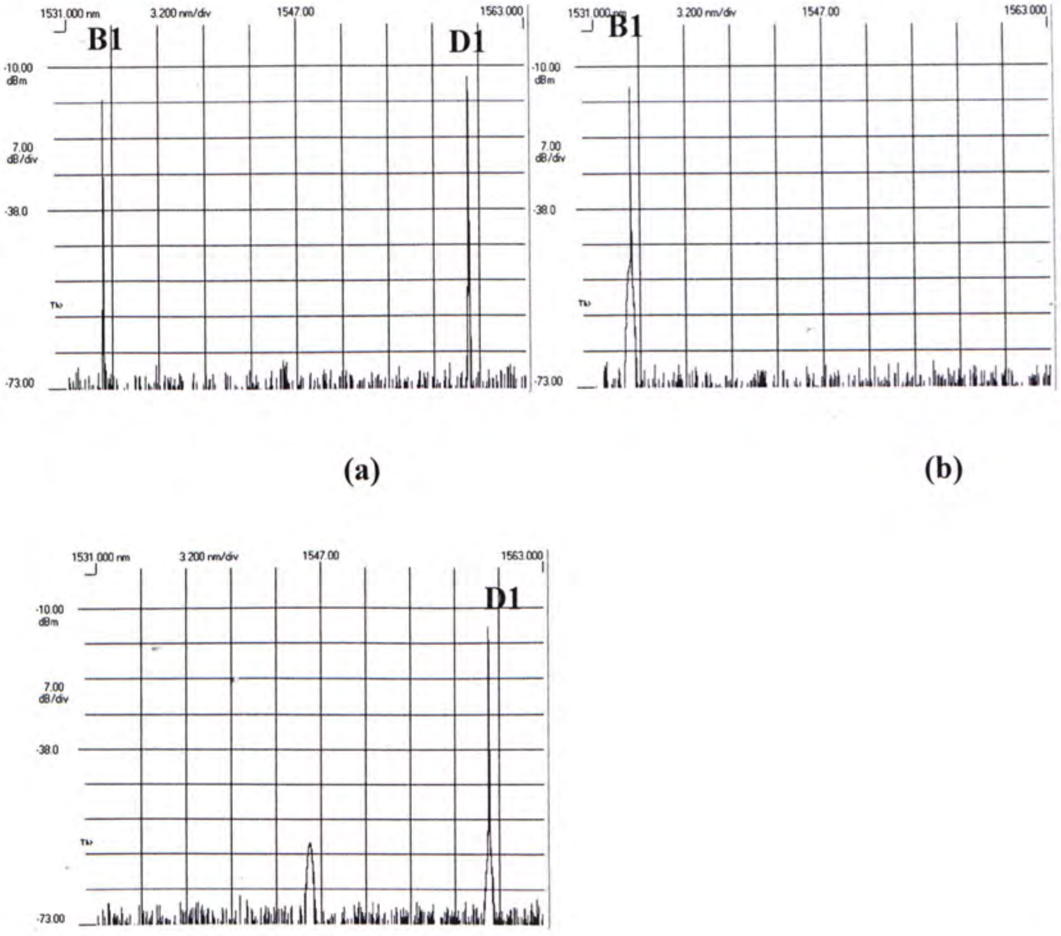


Fig. 4.4 Experimental Setup for the Hybrid Ring scheme.

4.3 Experimental Result

4.3.1 Optical Spectrum

At OLT, two DFB lasers were used illustrate the operation of the downstream side of the system. First, the two downstream wavelengths (B1 & D1) were combined by the Red/Blue filter (Fig. 4.5(a)), and then passed through the AWG in the OLT. Fig. 4.5 (a) shows the optical spectrum of output signal from OLT. The downstream signal was then passed over a piece of 18km single-mode fiber to the RN's AWG and then reached the ONU#1 and ONU#2. At ONU#1 and OLT#2, the two downstream wavelengths were separated by a Red/Blue filter and each of them was detected at the respective ONU. Figs. 4.5(b) and 4.5(c) show the optical spectra of the downstream wavelength, B1, received at ONU#1 and the downstream wavelength, D1, received at ONU#2.



(a)

(b)

(c)

Fig.4.5 (a) to (c): Optical spectra of the downstream signals at (a) output of OLT; (b) ONU#1; and (c) ONU#2.

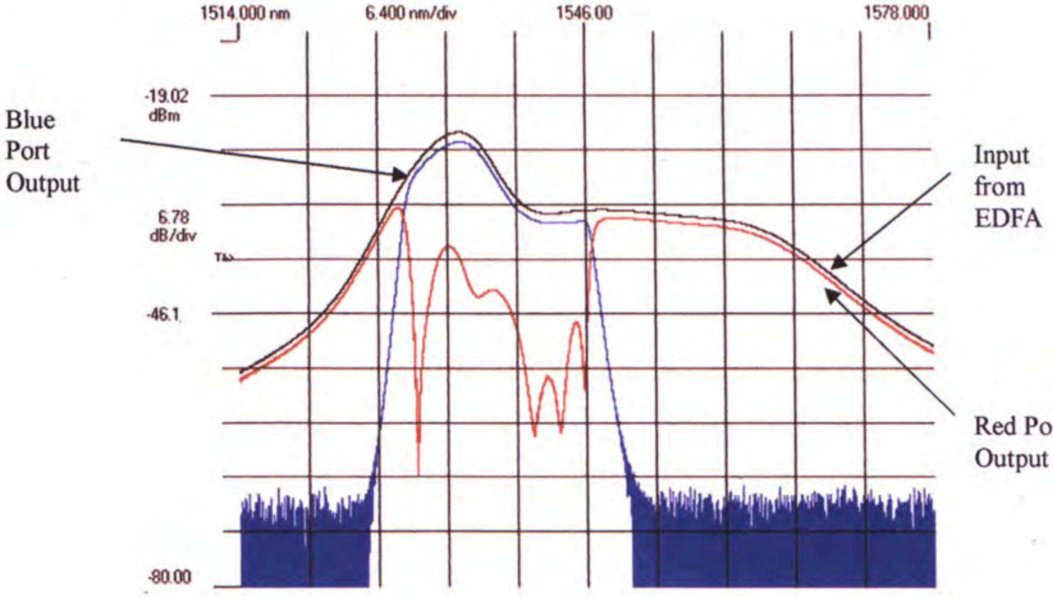


Fig 4.6 Transmission Characteristic of the Red/Blue Filter

Fig. 4.6 shows the transmission spectrum of the Red/Blue filter. The black curve is the input spectrum, which was obtained from the ASE of the EDFA. The blue curve is the output from the blue port, which passes the wavelengths from 1528 nm to 1543 nm. The red curve is the output from the red port, which passes the wavelengths from 1546 nm and above.

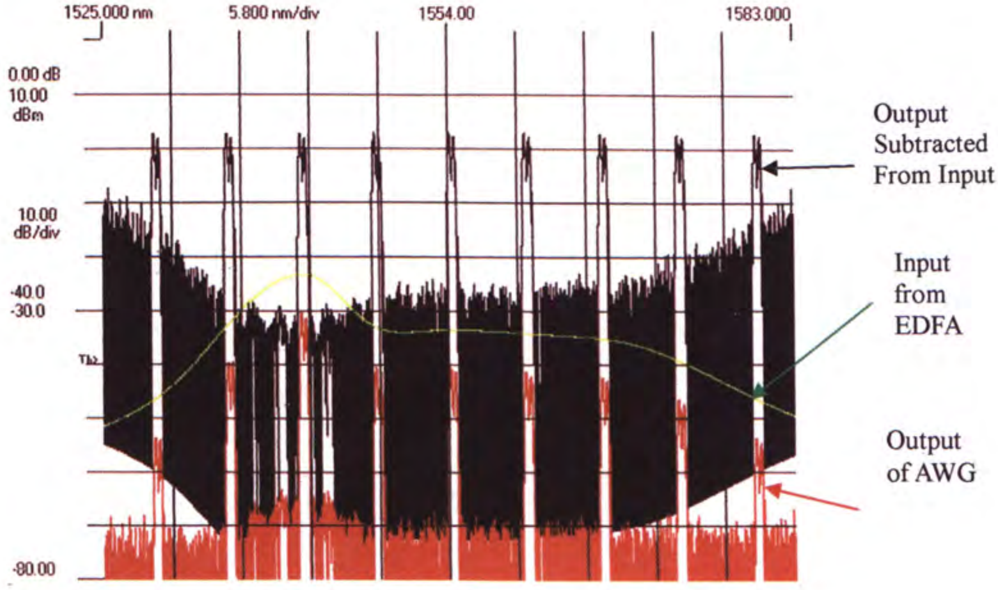


Fig 4.7 Transmission Characteristic of the AWG

Fig. 4.7 shows the transmission spectrum of the AWG. We connect two ports of the AWG to the EDFA, and the input spectrum is shown in green curve. The red curve is the output of the AWG, and the black curve is the subtraction of the red line from the green curve. It shows that the each port of the AWG is capable to transmit more than one wavelength, provided that they are separated by multiples of FSR. The black curve shows that the response of the AWG over several FSRs remains very flat.

4.3.2 Transmission performance

GPA Scheme

We have measured the bit-error-rate (BER) performance using 2.5-Gb/s 2^{23}-1 PRBS data for both the upstream and the downstream traffic; and the measurement results were depicted in Fig. 6.6. 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 RN 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 –25 dBm to –27 dBm. From Fig 4.8, there is a small power penalty (less than 2 dB), which can be attributed to chromatic dispersion, imperfect filtering of the AWG and filters, and reflections from the optical switches and the connectors.

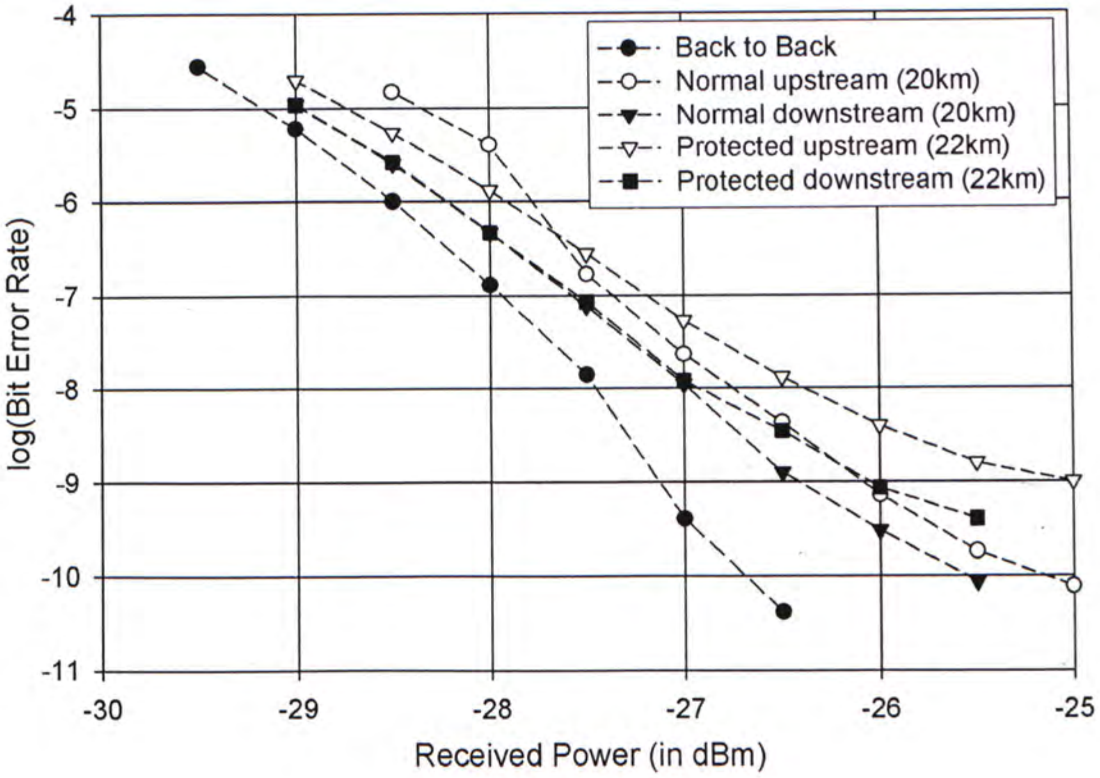


Fig. 4.8 Measured BER Curves for the GPA scheme

EGPA Scheme

The bit-error-rate(BER) performance using 2.5-Gb/s 2^{23}-1 PRBS data for both the upstream and the downstream traffic; and the measurement results were depicted in Fig. 4.9. 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 RN 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 –31.5 dBm to –32.6 dBm. The small (less than 1 dB) induced power penalty was mainly due to chromatic dispersion, imperfect filtering of the AWG and filters, and reflections from the optical switches and the connectors.

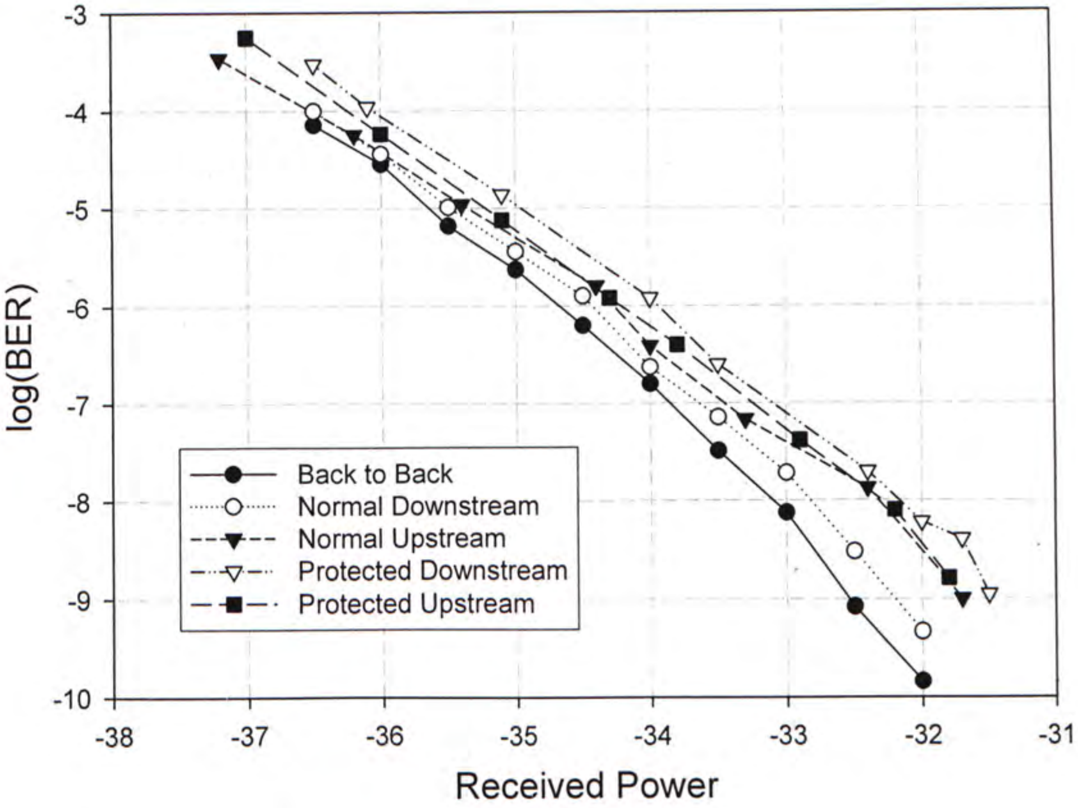


Fig. 4.9 BER measurement of the upstream and the downstream wavelengths of the EGPA scheme

HR Scheme

The bit-error-rate(BER) performance using 2.5-Gb/s 2^{23}-1 PRBS data for both the upstream and the downstream traffic; and the measurement results were depicted in Fig. 4.10. 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 RN 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 –30.5 dBm to –31 dBm. The small (less than 1 dB) induced power penalty was mainly due to chromatic dispersion, imperfect filtering of the AWG and filters, and reflections from the optical switches and the connectors.

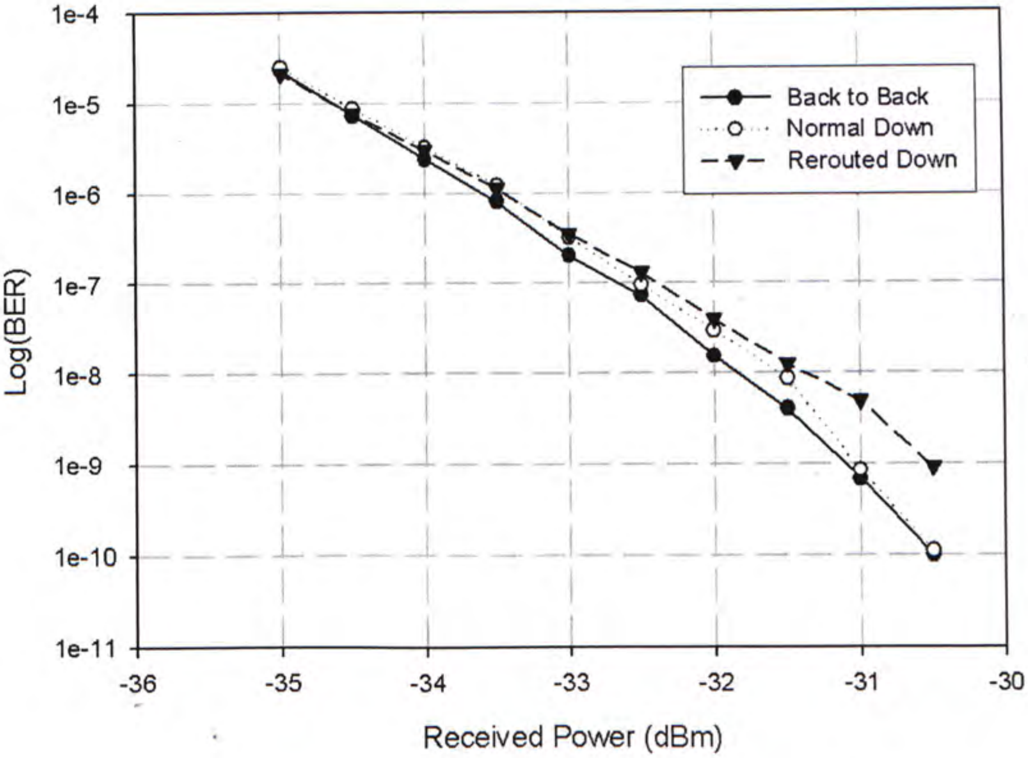


Fig. 4.10 BER measurement of the downstream wavelengths of the Hybrid Ring scheme

4.3.3 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 RN. The optical power of the downstream signals from the RN and from the ONU^2_i were monitored and the result was shown in Fig. 4.11. 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. The switching time was measured to be about 18 ms for GPA scheme and 9 ms for EGPA and HR scheme. This corresponded to the network traffic restoration time. Faster restoration time was achieved in EGPA and HR schemes since only one switch has to be reconfigured, as illustrated in Fig. 4.12. One point to note is that the actually switching operation of the optical switch is only around 3ms. The remaining time is actually the electronic circuit delay.

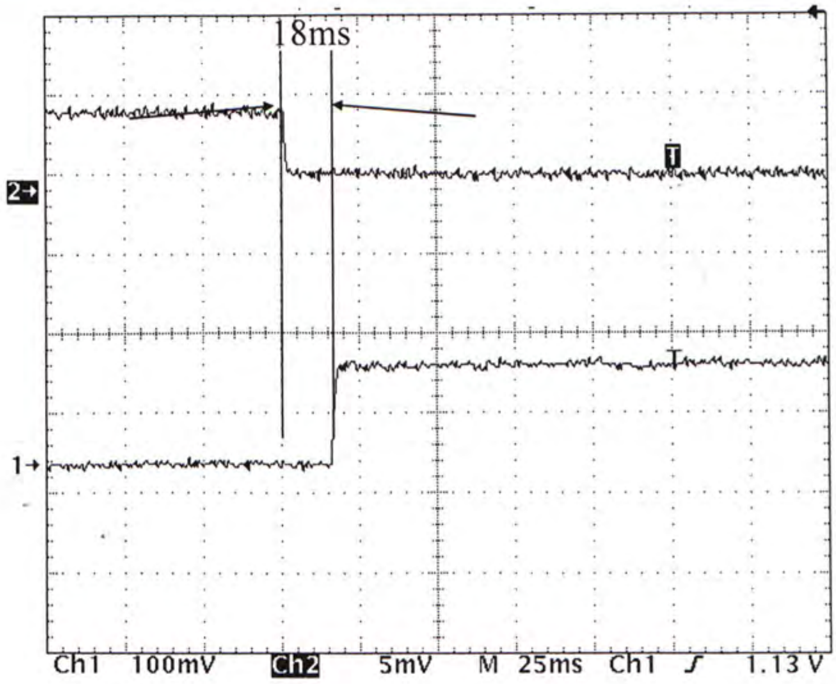


Fig. 4.11 Switching time for GPA scheme

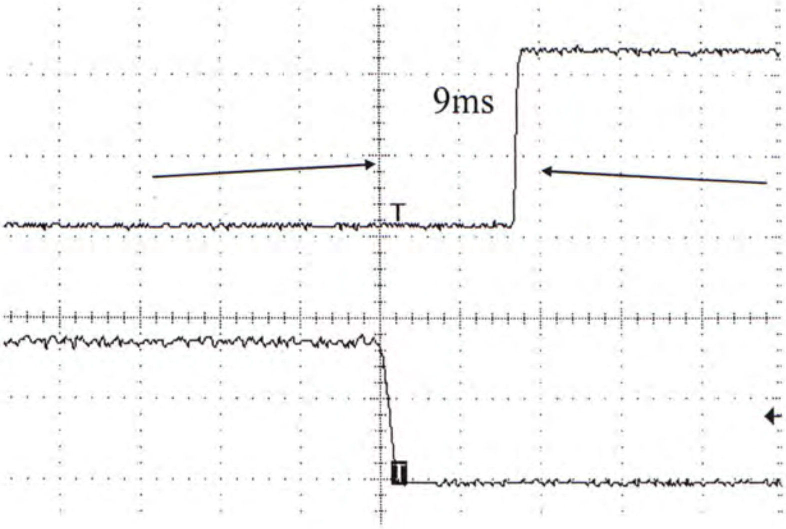


Fig 4.12 Switching time for EGPA and HR scheme

4.3.4 Crosstalk Penalty

The possible penalty induced by multiple wavelengths was also measured. One crosstalk channel and six adjacent upstream/downstream wavelengths were operated at the same time in the proposed network. In all cases, the crosstalk penalty induced was found to be about 0.5dB. The BER performance of the crosstalk case is shown in Fig. 4.13.

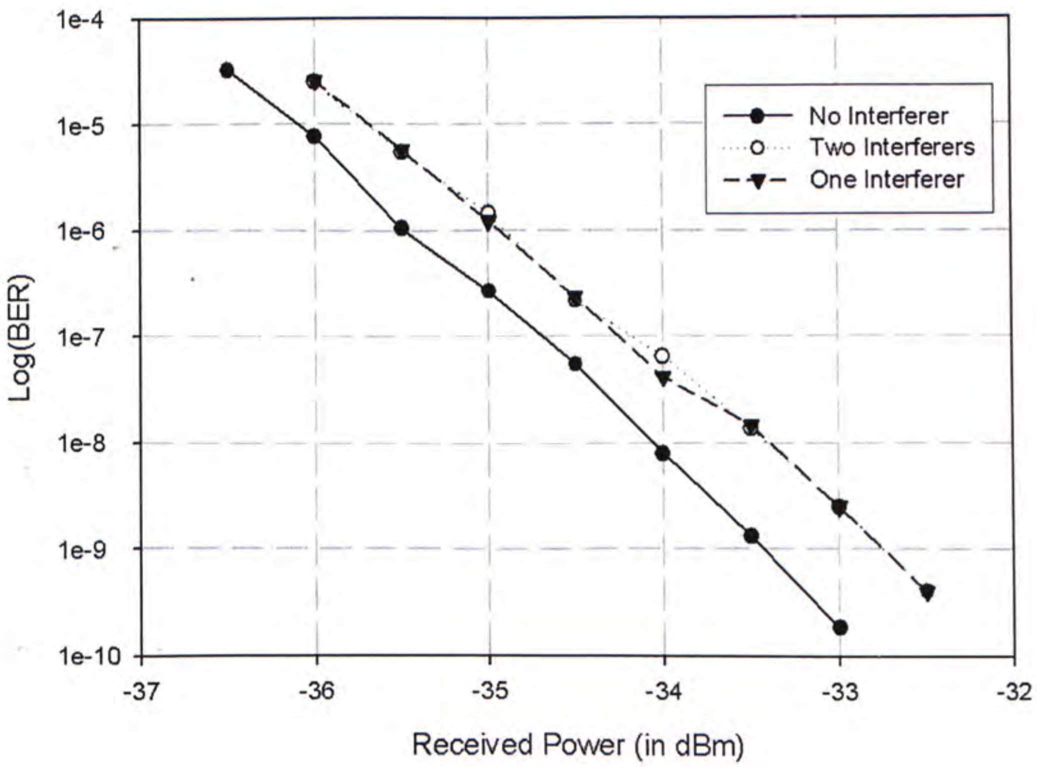


Fig. 4.13 BER measurement of the various crosstalk channels

4.4 Conclusion

We have experimentally investigated the performances of the three proposed schemes for WDM-PONs. We verified that by incorporating simple optical switches and optical filters into the ONUs and by connecting two ONUs in the same group by a single piece of fiber, protection of the bi-directional data signals can be achieved. Thus the isolated ONU can still communicate with the OLT in case of fiber cut. The transmission aspect of 2.5Gb/s signals was experimentally characterized, including the BER performances, switching speed and crosstalk penalty.

Chapter 5

Conclusions and Future Works

5.1 Introduction

In this chapter, we will draw some conclusions on the project and make recommendations on future directions. In section 5.2, we will draw some conclusions on the three proposed schemes and the experimental results. In section 5.3, we will give some recommendations on possible future works.

5.2 Conclusion

In this thesis, we have proposed three novel schemes of WDM-PON which have various levels of survivability. They are superior to common ATM or Ethernet based schemes because of the following reasons: i) they can provide a higher bandwidth for each ONU because of the use of a dedicated wavelength for each user, ii) they have a longer reach than the TDM-based PON which are typically in the range of 20 km, iii) they provide higher security because an ONU will not be able to receive the data destined for other ONUs, iv) they are more scalable, and v) they can provide a higher level of survivability.

There are two issues concerning the proposed network architectures. The first one is the feasibility issue, which primarily concern with the expensive equipments used, such as AWG and DFB lasers used, and also the capital cost of the system such as the cost of laying the additional fiber. The prices of various DWDM equipments are dropping dramatically in recent years, and we expect this drop in price to continue so that the use of optical fiber in access network can be as cost effective as copper wire technology given its huge bandwidth available. The second issue concerns the use of AWG in the RN, which requires a temperature control unit such that it becomes an active component in the PON. A way to work around this is the use of athermal AWG which is commercially available in the market.

5.3 Future Works

There are a number of interesting future directions to further extend this project:

Firstly, we can focus more on the use of more low cost components. Although the proposed networks consist of mainly passive components, some of them are still quite expensive nowadays, for example DWDM lasers and optical switches. A possible way to reduce cost would be using CWDM transmitters, which are much lower in cost and can provide similar performance within a short range. However, with CWDM, we do not have a suitable component that can replace AWG in DWDM systems. Therefore we need to reconsider the wavelength assignment that are used in all three schemes.

Secondly, we can consider topologies other than two levels tree, such as multi-levels tree and other ring topologies. As this scheme is protocol transparent, it can be used in combination with other TDM or SCM based schemes.

Finally, a possible investigation into the use of wireless link instead of the additional fiber can be done, and also the combination of this architecture with wireless base station or wireless LAN can be studied.

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