Internetworking Architectures for Optical Network Units in a Wavelength Division Multiplexed Passive Optical Network

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A Thesis Submitted in Partial Fulfilment

of the Requirements for the Degree of

Master of Philosophy

in

Information Engineering

August 2007

Acknowledgement

First of all, I would like to express my deepest gratitude to my thesis supervisor, Prof. Chun-Kit Chan, for his continuous support and guidance in my research. Throughout my postgraduate studies, he has taught me a lot of research methods and experimental skills. The discussion with him helped me to build a comprehensive view about this field. His scholarship and working attitude have always been inspirational to me. He has in-depth knowledge in many areas of optical communications. His advices and encouragement have inspired many research ideas which eventually led to this thesis. I would also like to thank Prof. Lian-Kuan Chen and Prof. Chinlon Lin for their continuous support and guidance.

It is my pleasure to have a chance to work alongside many talented postgraduate students in Lightwave Communications Laboratory in the Department of Information Engineering. In particular, I would like to thank Mr. Xiaofeng Sun, Mr. Ning Deng, Mr. Yuen-Ching Ku and Dr. Li Huo for their fruitful discussions and experimental guidance. I would also like to express my appreciation to lab members including Dr. Zhaoxin Wang, Dr. Guowei Lu, Mr. Jian Zhao, Mr. Siu-Ting Ho, Mr. Bo Zhang, Mr. Yin Zhang, Mr. Zhenchang Xie. Thanks must also go to Mr. W. H. Siu for his support in the fabrication of electronics and hardware.

Last but not the least, I am deeply indebted to my families for their long-term support, tolerance and encouragement. This thesis is dedicated to them.

Abstract

With the ever-increasing bandwidth demand of the broadband applications, the wavelength division multiplexed passive optical network (WDM-PON) is very promising for the future access networks to deliver high bandwidth data traffic. However, the conventional WDM-PON architectures only support both of the upstream transmission and downstream transmission, while the optical network units (ONUs) can not directly communicate with each other. The inter-ONU traffic signals have to be first transmitted to the optical line terminal (OLT), together with the upstream signal, and then be electronically routed to the destined ONUs. The round-trip propagation will also impose extra latency to the inter-ONU traffic. Therefore, it is desirable to provide the inter-ONU communication in optical layer. In this thesis, internetworking architectures with ONU broadcasting (ONU-broadcast) functionality and formation of virtual private groups of ONUs (ONU-VPG) are designed and demonstrated to achieve flexible inter-ONU communication.

In this thesis, we propose to employ the designated wavelength assignment and re-modulation technique to achieve ONU-broadcast functionality in optical layer for a WDM-PON with negligible signal interference. The network design and experimental investigation will be discussed in this thesis to show the feasibility of our proposed scheme.

In terms of ONU-VPGs formation capability, we propose two novel architectures to distinguish inter-ONU signal among different ONU-VPGs in electronic layer and optical layer, respectively. Based on the ONU-broadcast network architecture, we employ RF tones on the inter-ONU traffic signal as the identification tag. With

tunable RF components, the formation of ONU-VPGs can be dynamically re-configured by modifying the local RF tone module at the ONU.

To reduce the electronic complexity at the ONU, it is highly desirable to realize the ONU-VPGs formation functionality in optical layer. In this thesis, we propose a novel remote node (RN) design to support the flexible and reconfigurable formation of ONU-VPGs. The network can be flexibly and physically partitioned into several ONU-VPGs by employing respective star couplers at the RN.

In general, the above proposed ONU-internetworking architectures can achieve the direct communication among different ONUs in optical layer.

摘要

隨著寬帶應用需求的帶寬不斷增長，多波長無源光網絡（WDM-PON）爲光接入網傳輸寬帶數據提供了一個有效的解決方案。可是，傳統多波長無源光網絡只支持上行傳輸和下行傳輸，而光網絡單元（ONU）間並不能直接互相通信。光網絡單元互聯通信的數據必須伴同上行數據先傳輸到光纖路終端(OLT),然後由光纖路終端路由到相應的光網絡單元。這雙向傳輸會爲光網絡單元互聯通信的數據帶來額外的延遲。爲了提高網絡帶寬應用效率，在光層上提供光網絡單元互聯是必要的。本論文提出並討論了不同的光互聯網絡結構來實現光網絡單元廣播和光網絡單元虛擬組播。

要在多波長無源光網絡實現光網絡單元廣播功能，在本論文中，我們提出應用特定的波長分配計劃和再調制技術來在光層上實現多波長無源光網絡的光網絡單元廣播功能，並且信號間的干擾極小。本論文將會以實驗驗證該方案的可行性。

在光網絡單元虛擬組播方面，我們提出了兩種分別在電子處理層和光層上分辨不同光網絡單元虛擬群組的數據的網絡結構。基于光網絡單元廣播的網絡結構，我們附加特定的射頻載波組合在光網絡單元互聯通信的基帶信號上作爲光網絡單元虛擬群組的識別標簽。應用可調諧的射頻組件，光網絡單元虛擬群組可以動態設置。

爲了減少光网絡單元的電子復雜度，在光層上實現光网絡單元虛擬群組的功能是非常必要的。在本論文中，我們提出了一種新的遠端節點（RN）設計來支持方便和可重置的光網絡單元虛擬群組。在遠端節點上安放對應的星型耦合器，接入網絡可以方便地被物理上劃分爲不同的光網絡單元虛擬群組。

綜上所述，我們提出的光網絡單元互聯結構可以在光層上實現不同光網絡單元的直接通信。

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Introduction

1.1 Telecommunications network hierarchy

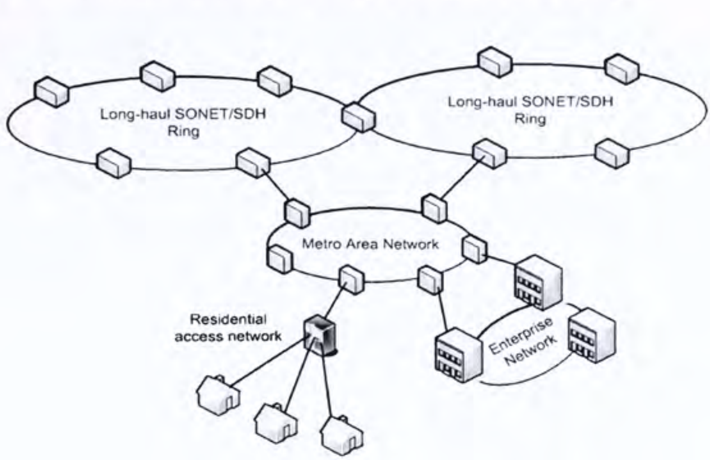


Fig. 1-1 Schematic diagram of the fibre network infrastructure

With the ability to support ultrahigh capacity for data transmission, optical communications play a major role in telecommunications network infrastructure nowadays. Typical telecommunications networks can be divided into a 3-tier hierarchy [1]: long-haul transport networks, metropolitan networks and access networks. The role of fiber optic systems will be examined with respect to these three layers.

Long-haul networks

The long-haul transport networks, also known as backbone networks, are located at the top of the hierarchy, as illustrated in Fig. 1-1. The long-haul networks usually span thousands of kilometers connecting major network hubs in different countries across different continents. Such networks are optimized in terms of transmission distance and capacity. In this area, optical fibers have been the dominant media to support such long distance high speed transmission systems. The technology breakthrough of Erbium-doped fiber amplifier (EDFA) [2] and wavelength division multiplexing

(WDM) have dramatically brought down the cost of long-haul networks and have also increased the system capacity.

Metropolitan networks

Between the access networks and the long-haul networks, metropolitan networks, with an area coverage between 10-km and 100-km, serve as feeder networks which gather and distribute traffics from access networks and aggregate them for long-haul transmission, when necessary. To successfully deliver the voice traffic, a circuit-based synchronous optical network (SONET)/synchronous digital hierarchy (SDH) has been adopted as the dominant metropolitan network architectures. To enhance network protection and restoration, the metropolitan networks can be designed with protection ring. Nowadays, to satisfy the Internet bandwidth demand, WDM technique is widely deployed in metropolitan networks to increase the system capacity.

Access networks

At the bottom layer of the hierarchy, access networks span only tens of kilometers (0 – 20-km) and they provide broadband connections for end users. There are several solutions to relieve the “last mile” bottleneck: digital subscriber line (DSL), hybrid fiber coax (HFC), Wi-Fi, powerline communication, fiber to the home (FTTH) and so on. Since it is very cost-sensitive for subscribers in access networks, the coper wire based access networks technologies play a dominant role in nowadays access networks. However, with the ever-increasing bandwidth demand of subscribers, the traditional coper wire based broadband access networks could not support such high bandwidth to deliver the emerging broadband applications such as High-definition television (HDTV) in future. Therefore, fiber optics based FTTH access networks will be very promising for the access networks. Among all optical access networks solutions, passive optical network (PON) is the most promising broadband optical fiber access networks solution. This type of optical access networks employs only passive optical components in the outside plant. Therefore, the network deployment and maintenance cost can be effectively reduced.

1.2 PON architectures for access networks

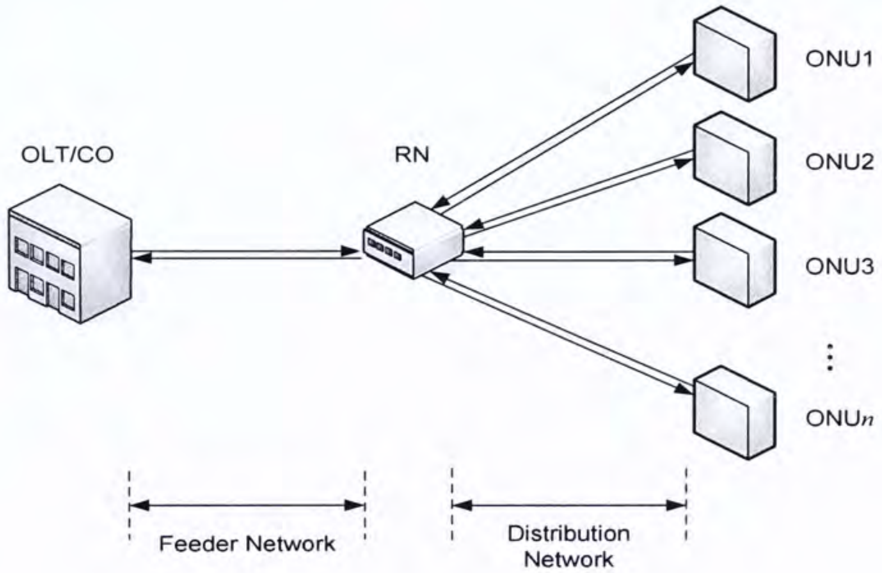


Fig. 1-2 Network architecture of passive optical network

The common optical access network is based on a tree topology as shown in Fig. 1-2. The optical network units (ONUs) located at end user premises are connected to a remote node (RN) through distribution fibers, which usually span about several kilometers. At the RN, specific components are employed to multiplex and de-multiplex the downstream and upstream, respectively. Then the RN is connected to the central office (CO) of network operators with the long fiber link, which is named as feeder fiber. Because the RN is shared by all ONUs in the network and the required fiber length is much less than the case of direct connections between ONUs and CO, the network deployment cost can be significantly reduced[1]. PON is the most popular broadband optical fiber access networks solution. It employs only passive optical components, without the presence of any electronic amplifier or regenerator, between CO and ONUs. Therefore, the network maintenance cost can be effectively reduced. Moreover, without electronic component, it can benefit the network operators to construct a robust network infrastructure for broadband application.

1.2.1 TDM-PON

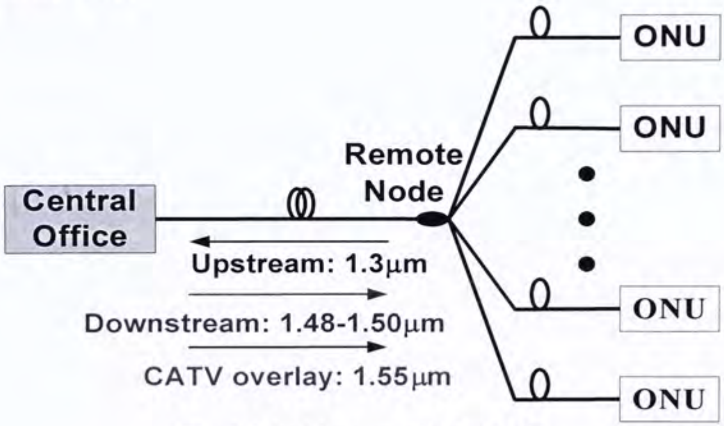


Fig. 1-3 Architecture of TDM-PON

The time-division multiplexing technology is introduced in conventional PON, which is known as time-division multiplexed PON (TDM-PON) or power splitting PON (PS-PON) [3]. Fig. 1-3 shows a typical architecture of TDM-PON [4]. A passive tree coupler is employed at the RN in a TDM-PON to achieve the downstream and upstream services. Both of the downstream and the upstream bandwidths are time-shared among all ONUs by time division multiplexing technique. Downstream optical signal is power-split into multiple replicas at the RN to be broadcasted to all subscribers in the network. At each ONU, the desired downstream signal will be filtered out by its designated time slots. On the other hand, the upstream signals from all ONUs will be coupled together at the RN, then be transmitted back to the OLT. A point-to-multipoint media access control (MAC) protocol is required to schedule the data transmission to avoid data collision.

TDM-PONs are mature PON architectures. There are several commercial PON standards: ATM PON[5], Ethernet PON[6], and Gigabit-capable PON[7]. Because the implementation for TDMA is achieved in the electronic domain and identical transceivers can be employed for all ONUs, TDM-PONs become practical and cost-effective solutions for access networks around all the world. However, by the time-sharing nature of TDM-PONs, each subscriber can only get a small portion of the downstream and upstream bandwidth. It can be anticipated that the available bandwidth for each subscriber by the TDM-PON can not satisfy the bandwidth requirement for broadband network in future. Moreover, the downstream signal is broadcasted to all subscribers in the network. The privacy issue can not be satisfied unless encryption is employed. Lastly, the ranging problem and the burst-mode receiver are required in the TDM-PON. They will increase the system cost for the comparable high electronic complexity.

In general, this power-splitting and time-sharing nature of TDM-PON impose some limitations on the scalability and security of the system. They can be alleviated by introducing wavelength division multiplexing (WDM) into PON.

1.2.2 WDM-PON

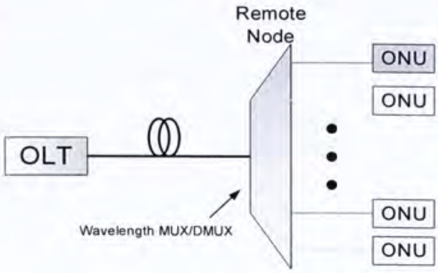


Fig. 1-4 Architecture of WDM-PON

To overcome the limitations for TDM-PON, wavelength division multiplexed PON (WDM-PON) [8][9][10] has attracted more and more attention in the academia and industry to provide an ultimate solution for broadband access networks. In the typical WDM-PON architecture shown in Fig. 1-4, multiple wavelengths are employed as the downstream and upstream carriers for the communication between ONU and OLT. At the RN, a WDM multiplexer and demultiplexer are required to route the specific wavelength to a particular ONU. This multiplexer is usually made of an array waveguide grating (AWG)[11] or thin-film filter. Therefore, each subscriber is designated with dedicated wavelengths for upstream and downstream transmissions. Each ONU can be guaranteed a certain quality of service (QoS) for broadband applications. Moreover, there is no ranging problem and power deviation problem in upstream signal in the WDM-PON. It can simplify the electronics and control in the network.

Although the cost for dedicated transceiver for each ONU is still high compared with that in a TDM-PON, both of the network operators and subscribers can benefit from the "unlimited" bandwidth provided by a WDM-PON. Therefore, many aggressive network operators pay a lot of attention to the deployment of WDM-PONs. *NTT* in Japan [12], *Verizon* [13] and *SBC* [14] in USA are the leading companies to deploy the practical FTTx access networks. With the maturity of WDM technologies and novel WDM-PON architecture with "colorless" ONUs in future, it can be expected that the cost issue for WDM-PON can be potentially reduced further.

1.3 Motivation of this thesis

As mentioned in the previous section, WDM-PON is emerging as a promising broadband access technique to meet the ever-increasing bandwidth requirement for the end users. Recently, peer-to-peer internet applications, such as sharing of data or video among peers, as well as virtual private connections among branch sites in enterprise arena are getting more popular. Therefore, it is anticipated that the amount of traffic among the subscribers in a PON is getting significantly large. Nevertheless, conventional WDM-PON architectures only support both of the downstream and the upstream transmission with a dedicated set of wavelength channels for communications between the OLT and each ONU. The ONUs could not directly communicate with each other. The inter-ONU traffic must first be transmitted, via the upstream carrier, back to the OLT, where it would be electronically routed [15] and modulated on the respective downstream carriers destined to other ONUs. This would consume the bandwidth on both of the downstream and the upstream carriers. Besides, the additional round-trip propagation time between the ONU and the OLT, as well as the increased loading to the OLT for electronic scheduling and routing of the inter-ONU traffic would impose extra latency to the inter-ONU traffic. Therefore, it is desirable to provide direct connections for internetworking of ONUs in WDM-PONs.

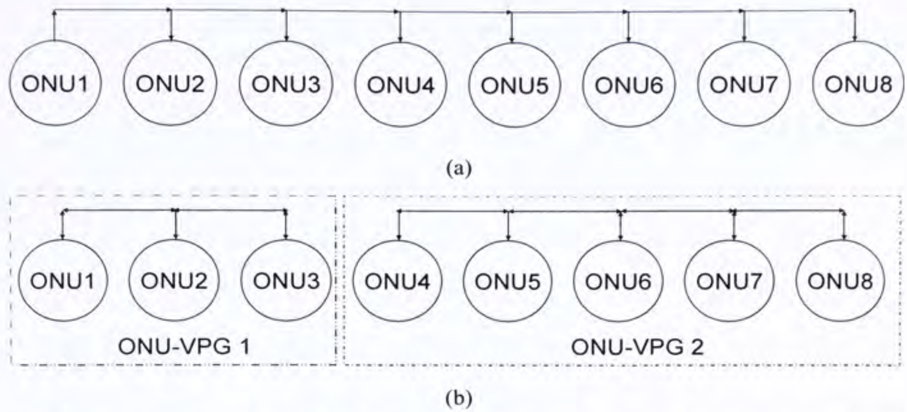


Fig. 1-5 (a) An example of ONU-broadcast in which each ONU can communicate all other ONUs in the network.; (b) an example of having two ONU-VPG in the network in which each ONU can only communicate with those ONUs in its own ONU-VPG.

The ONU internetworking functionality could be implemented in two different scenarios, namely, inter-ONU broadcasting functionality (ONU-broadcast) and the formation of virtual private group of ONUs (ONU-VPG). In the ONU-broadcast scenario, the inter-ONU traffic from an ONU can be broadcasted to all other ONUs, as illustrated in the example in Fig. 1-5(a). On the other hand, in some practical situations, inter-ONU communication is needed among a few ONUs only in the WDM-PON, therefore, it is desirable to have a number of ONUs grouped together to form a virtual private group, such that the inter-ONU traffic sent from one ONU would be broadcasted to the ONUs which belong to its virtual private group only, while ONUs belonging to other virtual private groups could not access that traffic, as illustrated in the example in Fig. 1-5(b). The formation of such virtual private groups of ONUs should be arbitrary and flexible and a WDM-PON can support several ONU-VPGs, simultaneously.

In this thesis, we propose and demonstrate novel architectures to support direct communication for ONUs in WDM-PONs in optical layer to improve the system performance.

In terms of ONU-broadcast functionality, we propose and experimentally demonstrate a novel flexible ONU internetworking architecture over a WDM-PON in this thesis. By employing our designated wavelength assignment and re-modulating the downstream DPSK signal as the ONU-internetworking carrier, one ONU can broadcast its own message to all other ONUs except itself, with negligible signal interference.

In terms of ONU-VPGs scenario, novel architectures to facilitate the ONU-VPGs formation in electronic layer and optical layer are proposed and experimentally demonstrated. Based on the ONU-broadcast architecture, the inter-ONU communication can further be partitioned into arbitrary virtual private groups of ONUs by employing designated RF tones for identification and control. It was experimentally demonstrated that the performance degradation due to the introduction of RF tones is negligible compared with the full broadcast case.

To reduce the electronic complexity by introducing the additional RF tones at the ONU, we propose a novel wavelength assignment and design of RN to facilitate the ONU-VPGs formation in optical layer directly. With identical transmitters for inter-ONU traffic for all ONUs, the cost for implementation for our proposed architecture can be potentially reduced.

In general, our proposed schemes can provide high flexibility and practical inter-ONU communication in a WDM-PON.

1.4 Outline of this thesis

The organization of the remaining chapters of this thesis will be as followings:

Chapter 2: Previous internetworking architectures are reviewed.

Chapter 3: Novel ONU-broadcast architecture based on specific wavelength assignment and re-modulation technique is proposed and experimentally demonstrated.

Chapter 4: Novel architectures with ONU-VPGs formation capability are proposed and discussed. The ONU-VPGs formation functionality is achieved in two approaches: electronic identification technique and direct optical layer.

Chapter 5: Summary and future works.

Chapter 2
Previous Internetworking Architectures for Optical Network Units in Passive Optical Networks

2.1 Introduction

As mentioned in the previous chapter, the conventional WDM-PONs can not support direct communication among ONUs in the network. Providing direct optical connections among ONUs in the network can benefit both of the network operators and the network customers. In terms of network operators, the inter-ONU traffic can be directly transmitted and received among the ONUs without the requirement for centralized complex routing protocol at the OLT, if the direct physical connections for ONUs are provided in the networks. Thus, the bandwidths of downstream and upstream can be fully applicable for the high value-added broadband applications, just as HDTV, Internet Protocol Television (IPTV) and so on, with guaranteed certain QoS. On the other hand, the direct physical connections among ONUs can support the secure transmission for the local private data. The security issue is an increasing concern for business networking applications nowadays. Therefore, the direct connections among ONUs is highly desirable in WDM-PONs in future.

The major research interest on this topic is to develop a practical and feasible internetworking architecture for access networks. Besides, there are also some research interests to use one single laser diode to transmit both of the upstream and the inter-ONU traffic[16] [17] to reduce the cost for ONU. In this chapter we will review several previously proposed schemes providing the internetworking capability among ONUs in the PONs. Basically, these schemes can be divided into two categories: ONU-broadcast in the PONs, ONU-VPGs formation in the PONs. Besides, a protection scheme for the internetworking architecture is also reviewed.

2.2 Previous internetworking architectures with ONU-broadcast capability

In an ideal case of ONU-broadcast scenario, the local ONU can directly communicate with other OUNs in the network without the co-ordination by the OLT. Recently, several schemes were reported to achieve the ONU-broadcast functionality in the PON architectures. These schemes can be categorized into three approaches: virtual ring network construction [18], reflection mechanism employing a fiber Bragg grating (FBG) [19] and loop-back connections architecture in TDM-PONs [20].

2.2.1 Virtual ring network construction

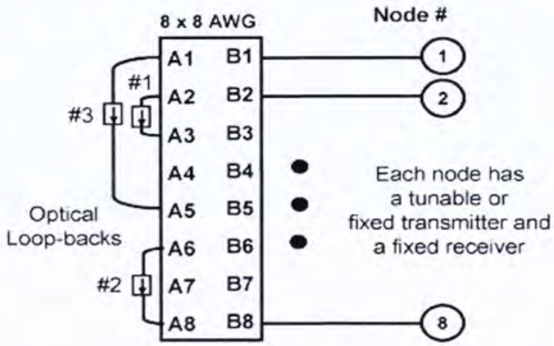


Fig. 2-1 Virtual Ring Network Architecture [18]

In [18], a network architecture employing the cyclic property of AWG located at the RN was proposed and demonstrated. With tunable launching wavelength or tunable optical filter, the inter-ONU traffic can be routed to a specific output port of AWG, therefore can be destined to the specific ONU. In this way, the internetworking capability among ONUs can be implemented. However, because the internetworking capability was realized in the way of ring nature, the inter-ONU traffic cannot be broadcasted in the network. It would impose additional latency compared with the broadcasting nature. Moreover, a tunable laser source or tunable optical filter was required to implement the dynamic routing of inter-ONU traffic. It was not cost-effective to employ tunable optical components at the ONU.

2.2.2 Reflection mechanism employing a FBG

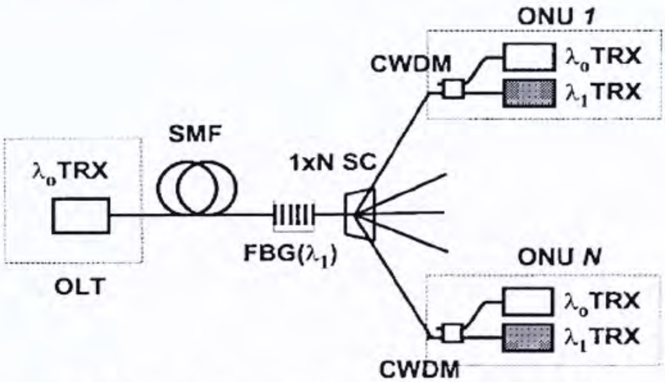


Fig. 2-2 Reflection mechanism based on a FBG [19]

The basic working principle of this scheme in [19] was to differentiate the designated inter-ONU traffic signal by the FBG located before the $1 \times N$ star coupler at the RN. Further in [21], to save one additional laser source for the inter-ONU traffic, RF subcarrier technique was employed to shift the inter-ONU traffic signal to a higher frequency. The reflected spectrum of FBG was designed to be aligned with the carrier frequency of the inter-ONU traffic signal. In this way, the inter-ONU traffic signal can be reflected by the FBG located before the star coupler at the RN, and then be power split and broadcasted to all other ONUs in the same network. This configuration can be compatible with the conventional TDM-PON architectures. Only one additional passive FBG was required at the RN. However, the inter-ONU traffic signal would suffer from a round trip of high splitting loss of the $1 \times N$ star coupler. It would cause the power limitation issue to limit the transmission data rate for the inter-ONU traffic. Besides, the outgoing inter-ONU signal and the reflected signal from the FBG were simultaneously transmitted over the same distribution fiber. This may lead to possible power penalty due to Rayleigh back-scattering-induced interference.

2.2.3 Loop-back mechanism in TDM-PON

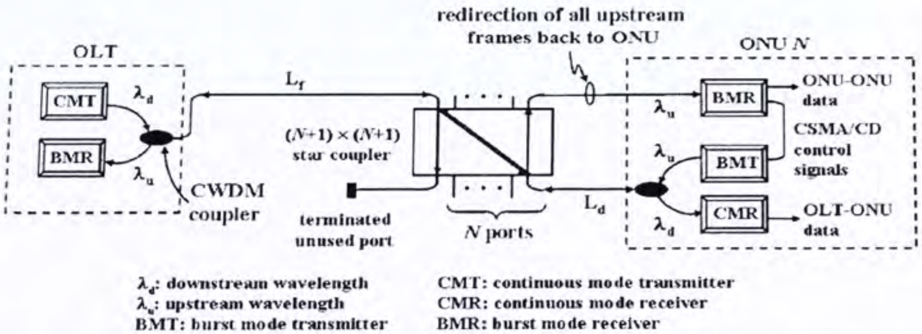


Fig. 2-3 Loop back connections architecture based on $(N+1) \times (N+1)$ star coupler [20][22]

A loop-back mechanism was proposed to achieve the ONU-broadcast functionality for TDM-PONs in [20] [22]. The $(N+1) \times (N+1)$ star coupler was employed at the RN to redirect the inter-ONU traffic signal to all ONUs in the network. Compared with the previous reflection mechanism based on a FBG, the inter-ONU traffic would not experience high insertion loss by the round-trip transmission through star coupler. Therefore, it can greatly alleviate the power limitation in this scheme to support high-speed data transmission. However, the scheme is suitable for TDM-PONs only.

2.3 Previous internetworking architectures with ONU-VPGs formation capability

As mentioned in the chapter 1, it is necessary to provide ONU-VPGs formation capability in a WDM-PON. With the ONU-VPGs formation ability, the data sharing can be limited in a specific group of ONUs in the network. Therefore, the flexibility and security of data transmission can be enhanced. To achieve the ONU-VPGs formation, there are three major reported schemes: electronic code-division multiple access (E-CDMA) application [23], subcarrier multiplexed (SCM) technique [24], and reflective waveband grouping mechanism [25] .

2.3.1 E-CDMA application

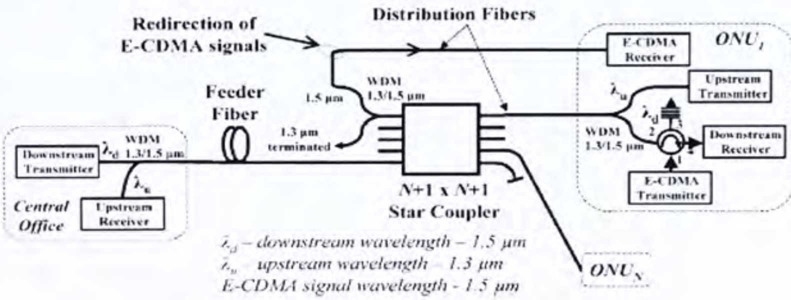


Fig. 2-4 Multiple ONU-VPGs architecture based on E-CDMA [23]

To achieve a designated ONU-VPGs formation in the network, E-CDMA was employed to provide the identification control for the inter-ONU traffic. The operation principle was illustrated in Fig. 2-4. It was based on the loop-back connections to broadcast the inter-ONU traffic. Other than providing the identification functionality in the higher layers, the E-CDMA encoder and decoder were employed in the physical layer at each ONU. The same code was shared in each ONU-VPG.

The advantages for E-CDMA technique were that no additional modification in the optical layer was required to distinguish among different ONU-VPGs in the broadcasting networks. The E-CDMA encoders and decoders can be flexibly to be reconfigured at the ONUs according to the application requirements. Moreover, the E-CDMA encoders and decoders were mature equipments with mature electronics processing techniques. Therefore, they could be potentially low cost for implementation at the ONU. However, the employment of E-CDMA would suffer from two drawbacks: First, the demonstrated transmission speed for inter-ONU traffic was quite limited at 40-Mb/s for each ONU group. The transmission speed was mainly limited by multiple access interference (MAI) and optical beat interference (OBI) when inter-ONU traffic signals of different ONU-VPGs were transmitted on the same carrier. Secondly, the coding gain of CDMA would require the transmitter to perform at much higher data rate than the data rate of the inter-ONU traffic. It would increase the cost of the high-speed laser diodes at the ONUs. Therefore, it was necessary to improve the transmission speed and reduce the system cost for the ONU design.

2.3.2 SCM technique

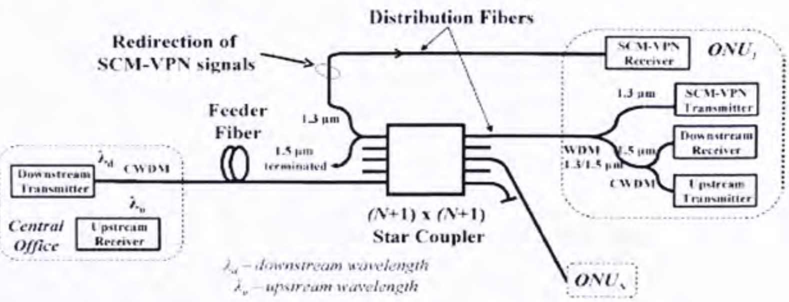


Fig. 2-5 Multiple ONU-VPGs based on SCM technique [24]

Subcarrier multiplexed technique was an alternative approach to provide the identification control for the inter-ONU traffic in different ONU-VPGs. In [24], the multiple ONU-VPGs formation based on employment of the SCM technique in broadcasting loop-back connections network architecture was demonstrated. For each distinct ONU-VPG, a specific subcarrier frequency was assigned and multiplexed with the baseband data of inter-ONU traffic. After power splitting of the star coupler, all the signals multiplexed with baseband inter-ONU data would be broadcasted to all ONUs in the network. To distinguish different data for different ONU-VPGs, an electronic bandpass filter at the ONU was required to filter out the specific signal for that ONU-VPG. In this way, the network can be divided into multiple ONU-VPGs. The inter-ONU traffic of one ONU-VPG would be received by other ONUs within the same ONU-VPG only. Similar to the previous case employing E-CDMA technique, SCM technique would also make the inter-ONU signal suffer from MAI and OBI noise. The inter-ONU signal transmission speed was thus limited. Furthermore, SCM technique may be complex and difficult to re-configure the ONU-VPGs connection dynamically. As the ONU-VPG functionality was realized in the electronic domain sharing the same physical optical network, the security issue was not guaranteed unless encryption was employed. It was better to provide the ONU-VPGs formation in the optical layer to enhance the security issue and flexibility.

2.3.3 Reflective waveband grouping mechanism

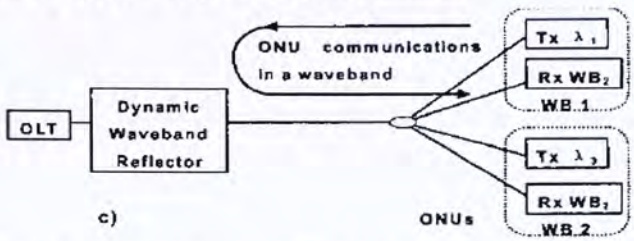


Fig. 2-6 Reflective waveband grouping mechanism [25]

In [25], a waveband grouping mechanism was employed to realize the internetworking functionality among ONUs in the network. The operation principle was that each ONU-VPG employed specific waveband transceivers for the inter-ONU traffic. A dynamic waveband reflector located at OLT was employed to reflect the selected wavelength to all ONUs. The optical filter at the ONU can selectively filter out the required inter-ONU traffic signal for that ONU-VPG. Therefore, the internetworking capability can be realized by the help of waveband grouping mechanism and dynamic waveband reflector. However, it was required to modify the waveband reflector and the waveband of ONUs when ONU-VPGs formation was required to be modified after initial network deployment.

A similar architecture was proposed in [26] to provide the inter-ONU capability for ONUs in different PONs. However, the internetworking functionality was limited to ONUs with the same colour in different PONs. It would limit the applications of this kind of network architecture in terms of flexibility and reconfigurability. Moreover, synchronization or signalling was required between the waveband reflector at the OLT and the inter-ONU traffic signal at the ONU. It would increase the implementation complexity of the system.

2.4 Previous protection scheme for internetworking architectures

To provide the robust broadband network for subscribers, survivable network architectures have drawn much attention in the academia and industry. Protection switching architecture was suggested in *ITU-T G.983.1* to provide survivability in PON networks [5]. There are also several promising protection architectures proposed for WDM-PONs recently, such as the group protection architecture (GPA) [27]. For internetworking architectures, the survivability is also a critical issue to maintain smooth and robust data transmission for the inter-ONU traffic. In addition to the general issues faced by the protection in normal PON architectures, the protection for the internetworking architecture has its own features. Therefore, survivable protection functionality is highly desirable for internetworking network architectures.

2.4.1 Local ring protection in TDM-PON

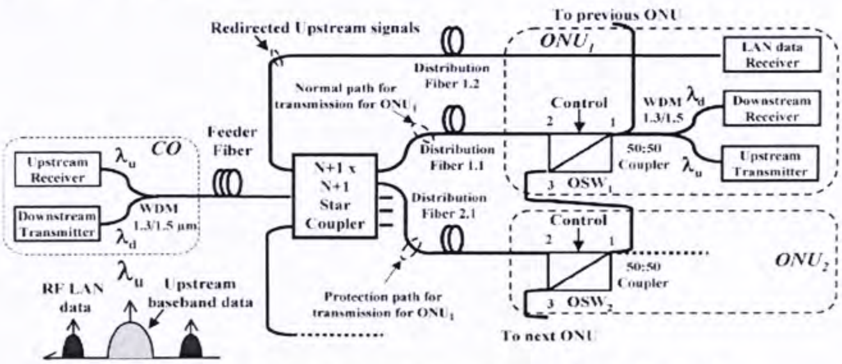


Fig. 2-7 Local ring connection protection in TDM-PON [28]

Recently, an automatic switching protection scheme was proposed to provide protection functionality for the internetworking architecture based on the reflection mechanism employing a FBG and the loop-back connections architecture [28]. As shown in Fig. 2-7, each ONU was connected to both of its two neighbouring ONUs. Therefore, it could provide alternative fiber paths for the ONU to transmit the inter-ONU traffic when the distribution fiber was broken. In the protectionmode, the inter-ONU traffic and the upstream signal would be transmitted through the protection path to the neighbouring ONU, before being fed back the RN. Therefore, the proposed scheme could provide survivability for the ONUs to facilitate the inter-ONU communication. However, the additional fiber and optical switches were required to construct the alternative paths for the ONUs. It may be high cost to deploy the fiber to connect the neighbouring ONUs.

2.5 Summary

In this chapter, previous internetworking architectures and related protection schemes have been reviewed. In terms of the internetworking functionality, the internetworking architectures can be mainly divided into two categories: ONU-broadcast in the PONs, ONU-VPGs formation in the PONs.

In terms of ONU-broadcast in the PONs, the proposed schemes were mainly achieved by virtual ring network construction, loop back connections and reflection mechanism based on FBG technique. All schemes suffered from limitations in terms of flexibility, transmission bit rate and reconfigurability.

In terms of ONU-VPGs formation in the PONs, there were three major approaches in electronic processing layer and optical layer, respectively. The electronic multiplexing techniques, such as E-CDMA and SCM, were employed to distinguish the specific inter-ONU traffic to facilitate the ONU-VPGs formation in the PONs. Such kinds of electronic techniques would make the network suffer from low transmission bit rate limited by the MAI noise. On the other hand, the waveband grouping mechanism was also proposed to achieve the ONU-VPGs formation in optical layer with the help of dynamic waveband reflector located at the OLT.

In the last part of this chapter, the protection issue of internetworking architecutres has also been reviewed.

In the following chapters, novel ONU-internetworking architectures for ONU-broadcast and ONU-VPGs formation capability in a WDM-PON will be proposed and experimentally demonstrated in chapter 3 and 4, respectively.

Chapter 3
Novel Internetworking Architecture with ONU-Broadcast Capability in a WDM-PON

3.1 Introduction

Nowadays, the major challenge for broadband network is to deliver the high bandwidth applications for the end users. To satisfy the ever-increasing bandwidth demand, the major research attention is to improve the downstream and upstream transmission bandwidth. Novel techniques and architectures are emerging in the academia and industry, just as the 10-Gb/s WDM-PON architecture. On the other hand improving the utilization efficiency of the available bandwidth can be also an alternative way to relieve the bandwidth bottleneck for the local subscribers. For example, in some applications, the local exchanging data would be dominant in the data transmission pattern. In these scenarios, the conventional processing strategy will take the inter-ONU traffic as the normal upstream traffic, that is, the inter-ONU traffic would be first transmitted to the OLT along with the upstream traffic, before being electronically routed by the centralized router to the destined ONUs. In this kind of conventional processing procedure, not only both of the downstream and the upstream bandwidths are partly occupied by the inter-ONU traffic, the long feeder-fiber (say about 20-km in normal standard) transmission would also impose additional latency for the inter-ONU traffic data. Therefore, providing direct communication among ONUs can relax the bandwidth occupied by inter-ONU traffic in both of the downstream and the upstream signals. This can also enhance the system performance of inter-ONU applications.

As mentioned in chapter 1, ONU-broadcast functionality is to allow each ONU to broadcast its own data to all other ONUs in the network. In this chapter, a novel ONU internetworking architecture with ONU-broadcast capability is proposed and experimentally demonstrated. Re-modulation[29] of the downstream carrier is employed at the ONU to save the dedicated optical transmitter for the inter-ONU traffic at the ONU. The ONU-broadcast is realized by a designated connection pattern between the AWG and the star coupler at the RN. Therefore, the inter-ONU traffic from an ONU can be broadcasted to all other ONUs except itself, thus could alleviate the problem of backscattering-induced crosstalk on the distribution fiber in the previously proposed scheme [19].

3.2 Network topology and wavelength assignment

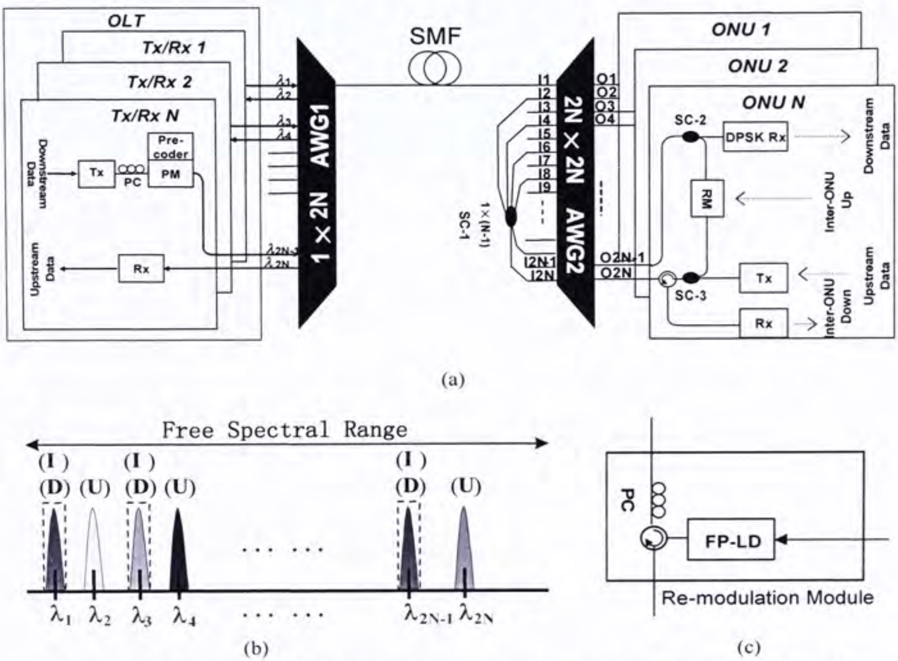


Fig. 3-1 (a) Proposed ONU-internetworking architecture for WDM-PONs. PM: optical phase modulator. RM: re-modulation module. SC: star coupler; (b) wavelength assignment plan. D: downstream wavelength. U: upstream wavelength. I: inter-ONU traffic wavelength; (c) an example re-modulation module based on employing the injection locking of an FP-laser diode.

Fig. 3-1(a) and (b) illustrate our proposed ONU-internetworking architecture for a

WDM-PON with N ONUs, and the wavelength assignment, respectively. At the OLT, N transceivers are designated for the N respective ONUs. The downstream wavelengths and the upstream wavelengths for ONU(i) are designated as λ_{2i-1} (say λ_1, λ_3, ..., λ_{2N-1}) and λ_{2i} (say λ_2, λ_4, ..., λ_{2N}) (for $i=1$, ..., N), respectively, as depicted in Fig. 3-1(b). They are chosen to match with the transmission passbands of the $1\times2N$ AWG (labeled as AWG1) at the OLT, as well as the $2N\times2N$ AWG (labeled as AWG2) at the RN. The FSR of the AWG1 is the same as that of the AWG2. All the downstream wavelengths and the upstream wavelengths are assigned within one free spectral range (FSR). At the OLT, they are multiplexed (or de-multiplexed) via AWG1 and are delivered to the RN via the feeder fiber. At the RN, a $2N\times2N$ AWG (AWG2) is employed to route the wavelengths to their destined ONUs, and its input port 1 (say I1) is connected to the feeder fiber. Each ONU is connected with two output ports of the AWG2 via two respective distribution fiber links: the first one is to carry the downstream traffic, the second one is to carry the upstream traffic, as well as the inter-ONU traffic. To perform the duplication of inter-ONU traffic, a $1\times(N-1)$ star coupler is also employed at the RN. The input port of star coupler is connected to the input port 2 (say I2) of the AWG2, while the (N-1) output ports of the star coupler are connected to the, $2k^{th}$ (k=2, ..., N) input ports (say, I4, I6, ..., I2N) of the AWG2, as depicted in Fig. 3-1(a).

3.3 Operation principle

In our proposed scheme, the downstream signals are in optical differential phase-shift keying (DPSK) modulation format [30]. Thus, the downstream optical carrier can be directly re-modulated by the upstream data traffic, and is re-used as the upstream optical carrier. As the downstream DPSK modulation format exhibits constant intensity envelope, the possible interference to the re-modulated upstream data due to the downstream data can be kept minimal. Another feasible alternative is to employ OOK format for the downstream signal. However, the extinction ratio of the signal has to be reduced to facilitate the re-modulation for the upstream data at the ONU. Thus, the OOK downstream signal would suffer from additional induced performance degradation[31]. Therefore, in this paper, we propose to employ DPSK format for the downstream signal. Each transmitter at the OLT comprises a pre-coder and an optical phase modulator. The N DPSK downstream signals are transmitted and routed to their destined ONUs via the downstream links. At each ONU, the received DPSK downstream signal is split into two parts, via a 1×2 optical coupler. One part of the downstream signal is demodulated and received, via a conventional optical DPSK receiver, which comprises an optical delayed interferometer (DI), followed by a photo-detector. Conventional optical DI has to be thermally stabilized. However, athermal optical DI is currently commercially available, thus this greatly simplifies and eases the maintenance of the DPSK receiver. On the other hand, the other part of the received downstream signal is re-modulated by the inter-ONU traffic via a re-modulation device, such as injection locking Fabry-Perot (FP) laser [31], reflective semi-conductor amplifier (RSOA) [32], etc. Therefore, the received downstream wavelength becomes the optical carrier for the inter-ONU traffic. Fig. 3-1(c) shows an example of a re-modulation device including an optical circulator and an injection-locking FP laser.

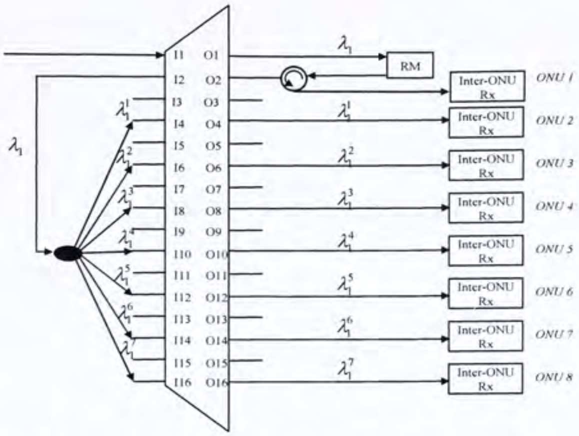


Fig. 3-2 Inter-ONU traffic routing example of ONU1.

The inter-ONU carrier propagates back to the RN via the optical circulator and the upstream link, together with the respective upstream signal. The upstream signal is routed out from the first input port of the AWG2 at the RN, where it is further delivered back to the OLT via the feeder fiber; while the inter-ONU traffic signal is routed out from the second input port of the AWG2, where it is further power-split into (N-1) copies by the 1×(N-1) optical star coupler. The j^{th} copy is denoted as λ_{2i-1}^{j}(for i=1, …, N, j=1,…,(N-1)), where the index i refers to the source ONU(i) and the respective inter-ONU carrier is λ_{2i-1}. The j^{th} copy is then fed into the 2(j+1)th input port of the AWG2. Fig. 3-2 illustrates the ONU internetworking routing principle in a WDM-PON having eight ONUs, for instance. The inter-ONU traffic from ONU(1) is modulated onto the received downstream wavelength λ_1 before being routed back to the RN, where it is power-split into seven copies. These inter-ONU traffic copies, $(\lambda_1^1,\ldots,\lambda_1^7)$, are fed into the input ports, (I4, I6, I8, … , I16) of the AWG2, respectively. Due to the input-output property of the AWG, they are routed to the output ports (O4, O6, O8, … ,O16) of the AWG2, where they are further delivered to the respective ONU(2), ONU(3), ONU(4), …, ONU(8), via the respective fiber links for the inter-ONU traffic. Therefore the inter-ONU traffic from ONU(1) would be distributed to all other ONUs except itself.

Table 3-1

Routing Pattern Example among Different ONUs

Destined ONU

Source ONU

	ONU1	*ONU2*	*ONU3*	*ONU4*	*ONU5*	*ONU6*	*ONU7*	*ONU8*
ONU1		λ_1^1	λ_1^2	λ_1^3	λ_1^4	λ_1^5	λ_1^6	λ_1^7
ONU2	λ_3^7		λ_3^1	λ_3^2	λ_3^3	λ_3^4	λ_3^5	λ_3^6
ONU3	λ_5^6	λ_5^7		λ_5^1	λ_5^2	λ_5^3	λ_5^4	λ_5^5
ONU4	λ_7^5	λ_7^6	λ_7^7		λ_7^1	λ_7^2	λ_7^3	λ_7^4
ONU5	λ_9^4	λ_9^5	λ_9^6	λ_9^7		λ_9^1	λ_9^2	λ_9^3
ONU6	λ_{11}^3	λ_{11}^4	λ_{11}^5	λ_{11}^6	λ_{11}^7		λ_{11}^1	λ_{11}^2
ONU7	λ_{13}^2	λ_{13}^3	λ_{13}^4	λ_{13}^5	λ_{13}^6	λ_{13}^7		λ_{13}^1
ONU8	λ_{15}^1	λ_{15}^2	λ_{15}^3	λ_{15}^4	λ_{15}^5	λ_{15}^6	λ_{15}^7	

With the same principle, the routing pattern among different ONUs in an eight-ONU WDM-PON is shown in Table 3-1, where the rows and the columns represent the source and the destined ONUs, respectively. λ_{2i-1}^j denotes the j^{th} copy of the inter-ONU carrier λ_{2i-1} sent from ONU$_i$ to all other ONUs. In general, the source ONU could communicate with the other ONUs via the respective inter-ONU traffic signal copies λ_{2i-1}^j, while its inter-ONU traffic would not be routed back to itself. Moreover, the upstream signals would not be affected by the inter-ONU traffic signals because they are transmitted on different wavelengths. Consequently, the ONU broadcast functionality could be realized by the above proposed re-modulation technique and wavelength routing mechanism.

3.4 Experimental demonstration

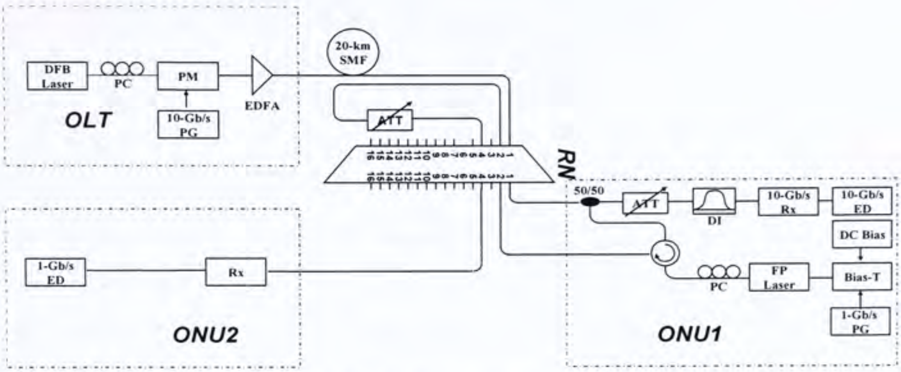


Fig. 3-3 Experimental setup. PG: pattern generator. ED: error detector. DI: delay interferometer. PC: polarization controller.

We have experimentally investigated the performance of downstream transmission and inter-ONU traffic in our proposed scheme on one particular wavelength channel. The experimental setup with two ONUs (ONU1 and ONU2) is depicted in Fig. 3-3. At the OLT side, a DFB laser at 1546.35 nm was externally modulated by a $LiNbO_3$ optical phase modulator with 10-Gb/s non-return-to-zero (NRZ) 2^{31}-1 pseudorandom binary sequence (PRBS) to form the downstream optical DPSK signal. The polarization-offset technique [30] was employed during the generation of the optical DPSK signal so as to facilitate the injection locking of the FP laser diode and to enhance data re-modulation at the ONU. The FP laser at the ONU was directly modulated by the 2^{7-1} NRZ PRBS inter-ONU data signal. The DPSK signal was amplified by an EDFA before it was fed into a piece of 20-km single-mode fiber (SMF). At the RN, a 16×16 AWG with 100-GHz channel spacing and an FSR of 12.8 nm was used. An optical attenuator with 10-dB attenuation was employed at the input port 2 of the AWG at the RN to simulate the power splitting ratio of the star coupler in a network with eight ONUs. At the ONU1, a 50/50 coupler was used to split the downstream signal for detection and inter-ONU data re-modulation, respectively. The inter-ONU traffic signal from ONU1 was routed to ONU2, via the RN, and was received by a p-i-n receiver at ONU2 for inter-ONU traffic detection.

Fig. 3-4 shows the bit-error-rate (BER) measurement results of the 10-Gb/s DPSK downstream. The induced power penalty of 10-Gb/s DPSK downstream was about 1.5-dB compared to the back-to-back case. The penalty was due to chromatic dispersion of 20-km SMF fiber and the employing of polarization-offset technique on the DPSK downstream [30]. The inset (a) and inset (b) of Fig. 3-4 show the respective eye diagrams for back-to-back case and after 20-km SMF transmission, respectively. At the ONU, part of the received signal was fed into an FP laser diode for injection locking so as to perform data re-modulation for the inter-ONU traffic. The injection power into the FP laser diode was about -10 dBm. The output power of the injection-locked FP laser diode was about -0.80 dBm at the output port of the optical circulator. Fig. 3-5(a) & (b) show the optical spectra of the output from the FP laser diode before and after injection locking with the received downstream carrier, respectively. It is shown that the side mode suppression ratio (SMSR) of the injection-locked FP laser diode was greatly improved to about 30.91-dB. The outgoing inter-ONU traffic signal was sent to ONU2, via the AWG at the RN, and it was measured to be about -21.40 dBm. The measured BER curves of the inter-ONU traffic signal are also shown in Fig. 3-6. The 0.3-dB power penalty between the back-to-back case and the inter-ONU traffic could be attributed to the slight mismatch between the transmission wavelength and AWG's passband wavelength. Such small power penalty is negligible for practical implementation.

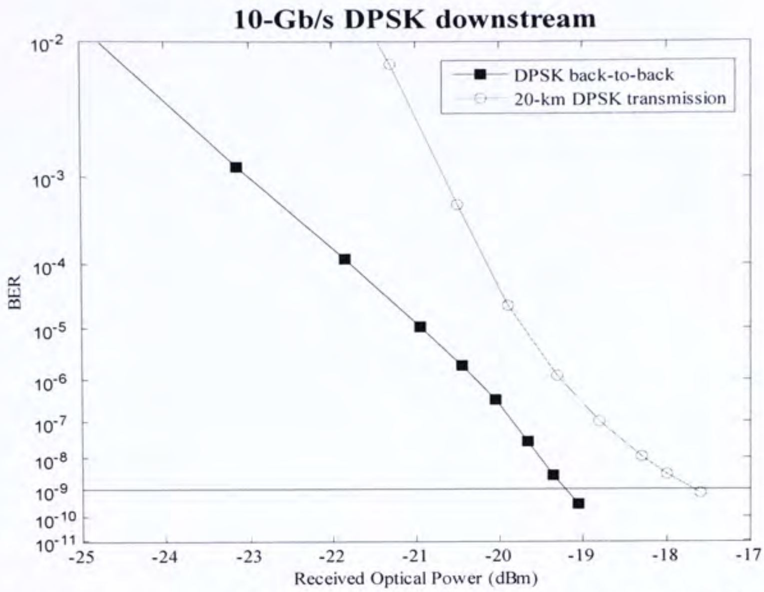
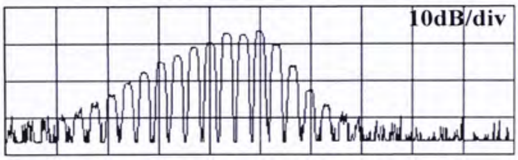
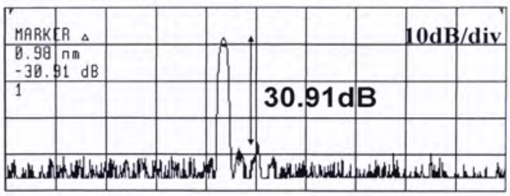


Fig. 3-4 BER measurement of 10-Gb/s DPSK downstream. Inset : eye diagrams of (a) DPSK back-to-back; (b) DPSK 20-km SMF transmission.



(a)



(b)

Fig. 3-5 Output optical spectra of the FP laser diode (a) before injection locking; (b) after injection locking.

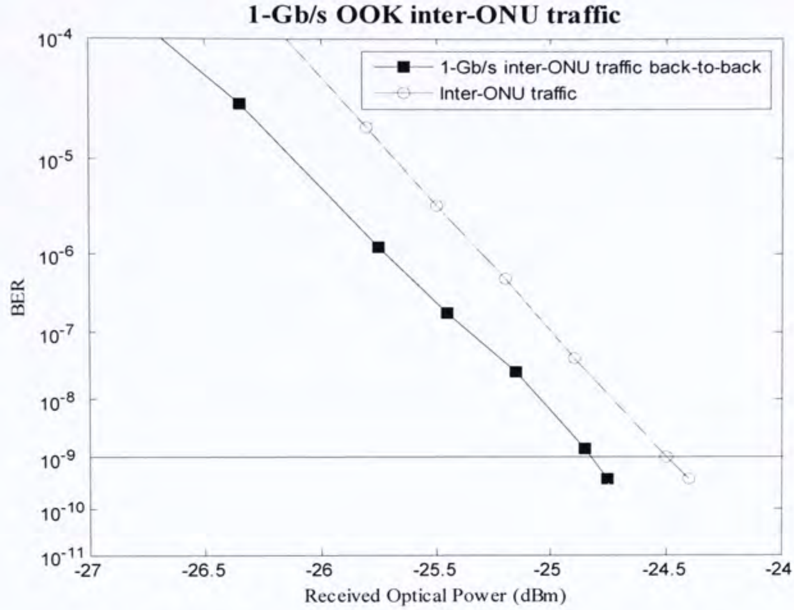


Fig. 3-6 BER measurement of 1-Gb/s OOK inter-ONU traffic..

3.5 Power budget and scalability

In our experiment, each inter-ONU traffic carrier traversed one circulator (~1-dB), round-trip transmission via the distribution fibers and one AWG at the RN (~12-dB), one optical attenuator (~10-dB) to simulate the 1×8 star coupler at the RN. Therefore, the loss budget was about 23-dB for eight ONUs. Assuming the network with sixteen ONUs is constructed with commercially available components and avalanche photodiode (APD) receiver for inter-ONU traffic, the typical power budget plans for the 10-Gb/s DPSK downstream traffic and the 1-Gb/s OOK inter-ONU traffic, are shown in Table 3-2 and Table 3-3, respectively. Both of the power margins for the 10-Gb/s DPSK downstream and 1-Gb/s OOK inter-ONU traffic are about 3-dB.

Table 3-2

Power budget of 10-Gb/s DPSK downstream signal in a WDM-PON with sixteen ONUs

Power after EDFA (dBm)	6
32×32 AWG (at RN) insertion loss (dB)	5
50:50 coupler loss (dB)	3.2
Single-ended DI insertion loss (dB)	4.7
Connector loss (dB)	2
17-km SMF (feeder fiber) loss(dB)	4.25
3-km SMF (distribution fiber) loss (dB)	0.75
Total loss (dB)	19.9
Injection power of FP-laser (dBm)	-10
Receiver sensitivity (dBm)	-18

Table 3-3

Power budget of 1-Gb/s OOK inter-ONU signal in a WDM-PON with sixteen ONUs

Power of FP-laser (dBm)	1
50:50 coupler loss (dB)	3.2
32×32 AWG insertion loss (round-trip) (dB)	10
Splitting loss of 1×16 star coupler (dB)	14
Connector loss (dB)	2
3-km SMF (distribution fiber) loss (round-trip) (dB)	1.5
Total loss (dB)	30.7
APD Receiver sensitivity (dBm)	-33

3.6 Summary

In this chapter, the ONU-broadcast functionality has been realized by novel wavelength assignment and re-modulation technique in a WDM-PON. It was experimentally demonstrated that 10-Gb/s DPSK downstream and 1-Gb/s OOK inter-ONU traffic can be supported with small power penalty by our proposed scheme. With commercial available optical components, our proposed scheme can support up to sixteen users with about 3-dB power margin.

Chapter 4
Novel Internetworking Architectures with ONU-VPGs Formation Capability in a WDM-PON

4.1 Introduction

As discussed in chapter 1, in the ONU-VPGs communication scenario, a number of ONUs can be grouped together to form a virtual private group such that each ONU can broadcast its inter-ONU traffic only to all other ONUs in the same ONU-VPG. Depending on the connectivity requirement of the ONUs in the WDM-PON, a number of ONU-VPGs can be supported. It is very desirable to implement the ONU-VPGs formation over a WDM-PON for some practical applications in future. There are several schemes proposed to achieve the ONU-VPGs formation functionality. In [23], E-CDMA technique was utilized to differentiate the inter-ONU traffic at a data rate limited to 40-Mb/s, due to the presence of OBI noise. SCM technique was also proposed in [24] to support multiple ONU-VPGs. These schemes multiplexed more than one data traffic on the same carrier, thus made the system suffer from interference, which limited the transmission data rate for the inter-ONU traffic. Moreover, they were based on the loop-back connections architecture proposed in [20] ; and were suitable in TDM PONs only. In [25], the ONU-VPGs formation can be achieved by employing wavelength grouping mechanism at the ONUs where optical filters with designated passbands were employed to pass the selected wavelengths. However, these optical filters were unique for individual ONU in the network, thus were not cost-effective in the initial network deployment. Any future network re-configuration of the ONU-VPGs would require replacement of the expensive and unique optical filters at the ONUs.

In this chapter, we propose and experimentally demonstrate novel network architectures facilitating the ONU-VPGs formation in the electronic layer and the optical layer. In terms of the ONU-VPGs formation in electronic layer, RF tone identification technique is employed at the ONU to work as the identification tag for different ONU-VPGs in a WDM-PON based on our proposed ONU-broadcast architecture discussed in chapter 3. In terms of the ONU-VPGs formation in optical layer, we propose and experimentally demonstrate a novel architecture to achieve the ONU-VPGs formation over a WDM-PON in the optical layer directly. It is realized by a special wavelength assignment for inter-ONU traffic and the different connection patterns between the optical star couplers and the AWG at the RN. Moreover, it is compatible with the conventional WDM-PONs architectures, such that the network upgrade is flexible and feasible.

In general, in the practical deployment of WDM-PONs with ONU-VPGs formation capability, the suitable one of our proposed architectures can be chosen according to the practical network environment and the cost budget.

4.2 Novel architecture with ONU-VPGs formation based on RF tone technique

4.2.1 Introduction

In this section, we propose and experimentally demonstrate a novel network architecture with ONU-VPGs formation functionality based on the previous discussed ONU-broadcast network with two conventional distribution fibers. It is achieved by employing the same proposed network architecture and wavelength routing principles as in the ONU-broadcast case, except that additional RF tones are employed at the ONUs for identification and access control. Each ONU-VPG is assigned with a distinct set of RF tone frequencies.

The formation of such virtual private groups of ONUs can be arbitrary and flexible and a WDM-PON can support several ONU-VPGs, simultaneously. With the mature electronic processing technique, the RF tone generation and detection modules are simple and low-cost. Dynamic ONU-VPGs formation could further be realized by employing frequency-tunable RF tone modules at the ONUs, thus enhances the network re-configurability.

4.2.2 Network topology and wavelength assignment

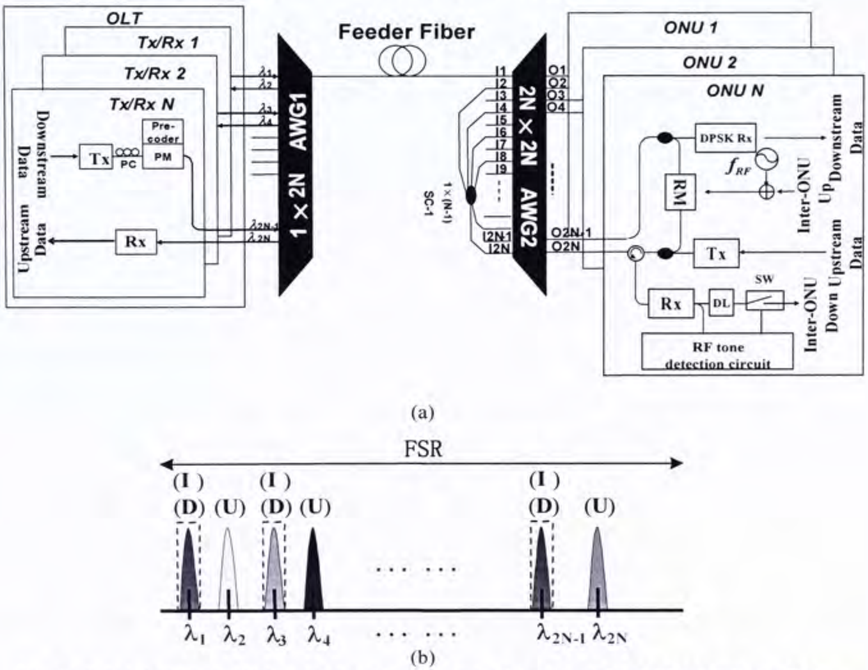


Fig. 4-1 (a) Proposed ONU-internetworking architecture for WDM-PONs. PM: optical phase modulator. RM: re-modulation module. SC: star coupler; (b) wavelength assignment plan. D: downstream wavelength. U: upstream wavelength. I: inter-ONU traffic wavelength.

As shown in Fig. 4-1, the network topology and wavelength assignment is the same as the previous ONU-broadcast architecture discussed in chapter 3. In general, by the specific wavelength assignment and re-modulating the downstream carrier, the inter-

ONU traffic would be broadcasted to other ONUs except the source ONU itself according to the wavelength routing principle of AWG2. Therefore, the ONU can directly broadcast its inter-ONU traffic to other ONUs with the proposed network topology and wavelength assignment.

To support the ONU-VPGs formation over the ONU-broadcast architecture, the ONU structure is modified with the RF tone generation and detection module to distinguish the specific inter-ONU traffic of a ONU-VPG. Whenever an ONU wants to broadcast a message within its own ONU-VPG, the outgoing inter-ONU traffic signal is first low-pass filtered before being multiplexed with a set of RF tones at distinct frequencies designated to its ONU-VPG. For a WDM-PON supporting M ONU-VPGs, $\log_2 M$ distinct RF tone frequencies are required at each ONU, such that the on-off pattern of the individual tones serves as the identification tag to distinguish among the ONU-VPGs. Table 4-1 shows an RF tone assignment for each ONU-VPG in a WDM-PON with four ONU-VPGs, for instance, and Fig. 4-2 shows an example spectrum of the inter-ONU traffic sent within ONU-VPG #4. After the wavelength routing and broadcasting via the RN, all other ONUs on the WDM-PON would receive the same inter-ONU traffic signal sent from the source ONU. At each ONU, all incoming inter-ONU traffic signal is detected first. The detected signal is electronically buffered using electrical delay lines or memory chips and part of it is fed through a RF tone detection circuit to determine whether the on-off states of the received RF tones match with the designated identification tag for its own ONU-VPG. If they match, it means that the destined ONU belongs to the same ONU-VPG as the source ONU. This triggers to close the on-off electronic switch, thus the incoming inter-ONU traffic signal would be successfully received by that ONU. Otherwise, the incoming inter-ONU traffic signal would be blocked and discarded by leaving the electronic switch open. In this way, only those ONUs which belong to the same ONU-VPG as the source ONU can properly access the incoming inter-ONU traffic signal.

Table 4-1
RF tone assignment example for four ONU-VPGs: "0" state means the presence of the tone; while "1" state means the absence of the tone.

RF tones	ONU-VPG #1	ONU-VPG #2	ONU-VPG #3	ONU-VPG #4
f_1	0	0	1	1
f_2	0	1	0	1

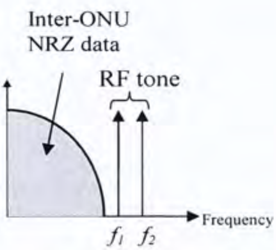


Fig. 4-2 An example spectrum for the inter-ONU traffic sent within ONU-VPG #4.

4.2.3 Media access control protocol: CSMA/CA protocol

For media access control of the inter-ONU traffic, carrier sense multiple access with collision avoidance (CSMA/CA) protocol [33] could be applied to resolve the possible collision during the inter-ONU traffic transmission. Before the inter-ONU traffic signal is sent, the source ONU would first broadcast a signaling message to all other ONUs to announce the occupancy of the following time slot for data transmission. All other destined ONUs would receive the signaling data and respond correspondingly by the MAC layer processing circuit. In the case of ONU-VPGs communication, in order to enhance the flexible reconfiguration of the ONU-VPGs formation, the RF tone generation and detection circuit could be made with frequency tunability. That is, tunable bandpass filter [34] or voltage controlled oscillator [35] with the frequency tunable range covering all required tone frequencies are employed. Moreover, these tunable electronics components can be integrated in one single chip with the mature semiconductor processing technique. In this way, the RF tone generation and detection unit in all ONUs could be made identical, thus enhances its practicality and cost-effectiveness. The reconfiguration of the RF tone frequencies could be easily controlled remotely at the OLT via some signaling protocols. Therefore, high flexibility in the ONU-VPGs reconfiguration could be achieved. Compared with the multiple secure network proposal with E-CDMA in [23], the incorporation of RF tones would not suffer from the severe MAI, which might limit the data rate of the inter-ONU traffic.

4.2.4 Experimental demonstration

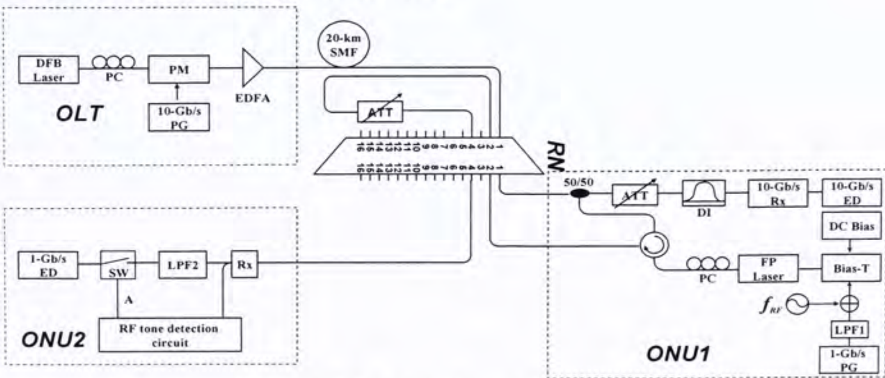


Fig. 4-3 Experimental setup. PG: pattern generator. ED: error detector. DI: delay interferometer. LPF: low-pass filter. PC: polarization controller.

The performance degradation of introduction of additional RF tones to the inter-ONU traffic was experimentally investigated. The experimental setup with two ONUs (ONU1 and ONU2) is depicted in Fig. 4-3. At the OLT side, a DFB laser at 1546.35 nm was externally modulated by a $LiNbO_3$ optical phase modulator with 10-Gb/s NRZ 2^{31}-1 PRBS to generate the downstream optical DPSK signal. To achieve the injection locking of the FP laser diode and to enhance data re-modulation at the ONU, the polarization-offset technique [30] was employed during the generation of the optical DPSK signal at the OLT. An EDFA was employed to amplify the downstream DPSK signal to compensate the transmission loss. Between OLT and RN, a piece of 20-km SMF was employed as the feeder fiber. At the RN, a 16×16 AWG with 100-GHz channel spacing and an FSR of 12.8 nm was employed. To simulate a network with eight ONUs, an optical attenuator with 10-dB attenuation was connected to the input port 2 of the AWG at the RN. At the ONU1, a 50/50 coupler was used to split the downstream signal for detection and inter-ONU data re-modulation, respectively. The inter-ONU data was first filtered by a low-pass filter (LPF1, Δf_{3dB}=1000MHz). It was then multiplexed with a locally-generated RF tone at 1.5 GHz, which simulated the identification tag for its own ONU-VPG, before being fed into the FP laser for direct modulation. The inter-ONU traffic signal from ONU1 was routed to ONU2, via the RN, and was received by a p-i-n receiver at ONU2 for RF tone detection circuit and inter-ONU traffic detection. An electronic switch was used at the receiver to control the reception of the inter-ONU traffic signal.

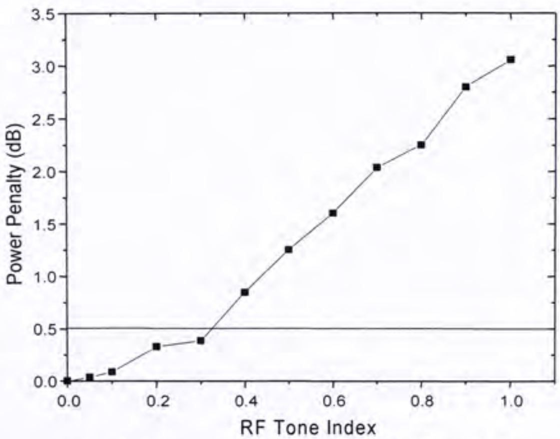
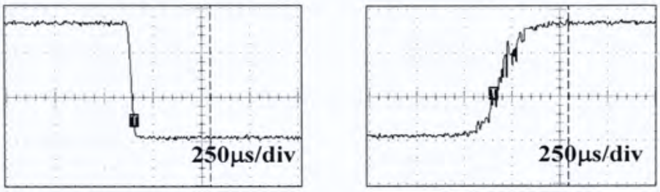


Fig. 4-4 Power penalty versus RF Tone index.

First, the power penalty of the inter-ONU traffic induced by the additional RF tone as the identification tag was investigated for the back-to-back case; and the measured results are depicted in Fig. 4-4. Here, RF tone index was defined as the ratio of the peak amplitude of the RF tone to that of the data signal. It is shown that the power penalty increased obviously when the RF tone index was increased beyond 0.3, where the power penalty was about 0.5-dB. With such low RF tone index, the possible optical beat interference as well as distortion induced by the RF tones would not be significant. Considered the chromatic dispersion after transmission in the distribution fiber, the power penalty could be even a little bit larger than that in the back-to-back case. Therefore, the RF tone index could be chosen as about 0.1 to assure a reasonably good performance, where power penalty was less than 0.1-dB in the back-to-back case and the power of the RF tone was strong enough for the RF tone detection circuit at the ONU. In our experiment, the peak amplitudes of the 1-Gb/s inter-ONU traffic signal and the added RF tone were 250 mV and 26.977 mV, respectively. It is shown that the RF tone can be clearly distinguished in the RF spectra of the received inter-ONU traffic signal with and without the RF tone, as shown in Fig. 4-5(a) and (b), respectively. At the ONU, to extract and detect the RF tone from the received incoming inter-ONU traffic signal, a band-pass filter centered at 1.5-GHz was employed. A decision circuit with a pre-set amplitude threshold was built to determine the presence of the RF tone at that designated frequency and its output was used to control the electronic switch to discard or receive the received inter-ONU traffic signal. Fig. 4-6(a) & (b) show the measured switching states of the control signal to the electronic switch at point A in Fig. 4-3 and the switching time was measured to be about 250 μs. This switching time could be further improved with better circuit design and circuit integration.

(a) (b)

Fig. 4-5 RF spectra of (a) Inter-ONU traffic with 1.5-GHz RF tone; (b) Received inter-ONU traffic without RF tone.



(a) (b)

Fig. 4-6 Output TTL control signal switching to (a)discard the received inter-ONU traffic signal; (b) process the received inter-ONU traffic signal.

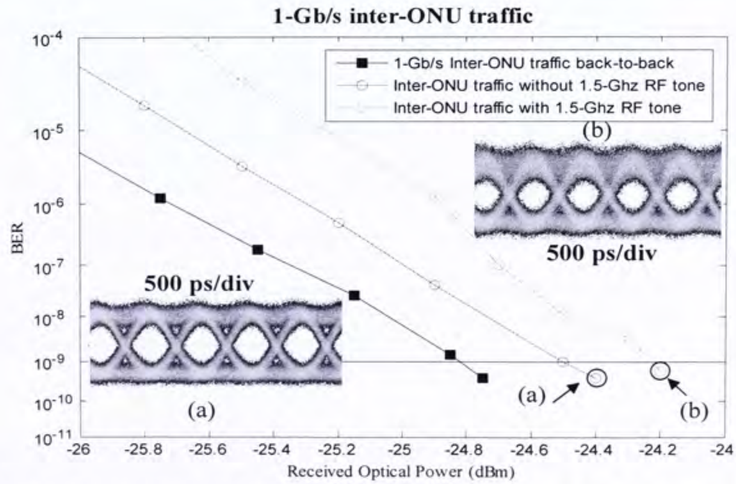


Fig. 4-7 BER measurements of 1-Gb/s OOK inter-ONU traffic. Inset : eye diagrams of (a) inter-ONU traffic without 1.5-GHz RF tone; (b) inter-ONU traffic with 1.5-GHz RF tone.

The measured BER curves of the inter-ONU traffic signal with and without RF tone are also shown in Fig. 4-7. The 0.5-dB power penalty between the back-to-back case and the inter-ONU traffic with RF tone could be attributed to the slight mismatch between the transmission wavelength and AWG's passband wavelength. On the other hand, the power penalty induced by the presence of RF tone was only about 0.2-dB as compared with the case without RF tone. The eye diagrams of the two cases are also shown in the inset (a) and (b) of Fig. 4-7, respectively. In the case of inter-ONU signal with RF tone, the "one" level appeared to be thicker than that in the case without RF tone. It might be attributed to the residual intensity fluctuation of the RF tone after the low-pass filter. Nevertheless, such small induced degradation is negligible for practical implementation.

4.2.5 Discussion

Table 4-2 & Table 4-3 show the typical power budget plans for the 10-Gb/s DPSK downstream traffic and the 1-Gb/s OOK inter-ONU traffic, respectively, assuming the network is constructed with commercially available components and eight ONUs are supported. With the recent advances in materials and fabrication techniques, the optical components could be manufactured with very low insertion losses. For example, perfluorinated polymer AWGs have been fabricated with ultra-low (< 3-dB) insertion losses [36] . Therefore, the loss budget could be potentially reduced and more ONUs could be supported in the network.

Table 4-2

Power budget of 10-Gb/s DPSK downstream signal in a WDM-PON with eight ONUs

Power after EDFA (dBm)	5
16×16 AWG (at RN) insertion loss (dB)	4
50:50 coupler loss (dB)	3.2
Single-ended DI insertion loss (dB)	4.7
Connector loss (dB)	2
17-km SMF (feeder fiber) loss(dB)	4.25
3-km SMF (distribution fiber) loss (dB)	0.75
Total loss (dB)	18.9
Injection power of FP-laser (dBm)	-10
PIN receiver sensitivity (dBm)	-18

Table 4-3

Power budget of 1-Gb/s OOK inter-ONU signal in a WDM-PON with eight ONUs

Power of FP-laser (dBm)	1
Circulator loss (round-trip) (dB)	1.4
50:50 coupler loss (dB)	3.2
16×16 AWG insertion loss (round-trip) (dB)	8
Splitting loss of 1×8 star coupler (dB)	11
Connector loss (dB)	2
3-km SMF (distribution fiber) loss (round-trip) (dB)	1.5
Total loss (dB)	27.1
APD receiver sensitivity (dBm)	-33

In general, our proposed scheme can support internetworking capability in WDM-PON with conventional two distribution fibers per ONU. The architecture of RN is required to be upgraded with passive components only; while the ONU is realized with flexible and potentially low cost optical or electronic components. The bit-rate of the inter-ONU traffic is chosen to be 1-Gb/s for the popular and cost-effective deployment of gigabit Ethernet (GbE). Any upgrade of this bit-rate is possible, as long as it satisfies with the power budget constraint. In terms of the identification and access control of the ONU-VPGs, our proposed RF tone-based scheme is non-intrusive to the baseband data. Another alternative for achieving this is to attach header bits to the data packets. However, bit-level synchronization and processing will be required and thus imposes overhead to the baseband data and decrease the data packet efficiency. Therefore, by incorporating the access control of the ONU-VPG in the physical layer using our proposed scheme, the higher layers can be off-loaded and thus can improve the network efficiency. Besides, with the mature semiconductor fabrication and processing techniques, all components required to perform the RF tone identification can be integrated in one single chip and are potentially low cost with volume production. All ONUs can even be made identical if frequency-tunable RF components are employed.

4.2.6 Summary

We have proposed a novel ONU-internetworking architecture over a WDM-PON. The ONU-internetworking functionality of our proposed scheme could support ONU-VPGs communication. To achieve the arbitrary and flexible formation of ONU-VPGs, additional RF tones are incorporated to the inter-ONU traffic signal as the ONU-VPG identification tag with proper access control mechanism. A WDM-PON can support several ONU-VPGs, simultaneously. Moreover, dynamic ONU-VPGs formation could also be realized by employing the frequency-tunable RF tone modules at the ONUs, thus enhances the network re-configurability. Such integrated RF tone generation and detection modules are simple and low-cost in high volume with the mature electronic processing and manufacturing technique.

4.3 Novel architecture with ONU-VPGs formation in optical layer

4.3.1 Introduction

In this section, a novel network architecture is proposed and experimentally demonstrated to provide flexible ONU-VPGs formation in the optical layer of a WDM-PON. By adopting the proposed wavelength assignment and placing passive optical star-couplers at the RN, direct inter-ONU communications with multiple ONU-VPGs could be realized. All ONUs in the WDM-PON employ identical transmitters for the inter-ONU traffic transmission, thus relaxes the wavelength management and reduces the manufacturing cost for the inter-ONU transmitters in high volume. Moreover, it is compatible with the conventional WDM-PONs and thus facilitates the network upgrade or re-configuration with only small modification at the RN. Compared with other schemes providing ONU-VPGs configuration, our scheme can provide flexible ONU-VPGs formation and high data rate up to 2.5-Gb/s for inter-ONU traffic in the optical layer.

4.3.2 Network topology and wavelength assignment

Fig. 4-8 illustrates our proposed architecture of multiple ONU-VPGs over a WDM-PON with N users, where N=8 for illustration. Similar to the conventional WDM-PON architectures, N downstream transceivers in the 1.55μm waveband are designated at the OLT. The $1\times2N$ (say 1×16) AWG1 is employed at the OLT to multiplex and demultiplex the downstream and the upstream carriers, respectively. To achieve the multiple ONU-VPGs formation over the WDM-PONs, multiple star-couplers and one $2N\times2N$ AWG2 (say 16×16) are employed at the RN according to the practical ONU-VPGs formation pattern. The FSR of the AWG1 at the OLT is the same as that of the AWG2 at the RN. A formation example of two ONU-VPGs (ONU-VPG1 & ONU-VPG2) in the network is shown in Fig. 4-8(b), where five ONUs (ONU1-5) are involved in the ONU-VPG1 and the other three ONUs (ONU6-7) belong to the ONU-VPG2. One 5×5 optical star coupler and one 3×3 optical star coupler are employed at the RN to duplicate and broadcast the inter-ONU traffic signals, via the AWG2 within their respective ONU-VPGs. The connection patterns between the star-couplers and the AWG2 are consistent with the ONU-VPGs configuration. For ONU-VPG1, the input ports of the 5×5 optical star coupler are connected to the I1, I3, I5, I7, I9 ports of the AWG2, while their output ports are connected to I2, I4, I6, I8, I10 ports of the AWG2, respectively. Similarly, the connection pattern for the ONU-VPG2 is illustrated in Fig. 4-8(a). At the ONU, two transceivers are employed, one for normal up-/downstream traffic transmission and the other for inter-ONU traffic transmission. Fig. 4-8(c) illustrates the wavelength assignment plan. The downstream wavelengths and the upstream wavelengths for ONU(i) are designated as λ_{2i-1} (say $\lambda_1, \lambda_3, \ldots, \lambda_{2N-1}$) and λ_{2i} (say $\lambda_2, \lambda_4, \ldots, \lambda_{2N}$) (for $i=1, \ldots, N$), respectively. They are chosen to match with the transmission passbands of the $1\times 2N$ AWG1 at the OLT, as well as the $2N\times 2N$ AWG2 at the RN. All the downstream wavelengths and the upstream wavelengths are assigned within the blue-band FSR of the AWG2, while the common inter-ONU traffic carrier, λ_{ONU}, is assigned with the first wavelength λ_{2N+1} (say λ_{17}) in the red-band FSR of the AWG2.

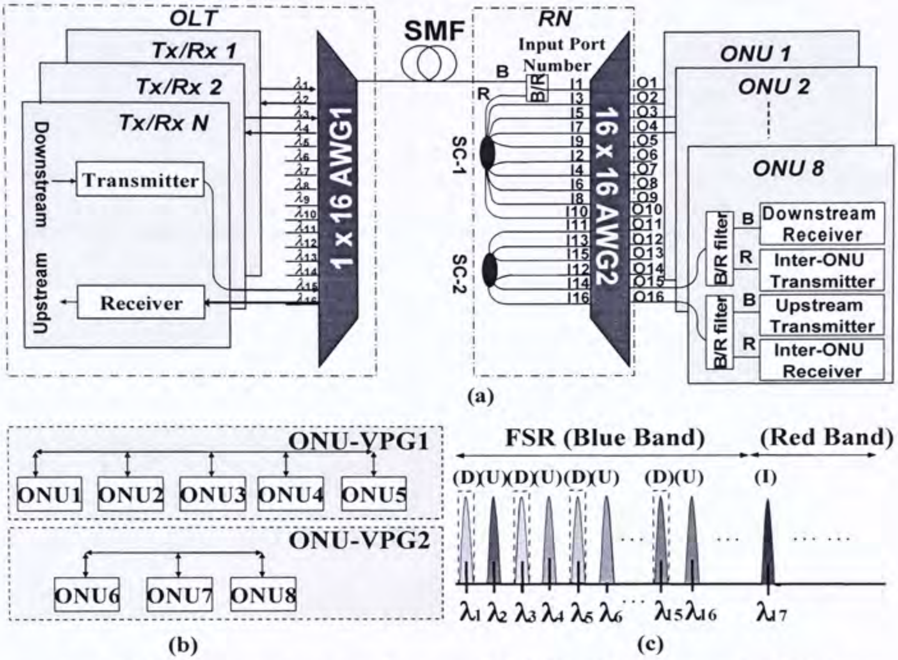


Fig. 4-8(a) Schematic diagram of proposed WDM-PONs with two ONU-VPGs configuration. SMF: single-mode fiber. SC: star-coupler. B/R: Blue/Red filter; (b) Logical connections of ONU-VPGs; (c) Wavelength assignment plan.

Take ONU5 for example, its designated downstream carrier and upstream carrier are λ_9 and λ_{10} respectively. Only one common inter-ONU traffic carrier is assigned, such that all inter-ONU traffic is carried on this common wavelength channel. Therefore, the inter-ONU transmitters can be identical for all ONUs in the network, no matter which ONU-VPG they belong to. As shown in Fig. 4-8(a), each ONU is connected to two designated output ports of the AWG2 via two respective distribution fiber links, where the first one is to carry the downstream traffic; while the second one is to carry the upstream traffic. To combine and separate the inter-ONU carrier in the normal up-/downstream carriers, two Blue/Red (B/R) filters are inserted at each ONU. At the RN, an additional B/R filter is required to maintain the normal operation of the downstream and upstream at the feeder fiber.

4.3.3 Operation principle

The formation of the ONU-VPGs is realized by the flexible setting of the optical star couplers configuration at the RN. One common inter-ONU carrier, λ_{ONU} (say λ_{17}), which is the first wavelength channel in the red-band FSR of the AWG2, is assigned to carry all inter-ONU traffic. According to the wavelength routing principle of the AWG2, λ_{ONU} has a special correspondence feature between the input port and the output port of the AWG2. That is, when λ_{ONU} is fed into the k^{th} input port of the AWG2, it would be routed to its k^{th} output port. Hence, when the optical star couplers at the RN are employed to broadcast this inter-ONU carrier within their respective ONU-VPGs, this special correspondence feature of the AWG2 supports flexible and arbitrary formation of ONU-VPGs by simply connecting the output ports of the optical star couplers to the respective input ports of the AWG2 whose corresponding output ports are connected to the destined inter-ONU receivers in the same ONU-VPG. Fig. 4-9 illustrates the flow of the inter-ONU traffic when they are originated from ONU1 and ONU6, respectively, as an example. The corresponding broadcasting pattern of the inter-ONU traffic among different ONUs is depicted in Table 4-4 , while the rows and the columns represent the destined and the source ONUs, respectively. Under this configuration, the inter-ONU traffic sent from ONU1 would be broadcasted to ONU1, ONU2, ONU3, ONU4, and ONU5 only in ONU-VPG1, while that sent from ONU6 would be broadcasted to ONU6, ONU7 and ONU8 only in ONU-VPG2. To avoid the conflict among the ONUs in the same ONU-VPG, a suitable media access protocol, such as carrier-sense multiple access[33], could be implemented to coordinate the data transmission by all ONUs among themselves. Hence, by simple modification of the conventional WDM-PON architecture, the

ONU-VPGs formation can be cost-effectively and flexibly configured. After the initial network deployment, the formation of ONU-VPGs could be flexibly modified by changing the connection patterns of the optical star couplers at the RN, without altering any ONU configuration.

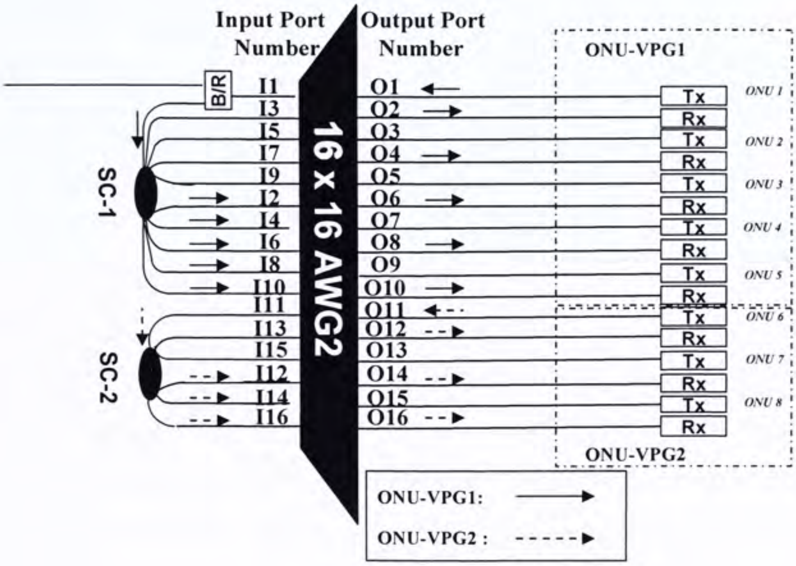


Fig. 4-9 Schematic example of an eight-ONU WDM-PON with two ONU-VPGs (1&2) and inter-ONU traffic are generated from ONU1 and ONU6. Only the inter-ONU transmitters and receivers at the ONUs are shown.

Table 4-4

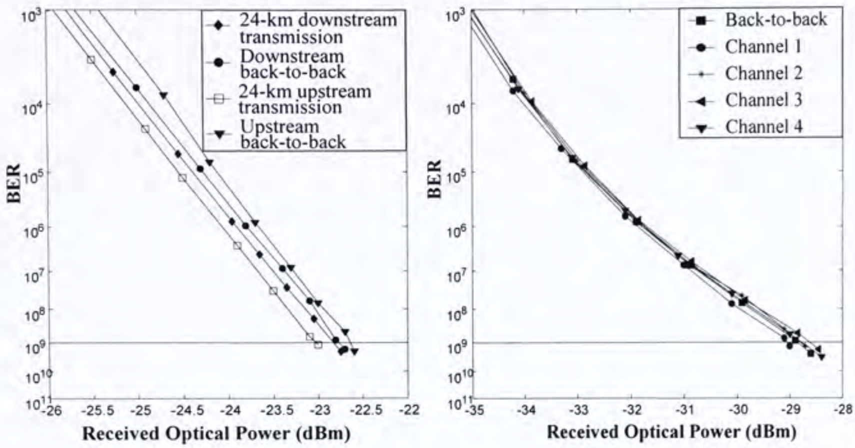
Routing table for the inter-ONU carrier within ONU-VPG1 and ONU-VPG2

Destined ONU

Source ONU	ONU1	ONU2	ONU3	ONU4	ONU5	ONU6	ONU7	ONU8
ONU1	λ_{17}	λ_{17}	λ_{17}	λ_{17}	λ_{17}			
ONU2	λ_{17}	λ_{17}	λ_{17}	λ_{17}	λ_{17}			
ONU3	λ_{17}	λ_{17}	λ_{17}	λ_{17}	λ_{17}			
ONU4	λ_{17}	λ_{17}	λ_{17}	λ_{17}	λ_{17}			
ONU5	λ_{17}	λ_{17}	λ_{17}	λ_{17}	λ_{17}			
ONU6						λ_{17}	λ_{17}	λ_{17}
ONU7						λ_{17}	λ_{17}	λ_{17}
ONU8						λ_{17}	λ_{17}	λ_{17}

4.3.4 Experimental demonstration

The experimental setup was similar to Fig. 4-8 so as to investigate the functionality and transmission performance of ONU-VPGs formation. Two DFB laser diodes directly modulated by 2^{31}-1 PRBS NRZ data at 2.5-Gb/s were employed as the downstream and the upstream transmitters. The upstream signal was received by a p-i-n receiver at the OLT. Two 16×16 AWGs, with an FSR of 12.8 nm and 100-GHz channel spacing, were employed as the AWG1 at the OLT and the AWG2 at the RN. They were connected by a piece of 20-km standard SMF, as the feeder fiber. A 4×4 star-coupler was used at the RN, with its first input port connected to the Red/Blue filter (18-nm passband) while the others were directly connected to the designated input ports of the AWG2. The distribution fiber between the RN and the ONU was 4-km SMF. At the ONU, a tunable laser, lasing at 1529.2nm and externally modulated by 2.5-Gb/s NRZ 2^{31}-1 PRBS, was employed as the inter-ONU traffic transmitter, due to component availability. The downstream signal and the inter-ONU traffic signal were received by a 2.5-Gb/s p-i-n receiver and a 2.5-Gb/s APD receiver, respectively.



(a) (b)

Fig. 4-10 BER measurements of (a) 2.5-Gb/s upstream and downstream transmission;(b) 2.5-Gb/s inter-ONU traffic transmission.

The BER measurement results for the upstream, the downstream as well as the inter-ONU traffic are depicted in Fig. 4-10. Compared to the back-to-back measurement, the negligible power penalty was less than 0.5-dB for both of the downstream and the upstream traffic after 24-km SMF transmission, as depicted in Fig. 4-10(a). Such small power penalty could be attributed by the fiber chromatic dispersion. The receiver sensitivities at BER=10^{-9} for the downstream and the upstream signals were measured as within -22.5 dBm and -23 dBm. Besides, the broadcasting transmission performance of inter-ONU traffic was also investigated in all four output channels of the star-coupler. As depicted in Fig. 4-10(b), error free operation was achieved in all cases, with the receiver sensitivities at about -28.5 dBm.

4.3.5 Discussion

As mentioned in the previous section, the same wavelength lights are applied for the inter-ONU traffic transmission in all ONU-VPGs. The employment of the same nominal wavelength as carriers for inter-ONU traffic would impose homodyne crosstalk in our proposed scheme. The homodyne crosstalk can be divided into coherent crosstalk and incoherent crosstalk [37][38], respectively. In terms of the generation of coherent crosstalk in our scheme, the signals of inter-ONU traffic could be assumed to experience the same path length of star coupler before fed into the AWG at the RN after the power splitting of star coupler, as shown in Fig. 4-11. These different parts of the signal can be regarded to be phase correlated with each other. Therefore, the signal destined to one specific ONU would be mixed with other coherent crosstalk components after the routing of AWG due to the imperfect crosstalk performance of AWG. On the other hand, when inter-ONU traffic signals from different ONU-VPGs are transmitted simultaneously, small portion of signals from different ONU-VPGs would leak to other ONU-VPGs, as shown in Fig. 4-11. Because inter-ONU traffic signals in different ONU-VPGs are transmitted by different laser diodes, these crosstalk components are not phase correlated to each other. The inter-ONU traffic signal for one specific ONU-VPG would be mixed with all other leakage incoherent crosstalk components. This would impose the incoherent crosstalk issue. Therefore, the impact of homodyne crosstalk caused by the leakage from AWG is necessary to be taken into consideration in our scheme.

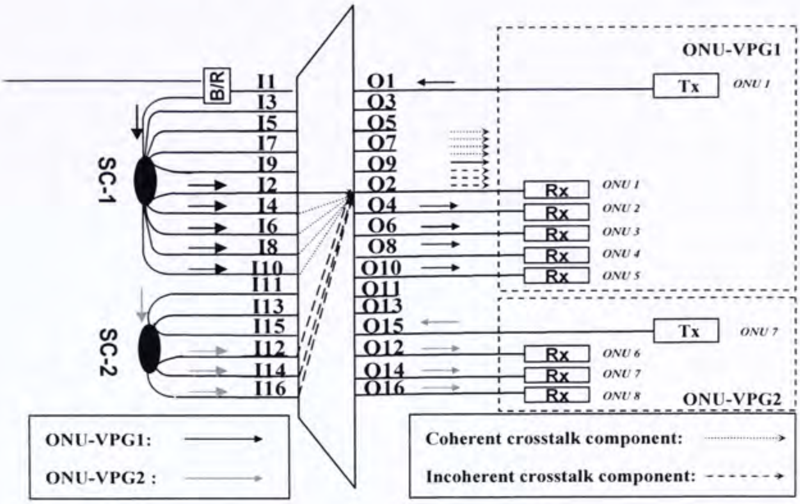


Fig. 4-11 Schematic diagram of crosstalk generation

The system performance degradation related to the crosstalk interference was investigated by experiment and simulation. It was experimentally demonstrated that the system performance degradation due to homodyne crosstalk interference was negligible in a WDM-PON with eight ONUs.

To investigate the performance degradation introduced by coherent crosstalk and incoherent crosstalk interference in our proposed scheme, two experimental setups are shown in Fig. 4-12 & Fig. 4-14. A 16 × 16 AWG was employed as the AWG at the RN. A 1 × 2 coupler and two 1 × 4 star couplers were employed as the 1 × 8 coupler in a WDM-PON network with eight ONUs. The connections of the coupler and the AWG were modified to generate the different number of crosstalk components in the experiment. A tunable laser lasing at 1529.2nm and an external intensity modulator were employed as the inter-ONU transmitter.

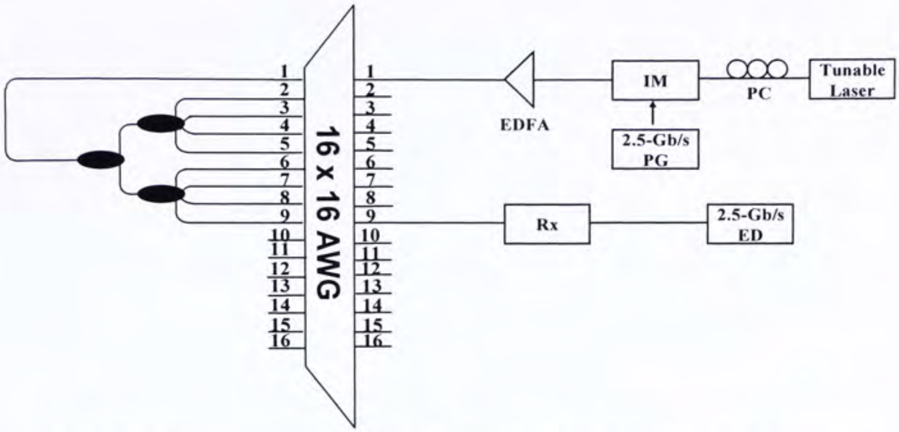


Fig. 4-12 Experimental setup for investigation of performance degradation by coherent crosstalk interference.

In Fig. 4-12, only coherent crosstalk components would be generated by the star couplers located before AWG. The output power of EDFA was about 6.5 dBm. The output power of each path of star coupler was maintained to be about -10.95 dBm. The experimental result is shown in Fig. 4-13. The received sensitivity was about -28.3 dBm for all cases. No obvious power penalty was observed to be related to the number of coherent crosstalk components..

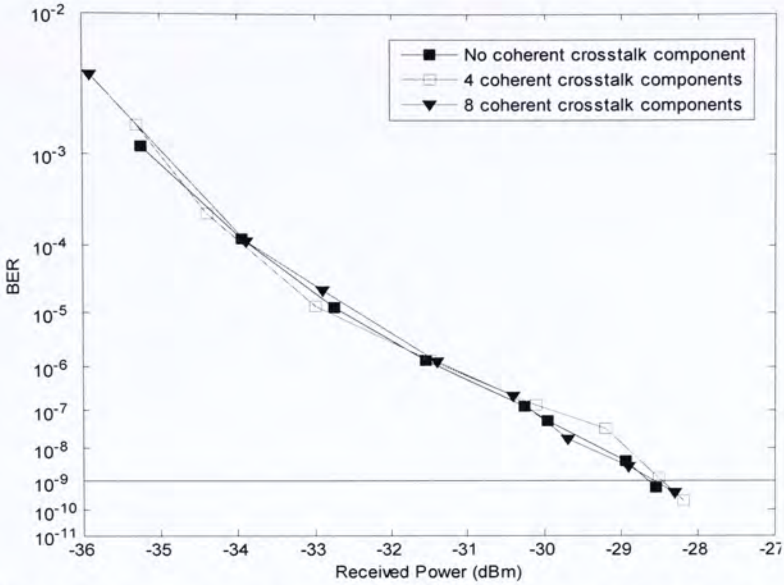


Fig. 4-13 BER measurements of network with different numbers of coherent crosstalk components.

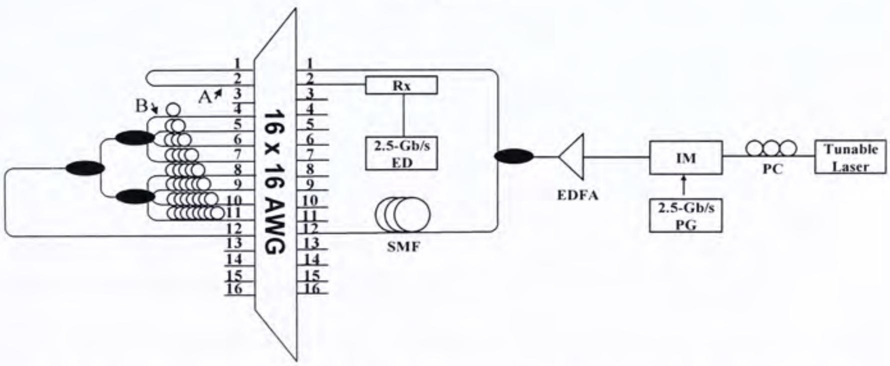


Fig. 4-14 Experimental setup for investigation of performance degradation by incoherent crosstalk interference.

In Fig. 4-14, two signals representing two ONU-VPGs were generated by 1 × 2 coupler, then were decorrelated by fiber delay line whose length was larger than the coherent length of the laser. The output power of EDFA was about 12.50 dBm. The inter-ONU signals at point A and point B before AWG were maintained to be about -14 dBm. The experimental results of the incoherent crosstalk degradation are shown in Fig. 4-15. The maximum power penalty was about only 0.5-dB for the case of eight incoherent crosstalk components compared with that of no incoherent crosstalk component.

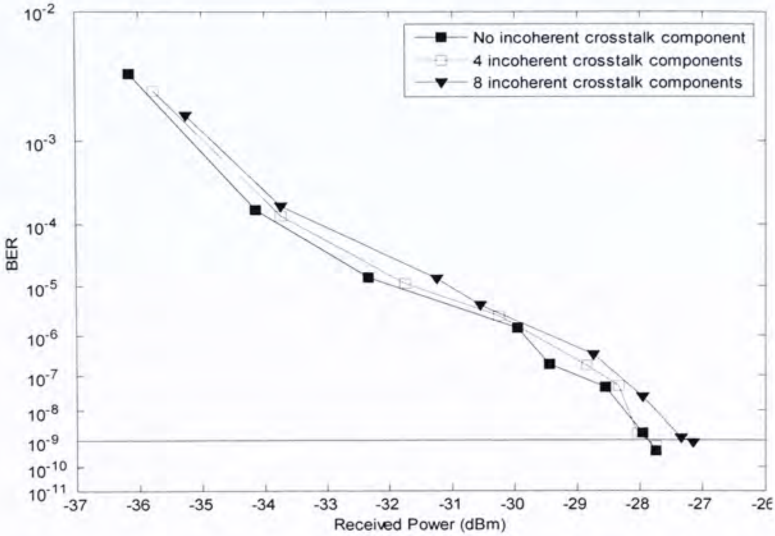


Fig. 4-15 BER measurements of network with different numbers of incoherent crosstalk components.

The experimental results show that system degradation was not severe for a WDM-PON with eight ONUs. The power penalty induced by incoherent crosstalk was much larger than that of coherent crosstalk. Moreover, in practical network deployment, the paths of the star coupler at the RN can be made with non-identical lengths to decorrelate the signals in different paths. Therefore, incoherent crosstalk should be the dominant and inevitable crosstalk in our proposed scheme. Here, the dependence of the system degradation and the number of incoherent crosstalk sources is further investigated. In [39], the power penalty caused by incoherent crosstalk can be expressed as

$$Penalty(dB) = -5\log[1 - R_c NQ^2]$$

for optimized decision-threshold receiver. Here R_c was defined as the optical power ratio of each crosstalk component to the signal, N was the number of crosstalk components. Fig. 4-16 shows the dependency relationship between the power penalty and the number of incoherent crosstalk components at a BER of 10^{-9}, assuming R_c was -35-dB which is easily satisfied by the commercial available AWG. It was shown that sixteen incoherent crosstalk components would introduce only 1-dB power penalty to the system performance. Therefore, the incoherent crosstalk issue would not impose severe performance degradation for a WDM-PON with sixteen ONUs.

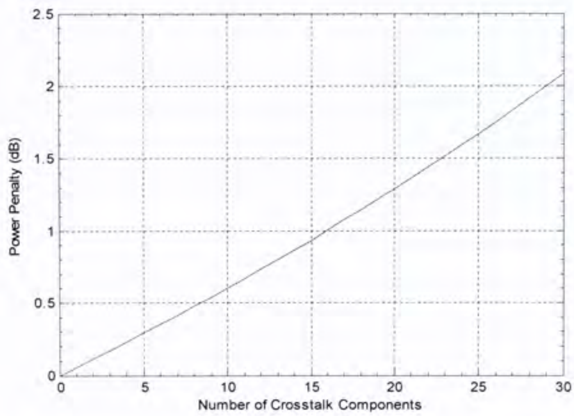


Fig. 4-16 Power penalty versus numbers of incoherent crosstalk components.

The loss budget for the inter-ONU traffic signal was about 22-dB, which included the round-trip transmission between the OLT and the RN via the AWGs (10-dB), one 4×4 star-coupler (7-dB), two Blue/Red filters (2-dB) and round-trip transmission of 4-km distribution fiber (3-dB). Thus it can provide more than 7-dB power margin at the receiver sensitivity of -28 dBm at 2.5-Gb/s, assuming the output optical power of inter-ONU traffic transmitter is 1 dBm. Assuming single ONU-VPG with eight ONUs in the network, the typical power budget plans for the 2.5-Gb/s down-/upstream traffic and 2.5-Gb/s inter-ONU traffic are shown in Table 4-5 and Table 4-6, respectively.

Table 4-5

Power budget of 2.5-Gb/s OOK downstream and upstream in a WDM-PON with eight ONUs

Output power of transmitter (dBm)	1
16 × 16 AWG insertion loss (dB)	4
two Red/Blue filter insertion loss (dB)	2
Connector loss (dB)	2
17-km SMF (feeder fiber) loss(dB)	4.25
3-km SMF (distribution fiber) loss (dB)	0.75
Total loss (dB)	13
Receiver sensitivity of PIN receiver (dBm)	-22

Table 4-6

Power budget of 2.5-Gb/s OOK inter-ONU traffic in a WDM-PON with eight ONUs

Output power of transmitter (dBm)	2
2 Red/Blue filter insertion loss (dB)	2
16 × 16 AWG insertion loss (round-trip) (dB)	8
Splitting loss of star coupler (dB)	11
Connector loss (dB)	2
3-km SMF (distribution fiber) loss (round-trip) (dB)	1.5
Total loss (dB)	24.5
Receiver sensitivity of APD receiver (dBm)	-28

4.3.6 Summary

We have demonstrated a novel flexible ONU-VPGs formation scheme in optical layer for WDM-PONs. The ONU-VPGs formation is flexibly realized by the special wavelength assignment and the star-couplers at the RN, where a cyclic AWG is employed. The connection patterns between the star-couplers and the AWG physically partition the network into multiple ONU-VPGs. The modification at the RN is small to keep the scheme cost-effective for deployment. Moreover, the conventional ONU architecture can work properly without any specific modification. Therefore, it is compatible with the conventional WDM-PONs architectures and provides a flexible solution to upgrade it to the WDM-PONs with ONU-VPGs formation capability.

4.4 Comparisons

In the previous sections, two schemes have been proposed to facilitate the ONU-VPGs formation in a WDM-PON. Table 4-7 summaries the comparisons between these two proposed schemes. In terms of the automatic reconfiguration of ONU-VPGs formation, the scheme based on RF tones (Section 4.2) can cost-effectively support the dynamic modification of ONU-VPGs formation after the initial network deployment, by easy reconfiguration of the RF tone frequency assignment. For the scheme in the optical layer (Section 4.3), it is required to manually modify the connection patterns of the star coupler at the RN according to the specific ONU-VPGs formation. However, the scheme based on RF tones suffers from high electrical complexity and low upgradeability for the RF tones generation and detection modules at the ONUs. The scheme in the optical layer is better in the case that the deployed network needs to be upgraded to equip with ONU-VPGs formation capability. In terms of the power budget, the scheme in the optical layer can support more users in one ONU-VPG because the splitting loss of star coupler is smaller than that with full connection to all ONUs in the electronic scheme. In general, our proposed schemes can be applicable to different application scenarios.

Table 4-7

Comparisons between proposed schemes

	RF Tones Technique (Section 4.2)	Optical Layer Approach (Section 4.3)
Automatic reconfiguration	Yes	No
Complexity in electrical design	High	Low
Complexity in optical design	Comparable	Comparable
Flexibility	High	High
Upgradeability from existing networks	Low	High
Power budget	Tight	Good

4.5 Summary

In this chapter, novel architectures with ONU-VPGs formation capability have been proposed and experimentally demonstrated. The ONU-VPGs formation can be realized in electronic layer and optical layer, respectively.

In terms of electronic layer, we have proposed to employ additional RF tones as identification tag for each ONU-VPG based on the ONU-broadcast architecture discussed in chapter 3. It has been experimentally demonstrated that the data rate for inter-ONU traffic could be up to 1-Gb/s. The power penalty induced by additional RF tone is negligible in practical system implementation.

In terms of optical layer, a novel architecture with specific wavelength assignment for inter-ONU traffic carrier has been proposed and experimentally demonstrated. With our proposed scheme, the ONU-VPGs formation can be achieved in the optical layer by the configuration between star-coupler and AWG at the RN.

In general, the ONU-VPG formation functionality can be practically realized by our proposed schemes.

Chapter 5
Summary and Future Works

Summary of the thesis

The objective of this thesis is to design and investigate novel internetworking architectures for ONUs in a WDM-PON to provide the direct connections for ONUs in optical layer to enhance the bandwidth efficiency and reduce the latency for inter-ONU traffic.

In chapter 1, the modern telecommunications network hierarchy has been reviewed. In particular, the access networks were discussed in two main streams of PON: TDM-PON and WDM-PON, respectively.

In chapter 2, previous internetworking architectures for ONUs in PONs have been reviewed. In general, the previous proposed schemes suffered from limitations in terms of flexibility, reconfigurability and data rate.

In chapter 3, the network architecture with ONU-broadcast functionality for WDM-PON has been proposed and discussed. We have proposed a novel remote node design and re-modulation technique to facilitate the ONU-broadcast functionality. Based on the wavelength routing property of the AWG at the RN, each ONU can broadcast data to other ONUs except itself. No interference problem would degrade the system performance in practical network deployment.

In chapter 4, the ONU-VPGs formation functionality for a WDM-PON was further discussed and implemented in the electronic layer and the optical layer, respectively. In terms of the proposed architecture based on electronic identification technique, additional RF tones are employed as the identification tag of different ONU-VPGs. It was experimentally shown that the power penalty introduced by RF tone was negligible in practical implementation. In terms of the proposed architecture in the optical layer, novel wavelength assignment and remote node design have been proposed to facilitate the flexible formation of ONU-VPGs in a WDM-PON. The network can be physically partitioned to multiple ONU-VPGs.

5.1 Future works

In the future, we will further explore the ONU internetworking architectures in a WDM-PON. There are three major prospects need to be improved in the ONU-broadcast and ONU-VPGs formation functionality in a WDM-PON. First of all, automatic reconfigurable architectures for ONU-VPGs formation in a cost-effective way should be further investigated. With the automatic reconfigurable architectures, the network operators can easily adjust the ONU-VPGs configuration. Secondly, the modification of the RN and the ONUs should be further reduced when the WDM-PON needs to be upgraded for the ONU-VPGs formation. Last of all, one single transceiver should be employed at the ONU to transmit and receive the upstream traffic as well as the inter-ONU traffic simultaneously to further reduce the cost to implement the internetworking functionality in a WDM-PON. With the improvement in these prospects, we can expect the internetworking architectures for WDM-PONs could be promising in future.

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